Blue-Green Systems

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Blue Green Systems for urban heat mitigation: mechanisms, effectiveness and research directions

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ABSTRACT

Reflected in the growing body of literature, urban heat mitigation is increasingly relevant as cities experience extreme heat, exacerbated by climate change and rapid urbanisation. Most studies focus on urban–rural temperature differences, known as the Urban Heat Island, which does not provide insight into urban heat dynamics. Here, we synthesise current knowledge on spatio-temporal variations of *heat sources* and *sinks*, showing that a targeted and absolute understanding of urban heat dynamics rather than an urban–rural comparison should be encouraged. We discuss mechanisms of *heat sinks* for microclimate control, provide a clear classification of *Blue Green Systems* and evaluate current knowledge of their effectiveness in urban heat mitigation. We consider planning and optimisation aspects of *Blue Green Infrastructure* (*greenery* and *water bodies/features*), interactions with *hard surfaces* and *practices* that ensure space and water availability. *Blue Green Systems* can positively affect urban microclimates, especially when strategically planned to achieve synergies. Effectiveness is governed by their dominant cooling mechanisms that show diurnal and seasonal variability and depend upon background climatic conditions and characteristics of surrounding urban areas. Situationally appropriate combination of various types of *Blue Green Systems* and their connectivity increases heat mitigation potential while providing multiple ecosystem services but requires further research.

Key words: connectivity, ecosystem services, multi-functional systems, nature-based solutions, urban microclimate, urban planning

HIGHLIGHTS

- Evaluation of urban heat dynamics; *heat sources* and *sinks*.
- Structure and systematic evaluation of different *Blue Green Systems*.
- Urban heat curtailed with strategically planned, site-specific *Blue Green Systems*.
- Cooling beyond the microscale possible with blue-green connectivity.

NOMENCLATURE

Land surface temperature (LST)	Temperature of a surface at its interface with a volume of air (Oke *et al.* 2017)
Air temperature	Temperature of an air layer or volume (Oke *et al.* 2017)
Physiological equivalent temperature (PET)	An index to assess the thermal environment that corresponds to the 'ambient temperature of a reference environment that will cause the same physiological response for a standard person as the actual environment would' (Lai *et al.* 2019)
Human thermal comfort	'[B]iometeorological parameter for the evaluation of comfort levels under different climate conditions' (Xu *et al.* 2010)
Microscale	10^{-2} to 10^3 m (Oke 1987)
Local scale	10^2 to 5×10^4 m (Oke 1987)
Mesoscale	10^4 to 2×10^5 m (Oke 1987)
Macroscale	10^5 to 10^8 m (Oke 1987)
Urban heat island (UHI)	Surface or air temperature difference between urban and rural sites (Oke 1987)
Urban heat island intensity	Difference between the urban peak and the rural temperature (surface or air) (Oke 1987)

Park cool island (PCI)	Urban park air temperature is generally cooler than in surrounding urban areas (Spronken-Smith & Oke 1998)
Urban boundary layer (UBL)	Layer of air adjacent to the urban surfaces (local to mesoscale) (Oke 1987)
Urban canopy layer (UCL)	Layer of air beneath the roof level, building-air-volume (microscale) (Oke 1987)
Urban canyon	Volume between the ground and walls of adjacent buildings (Oke 1987)
Urban geometry	Arrangement of buildings separated by urban canyons (Oke 1987)
Ecosystem services	'[B]enefits humankind derives from the workings of the natural world' (Ruefenacht & Acero 2017)
Blue Green Systems	The strategic and systematic planning, modelling, quantifying and optimising of Blue Green Infrastructure, its interactions with the built environment and practices that ensure the space and water availability required to provide various ecosystem services (Bozovic *et al.* 2017)
Blue Green infrastructure (BGI)	Strategically planned, multi-functional networks of *greenery* and/or *water bodies/features* that can include both natural landscape components and engineered systems (Sörensen *et al.* 2016; Ghofrani *et al.* 2017; Oral *et al.* 2020)
Greenery	Natural landscape components or engineered systems that are predominantly reliant on plants for their main processes (Coutts *et al.* 2013b)
Water bodies/features	Natural landscape components or engineered systems that are predominantly reliant on water for their main processes (Kleerekoper *et al.* 2012)
Hard surfaces	Urban components made of anthropogenic materials (i.e., non-BGI components of the urban fabric) (Bozovic *et al.* 2017)
Practices	The strategic planning to ensure the space and water availability required for an effective implementation of *Blue Green Systems* (Bozovic *et al.* 2017)

1. INTRODUCTION

Urbanisation, or an increase in impermeable surfaces and construction of dense building canyons, changes the local water cycle and energy balance (Oke 1987; Coutts *et al.* 2013b; Manoli *et al.* 2019). Consequently, temperatures in cities tend to be higher than in their surrounding rural areas, leading to discomfort or heat stress for urban dwellers during some periods of the year (Loughnan *et al.* 2010; Tian *et al.* 2021). Urban heat is likely to be exacerbated as climate change brings an expected increase in heat wave frequency and drought (IPCC 2014) and significant localised warming (Zhao *et al.* 2021). The combination of rapid urbanisation and climate change will reduce human thermal comfort (Coutts *et al.* 2013b; Broadbent *et al.* 2018c) and increase heat-related risks of morbidity and mortality (Loughnan *et al.* 2010; Stewart & Oke 2012; Akbari & Kolokotsa 2016; Voelkel *et al.* 2016; Erell 2019). With over half of the world's population now living in urban areas (United Nations 2019), cities will need to adapt in order to accommodate the growing population, while maintaining or improving quality of life.

Temperature increases between urban areas and the surrounding rural and natural hinterlands are particularly noticeable and are an extensively documented phenomenon known as the 'Urban Heat Island (UHI) effect' (Erell 2019; Jamei & Tapper 2019). City planners have sought to minimise UHI intensity, defined as the difference between the peak air temperature in the urban canyon and the background rural temperature (Oke 1987). However, within cities, the severity of urban heat and risk to the population is not necessarily measurable through studies contrasting them with rural areas (Martilli *et al.* 2020). Furthermore, urban surface and air temperatures are not homogenous and vary over time and space due to differences in land-use, urban geometry, meteorological and morphological influences (Oke 1987) that can be similar in magnitude to the urban–rural temperature difference (Broadbent *et al.* 2018c). In short, UHI intensity has become a fashionable concept in urban planning but represents somewhat of a 'red herring'. Recent criticism rightfully demonstrates that excessive focus on this comparative metric has little relevance for urban heat mitigation (Erell 2019; Martilli *et al.* 2020) and, consequently, for improving the liveability of urban environments. Research and communication of its findings need to transition towards a more targeted and absolute (rather than comparative) understanding of urban heat and its dynamics.

Strategies are thus needed to identify high-risk neighbourhoods and to moderate and mitigate heat events. A variety of strategies typically used for decentralised and sustainable urban (storm)water management (known by many names including Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID), sponge city technologies (Workman 2018) among others (Fletcher *et al.* 2015; Matsler *et al.* 2021)) have been praised for their multi-functional benefits including managing stormwater quantity and quality (e.g., Walsh *et al.* 2005; Jamali *et al.* 2020), facilitating the provision of alternative sources of water supply (e.g., Wong *et al.* 2013) and other ecosystem services (Kuller *et al.* 2017; Hou *et al.* 2019) and, more recently, mitigating urban heat (Broadbent *et al*. 2018c; Jamei & Tapper 2019; Zhang *et al.* 2020). Such systems are, to date, encompassed within the recent umbrella term of *Blue-Green Systems* (Lawson *et al.* 2014; Bozovic *et al.* 2017), which are also regarded as urban or 'small-scale' nature-based solutions (Ruangpan *et al.* 2020). Since conventional drainage infrastructure was historically designed to rapidly remove stormwater (Richards & Edwards 2018), these strategies generally aim to attenuate, infiltrate and/or retain surface runoff. They ultimately increase local evapotranspiration (ET) and provide evaporative cooling of urban surfaces. Concurrently, there is also greater recognition of the need to protect and enhance green space and water bodies (blue features) within the urban form due to their recognised human health, amenity and ecological functions (Bolliger & Silbernagel 2020; Oral *et al.* 2020).

The use and effectiveness of such decentralised measures, henceforth referred to as *Blue Green Systems*, is less often considered for urban cooling, but has been steadily gaining attention (Coutts *et al.* 2013b; Broadbent *et al.* 2018c) as evidenced by the rising number of scientific publications encompassing both topics (see Figure 1). Bibliographic analysis (see the search terms in the Supplementary Information) reveals a steady increase in publications (relative to the Scopus database's increasing trend – Figure 1(a)) on urban heat since 1967 and in relation to *Blue Green Systems* since the early 1990s (Figure 1(b)). Aspects of mitigation and human thermal comfort followed in the early 2000s (Figure 1(b)). Publications have emerged broadly across the world, spread across multiple countries and continents (Figure 1(c)).

Despite growing attention, many knowledge gaps remain, including how to harness the heat mitigation potential of *Blue-Green Systems* and implement appropriate types of measures. Improvements are particularly needed in understanding: (1) the mechanisms by which different *Blue Green Systems* mitigate urban heat, (2) their general effectiveness considering their decentralised and distributed nature; (3) the potential of combining different types of *Blue-Green Systems* and (4) their function under different spatial and temporal microclimate variations in different climate regions (e.g., Cui *et al.* 2021).

This study evaluates the state of knowledge of the potential of *Blue Green Systems* to mitigate urban heat and, concurrently, understand and provide guidance for their effective design and implementation. Most notably, we frame our study within the broader lens of urban heat mitigation as opposed to UHI mitigation, which is one subtopic thereof. We cover three key aspects: (1) reviewing current knowledge on the spatio-temporal variations of heat across the urban form (i.e., *heat sources* and *heat sinks*), (2) understanding current *Blue Green Systems* mechanisms by which potential *heat sinks* provide microclimate control and ultimately (3) evaluating and discussing the potential of *Blue Green Systems* to mitigate urban heat. Additionally, we highlight key research priorities for *Blue Green Systems* in urban heat mitigation applications and provide clarity and consistency in planning approaches, quantitative assessment and, notably, the communication of strategies to an interdisciplinary audience.

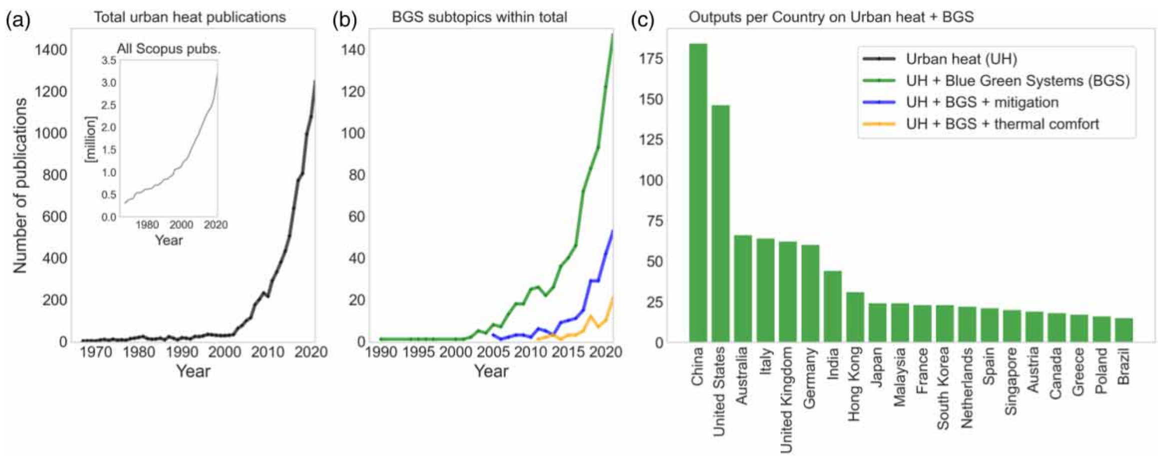

Figure 1 | Bibliographic analysis of publications on urban heat based on Scopus database; (a) total publications on urban heat since 1967 and reference to total Scopus publications, (b) subsets of publications on urban heat containing BGI search terms, mitigation and thermal comfort, (c) total number of publications relating to urban heat and BGI search terms (see Suplementary Information for search terms details) by country (Top 20). For detailed search queries, refer to Supplementary material.

Our literature search is based on the systematic combination of topics on urban heat and variants of the Blue Green Systems terminology (see Figure 1 and supplementary information for detailed search queries). It also includes, where relevant, examples from grey literature on known case studies. We focus specifically on the outdoor environment and consider both day- and night-time impacts of urban heat. Spatially, we remain within the urban environment, i.e., the Urban Canopy Layer (UCL) (Oke 1987), but acknowledge that effects are observable and influenced by the broader Urban Boundary Layer (UBL) (Oke 1987), i.e., well above rooftops, and by regional synoptic climate conditions. Notably, indoor thermal comfort and building energy efficiency are mentioned only marginally to evaluate the effectiveness of specific strategies from a holistic perspective (e.g., greening of buildings). Other aspects of *Blue Green Systems* such as economics and other benefits not related to urban heat are not explicitly evaluated.

2. SPATIO-TEMPORAL VARIABILITY AND URBAN HEAT MITIGATION MECHANISMS

A fundamental problem with the current body of urban microclimate literature is the lack of a clear differentiation in terminology between urban heat as a relative spatial phenomenon within the city and the UHI (Oke 1987) or Urban Cool Island (UCI) (Manoli *et al.* 2019) effects, which refer to the said difference between urban and rural temperatures. For clarity, we encourage a more comprehensive terminology that enables the discussion of intra-urban heat pattern variability and allows the comparison of thermal environments of cities in different climatic regions.

Within the urban fabric, *heat sources* release excess heat to their adjacent environment (e.g., traffic and other anthropogenic heat emissions and heat store derived from natural processes) (Li *et al.* 2017; Sun *et al.* 2018). *Heat sinks*, on the contrary, are land surface patches with low surface temperatures that dissipate heat from their surroundings (Santamouris *et al.* 2017) and thereby cool the adjacent environment (Coseo & Larsen 2014; Li *et al.* 2017). This surface classification framework is not static and the contributions of heat sources and sinks to the urban microclimate are temporally and spatially variable.

The main surface energy balance processes are presented in Figure 2 and encompass a balance between sensible (H), latent (LE) and soil (conductive - G) heat fluxes, resulting from net incoming solar radiation (Rn). Notably absent in such simple energy balances is the role of horizontal advection and reflection of radiation from buildings, which play a critical role in the heating and cooling across urban areas and partly determines the effectiveness and area of influence of *Blue Green Systems*.. Horizontal processes are more challenging to assess and frequently overlooked, especially in complex urban geometries. Radiation reflected off buildings will change depending on façade material, building height and presence of vertical greenery, which are also difficult to capture by simple two-dimensional analysis. These can, however, be quantifiable through more detailed three-dimensional studies, as demonstrated by Back *et al.* (2023) and Nice *et al.* (2018). Furthermore, radiant heat within the urban canyon also affects human thermal comfort, which is often not captured sufficiently through simple estimation or measurement of air temperature (Back *et al.* 2020) and requires consideration of humans' interaction with local heat exchange processes (e.g., Lindberg *et al.* 2008; Matzarakis *et al.* 2010).

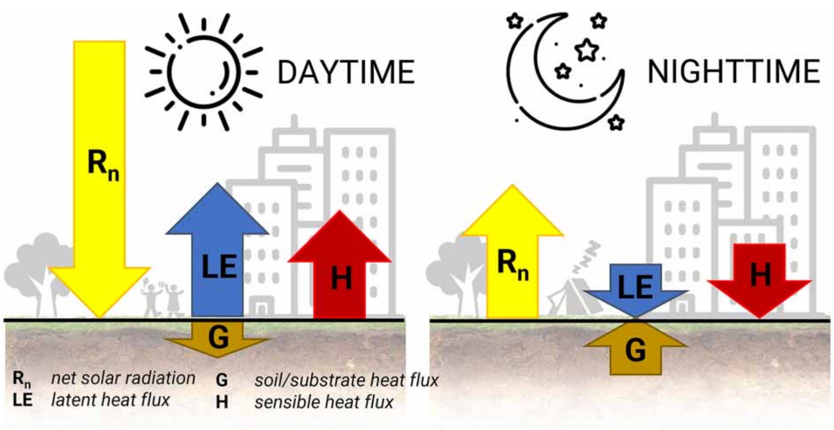

Figure 2 | Illustration of a typical surface energy balance with key flux components based on the net solar radiation during daytime and nighttime.

2.1. Heat sources and sinks

Sources of urban heat (i.e., *heat sources)* can be mitigated by altering the urban microclimate through changes in the energy and water balance and wind patterns. These alterations rely on (1) modifications to the urban form (e.g., geometry and morphology (Ruefenacht & Acero 2017)) as well as (2) a combination of distinct physical mechanisms, referred to as 'heat sinks,' including evaporative cooling, shading, heat storage (related to surface characteristics) and wind flow. *Blue Green Systems* have the potential to behave as heat sinks within the urban form.

Evaporation or *ET* links the energy balance with the hydrological cycle and occurs when a fraction of the energy stored in water is released as latent heat. Air temperature above the surface is thus reduced (He *et al.* 2019), a concept referred to as 'evaporative cooling,' because latent heat replaces sensible heat (Oke 1987). *Shading* reduces the amount of incoming solar radiation absorbed by the surface, thus reducing air temperatures and heat storage in the urban fabric below (Oke 1987). In some cases (e.g., shade from buildings or trees), pedestrians are also shaded, thus directly increasing human thermal comfort (Lai *et al.* 2019). *Heat storage,* which is limited by shading, is also reduced by increasing evaporative cooling (Shashua-Bar & Hoffman 2000) and/or altering urban surface characteristics (e.g., controlling the emissivity and surface temperature with pervious or reflective surfaces) (e.g., Oswald *et al.* 2012; Santamouris 2013; Nwakaire *et al.* 2020; Cui *et al.* 2021). Changes in heat storage in the urban fabric affect thermal comfort immediately, but through limiting heat storage during the day, re-emission of heat at night is also reduced. Concurrently, solutions must limit the amount of radiation reflected within the canyon to also ensure that pedestrians are not adversely affected during daytime (Taleghani 2018). *Wind patterns* affect the intra-urban air temperature distribution (Ha *et al.* 2020) and human thermal comfort (Lai *et al.* 2019).

The cooling mechanisms of urban *heat sinks* vary diurnally, seasonally and regionally, which ultimately influences their effectiveness. For instance, the effectiveness of evaporation from surface water increases as the discrepancy between water surface and ambient temperatures widens (Ampatzidis & Kershaw 2020; Hu & Li 2020). As a result, daytime evaporative cooling is most effective in early spring and mid-summer (Hathway & Sharples 2012) and during extreme heat events (Broadbent *et al.* 2018b) when water temperatures are low compared to the ambient temperature. However, evaporation from surface water increases air humidity, which may decrease thermal comfort (Theeuwes *et al.* 2013), especially in areas where humidity is already high (Jamei *et al.* 2020). These results are, however, controversial (Xu *et al.* 2010) since they depend on background climate conditions. Evaporative cooling is ultimately most effective in hot-dry climates with low ambient humidity (Norton *et al.* 2015). A summary of the significance, limitations and amplifying factors of the different cooling mechanisms for three climatic conditions (hot-humid, hot-dry and warm-temperate) is presented in Table 1 and discussed hereafter.

Shading can play a considerable role in temperature reductions and human thermal comfort, especially when ET is less effective. In summer, shading can delay diurnal peak air temperatures in humid regions (Chen *et al.* 2009) and account for the majority of temperature reductions in dry areas (Shashua-Bar & Hoffman 2000). The effectiveness of shading does, however, vary seasonally and diurnally (Back *et al.* 2020). Vegetation that shades the ground during the day reduces the heat storage in the urban fabric, making vegetation a particularly effective night-time heat sink (Upmanis *et al.* 1998; Sun *et al.* 2018; Hu & Li 2020). In contrast, water, which has a high heat capacity, releases stored heat slowly as air temperatures fall below water temperatures in the evening and thus acts as a thermal buffer (Steeneveld *et al.* 2014; Manteghi *et al.* 2015; Gunawardena *et al.* 2017; Targino *et al.* 2019).

It is noteworthy that urban dense vegetation can block ventilation, trapping daytime heat and therefore prevent fast cooling after sunset (Zheng *et al.* 2016; Ha *et al.* 2020). Ventilation corridors can be used to redirect cold air from the suburbs or neighbouring heat sinks (e.g., urban parks) into hotter city centres (Bowler *et al.* 2010), which is especially relevant for night-time cooling (Broadbent *et al.* 2018c; Peng *et al.* 2020a). However, the redirection of air from upwind heat sources (e.g., industrial areas) can increase heat exposure downwind (Coseo & Larsen 2014) thus familiarity with adjacent urban areas is relevant for planning.

Depending on the goals for urban heat mitigation (e.g., reducing peak temperatures, night-time heat exposure or thermal comfort), the given climatic conditions (i.e., ambient humidity and temperature) and the geometry and morphology of the urban fabric, the most suitable combination of heat mitigation measures should be selected based on their cooling mechanisms. In Section 3, Table 2 links the heat mitigation measures associated with *Blue Green Systems* to their main cooling mechanisms, thereby aiming to support the optimal design of *Blue Green Systems*.

Table 1 | Overview of strategies for creating urban heat sinks to cool cities considering different background climatic conditions

Cooling mechanism	
Evaporation from surface water	**Significance:** direct daytime cooling (latent heat fluxes partially replace sensible heat fluxes), indirect night-time cooling (heat storage reduction in the urban fabric) **Limitations:** high ambient humidity (in hot-humid conditions); low air temperatures (in warm-temperate conditions) **Amplifying factors:** wind speed
Evapotranspiration (ET) from vegetation and soil	**Significance:** no notable significance **Limitations:** low water availability, low soil moisture content (in hot-dry and warm-temperature climatic conditions) **Amplifying factors:** irrigation (high potential for alternative water sources – in hot-dry and warm-temperature climatic conditions)
Shading	**Significance:** direct daytime cooling, indirect night-time cooling (heat storage reduction in the urban fabric) → very important for human thermal comfort when evaporation and ET are limited **Limitations:** reduced effectiveness in narrow urban canyons (building shadows) **Amplifying factors:** high dense vegetation cover
Heat storage reduction	**Significance:** reduction of daytime heat storage in the urban fabric mitigates night-time re-emission of heat **Limitations:** heavy thermal masses (*hard surfaces:* e.g., buildings, streets), densification **Amplifying factors:** pervious surfaces, reflective surfaces, shading, evaporation from surface water, ET from vegetation and soil
Wind flow alteration	**Significance:** increases human thermal comfort in urban canyons, transports cool air from upwind *heat sinks* for night-time cooling (cold air drainage from surrounding rural areas) **Limitations:** buildings perpendicular to wind flow and dense vegetation cover can block ventilation **Amplifying factors:** ventilation corridors, building height diversity, wide and long urban canyons

2.2. Spatial variability of urban heat

Air temperature can vary considerably within cities or neighbourhoods (Zoulia *et al.* 2009). Observed air temperatures varied spatially by around 2 °C on average within a suburban neighbourhood in Adelaide (Australia, hot-dry summers) (Broadbent *et al.* 2018c) and from 1.2 to 7.0 °C (seasonal and diurnal variability) within the city of Beijing (China, dry winters/hot-humid summers) (Yan *et al.* 2014). City centres and their downwind areas are often day- and night-time heat sources (Peng *et al.* 2020a) due to a high percentage of impervious surfaces and a dense arrangement of buildings, making them especially prone to heat exposure (Stadt Zürich 2020). Nonetheless, hotspots can also develop in other parts of an urban conglomeration (Li *et al.* 2017; Peng *et al.* 2020a) and are particularly apparent in sprawled areas (Tian *et al.* 2021). These hotspots subsequently expand and connect to form larger aggregated areas. Previously unaffected areas evolve into hotspots, exacerbating impacts on health and urban climate (Yue *et al.* 2019).

According to some authors, wind may be the primary factor causing intra-city variability of daytime air temperatures. Regardless of season, an increase in wind speed during the day correlates to a decrease in air temperature (Ha *et al.* 2020); a 1 m s^{-1} increase in wind velocity can lead to a cooling effect of −0.6 °C (Broadbent *et al.* 2018c). Localised wind direction and speed are ultimately governed by regional air circulation systems, which may vary throughout the day. However, the airflow distribution within the urban canyon also depends significantly on urban geometry and morphology: Hathway & Sharples (2012) found that the wind velocity through an open street was twice as high as in an enclosed street.

2.3. Temporal (diurnal) variability of urban heat

Surface and air temperatures (i.e., urban heat) are also not static throughout the course of the day (Oswald *et al.* 2012; Broadbent *et al.* 2018c; Ziter *et al.* 2019) as they are driven by daily variations in the energy balance (see Figure 2), which, as demonstrated in various studies (Li *et al.* 2017; Hou *et al.* 2019; Yue *et al.* 2019; Peng *et al.*

Table 2 | Overview of different urban heat mitigation solutions, their classification and underlying cooling mechanisms. Practices are strategic planning measures that ensure space and water availability and therefore enhance cooling with BGI. The information is compiled from the literature review and from our own assessment

Symbology
✓ yes
◌ design/operation dependent
● cooling
●● enhanced cooling

		CLASSIFICATION				KEY COOLING MECHANISMS				
		Natural landscape component	**Engineered system**	**Blue Green Infrastructure**	**Blue Green System**	**Wind flow alteration**	**Shading**	**Evaporation from surface water**	**Evapotranspiration from vegetation and soil**	**Heat storage reduction**
Greenery	Short vegetation	✓		✓	✓				●	●
	Trees	✓		✓	✓	●	●		●	●
	Urban parks	✓		✓	✓	◌	◌	◌	●	●
	Littoral/riparian vegetation	✓		✓	✓	◌	◌		●	●
	Vertical greenery systems		✓	✓	✓	◌	◌		●	●
	Green roofs		✓	✓	✓	◌	◌		●	◌[a]
	Vegetated swales and bioretention systems		✓	✓	✓	◌	◌	●	●	●
Water bodies/ features	Natural ponds and lakes	✓		✓	✓			●		◌
	Constructed ponds and sedimentation basins		✓	✓	✓			●		◌
	Rivers	✓		✓	✓			●		◌
	Constructed urban wetlands		✓	✓	✓	◌	◌	●	●	◌
	Fountains and water sprinklers		✓	✓	✓			●		◌
Hard surfaces	Pervious pavements		✓	(✓)[b]	✓			◌	◌	◌
	Reflective surfaces		✓							●
Practices	Irrigation				✓				●●	◌
	Surface watering				✓			●●		●
	Planning of ventilation corridors				(✓)[c]	●●				

[a]In some situations, green roofs can increase heat storage when compared with bare roofs.
[b]Some designs of pervious pavements contain grass or other types of short vegetation (which makes them BGI).
[c]The strategic planning of wedged greenspaces or linear surface *water bodies* is also considered *Blue Green Systems*.

2020a), depend substantially on the land-use characteristics. Some researchers advocate that heat mitigation should prioritise daytime extreme heat events during the summer (Sun *et al.* 2018; Martilli *et al.* 2020). Yet, this focus may be too narrow as the importance of night-time cooling cannot be neglected, especially since night-time radiant heat impact on thermal comfort plays an important role in healthy sleep (Steeneveld *et al.* 2014) and general well-being. The slow night-time release of stored heat worsens nocturnal overheating of urbanised areas (Gunawardena *et al.* 2017; Erell 2019; Rodríguez *et al.* 2020).

3. HEAT MITIGATION POTENTIAL OF BLUE GREEN SYSTEMS

3.1. Defining Blue Green Systems

Blue Green Infrastructure (BGI) is the more recent umbrella term (Lawson *et al.* 2014; Bozovic *et al.* 2017; Ghofrani *et al.* 2017) that describes the variety of urban or small-scale nature-based solutions (NbS) (Ruangpan *et al.* 2020) combining blue, green and grey elements to provide multiple benefits. Despite previous attempts to consolidate terminology (Fletcher *et al.* 2015), semantics have often created confusion on how these systems should be defined. Literature specific to BGI (Sörensen *et al.* 2016; Bozovic *et al.* 2017; Ghofrani *et al.* 2017; Oral *et al.* 2020), however, outlines four commonalities including:

- comprising *greenery* (i.e., vegetation, green roofs, urban parks) and/or *water bodies/features* (i.e., rivers, ponds and fountains);
- existing either as natural landscape or engineered systems;
- underpinned by a strategic planning intent for which they are to be used; and
- provide ecosystem services and increase interconnectivity of natural spaces.

BGI are embedded within the broader concept of *Blue Green Systems,* comprising (i) strategic and systematic planning, modelling, quantification and optimisation of BGI, (ii) their interaction with the built environment and (iii) practices to ensure space and water availability such that BGI can provide their intended ecosystem services (Bozovic *et al.* 2017). Changes to the characteristics of *hard surfaces* can contribute to altering the urban water cycle and/or the energy balance (Nwakaire *et al.* 2020); however, *hard surfaces* are only considered as *Blue Green Systems* if they contain water (e.g., pervious pavements) or vegetation. For instance, altering the reflectivity of *hard surfaces* (e.g., high-albedo roofs) would not be classified as a *Blue Green System*; but, nonetheless, discussed in this review because of its heat mitigation potential and for comparison. Changes in urban geometry (e.g., planning of ventilation corridors), which can improve human thermal comfort in urban canyons are classifiable as *Blue Green Systems* if *greenery* (e.g., green corridor) or *water bodies* (e.g., river) are deliberately implemented therein. Some *Blue Green Systems* are strategic planning measures that ensure space and water availability required for effective implementation of BGI, hereafter referred to as *practices* (e.g., 'Uchimizu' – Solcerova *et al.* 2018). Water availability can also be increased by retaining alternative water sources within cities (e.g., rainwater), performed optimally in a decentralised manner (Oke 1987; Upmanis *et al.* 1998; Theeuwes *et al.* 2013; Yan *et al.* 2014; Manteghi *et al.* 2015; Gunawardena *et al.* 2017; Sun *et al.* 2018; Jamei & Tapper 2019; Targino *et al.* 2019; Hu & Li 2020). Water retention and reuse, which has the potential to preserve the 'natural' water cycle (Kleerekoper *et al.* 2012; Coutts *et al.* 2013b), can also include other alternative water sources.

Figure 3 illustrates a range of *Blue Green Systems*, other common measures and alternative water sources, ranging from large- (e.g., large ponds, river restorations), medium- (e.g., constructed wetlands, swales), to small-scale (e.g., permeable pavements, vertical greenery, green roofs). Not all engineered systems are necessarily *Blue Green Systems* (see also Table 2) but are included for comparison purposes. Table 2 provides more details of many common *Blue Green Systems*, for which the literature illustrates a comprehensive understanding.

The temperature reductions reported by the different *Blue Green Systems* are presented in Tables 3–6. It is noteworthy that these temperature reductions are strongly affected by the local conditions of the respective study and, therefore, the figures presented should always be considered with the corresponding metadata, as demonstrated by Stewart (2011). Other authors (e.g., Krayenhoff *et al.* 2021) used different metrics, such as the albedo cooling effectiveness (ACE) and the vegetation cooling effectiveness (VCE), for comparing the effectiveness of the different cooling measures. In this study, these metrics are not considered as the main goal is to provide a general overview of the potential of *Blue-Green Systems* for air temperature reduction and not to conduct a detailed assessment of the effectiveness of each of the different *Blue-Green Systems*.

Figure 3 | *Blue Green Systems* and other measures (reflective surfaces) for urban heat mitigation. *Blue Green Systems* include *Blue Green Infrastructure* (*greenery* and *water bodies/features*), some *hard surfaces* and *practices* that ensure space and water availability for enhanced cooling.

3.2. Greenery

Increasing vegetation cover has been shown to be one of the most effective strategies for cooling outdoor urban environments (Robitu *et al.* 2006; Zhao & Fong 2017; Jamei & Tapper 2019; Marando *et al.* 2022). Vegetation cover supports a decrease in surface (Liu *et al.* 2019) and daily peak air temperatures (Hamada & Ohta 2010; Ortega-Rosas *et al.* 2020) through a varied combination of various cooling mechanisms (see Table 2). Compared to *water bodies/features*, *greenery* strategies can contribute to higher temperature reductions during day and night (Hu & Li 2020). However, an accurate choice of the type of vegetation considering background climatic conditions is crucial. For example, in desert cities where cooling effects are important throughout the year, evergreen and native desert trees should be used (Ortega-Rosas *et al.* 2020). Table 3 summarises reported surface and air temperature reductions, achieved improvement in human thermal comfort and extent of cooling due to the integration of different forms of BGI that are predominantly reliant on *greenery*. These notably differ in terms of design (e.g., vegetation height, degree of shading, incorporation of water bodies/features) and are discussed hereafter.

3.2.1. Short vegetation

Short vegetation (i.e., lawns, shrubs) provides little shading. Notwithstanding, air temperatures above and downwind of such systems are usually cooler than above impermeable surfaces, indicating that ET and/or albedo contribute to changing the microclimate (Oke *et al.* 1989; Zheng *et al.* 2016; Lai *et al.* 2019). Due to low aerodynamic resistance, grass promotes nocturnal convective cooling (Bowler *et al.* 2010; Broadbent *et al.* 2018c). This phenomenon is less pronounced than in rural areas as the re-emission of stored heat from the surrounding urban landscape, which is especially pronounced after sunset, can inhibit the cooling effect of urban green spaces (Oke *et al.* 1989; Zoulia *et al.* 2009). Nevertheless, if the nocturnal surface temperature of short vegetation is lower than that of the surrounding urban areas, it still functions as a *heat sink* and the comparison to rural areas becomes less relevant.

The potential of grass to be a daytime *heat sink* decreases during dry periods when soil moisture is low (Norton *et al.* 2015; Broadbent *et al.* 2018c; Meili *et al.* 2019). This clearly indicates the potential of actively irrigating short vegetation to maximise its cooling effect. Mixing different vegetation types (e.g., grass, trees) creates a

Table 3 | Reported temperature reductions and area of influence of *greenery*

Mitigation measure	Reported temperature reductions	Area of influence	References
Short vegetation	**Surface temperature**: • grass-covered greenspace: 1–2.21 °C • day: 1.9 °C • night: 3.2 °C **Air temperature:** 2 m above the ground: • average: 0.1–2.2 °C, peak: 0.1–4 °C	**Surrounding surface temperature:** • grass-covered greenspace: 105 m **Air temperature:** *no results found*	Meili *et al.* (2019), Santamouris *et al.* (2017), Spronken-Smith & Oke (1998), Yang *et al.* (2020)
Trees	**Surface temperature:** • tree-covered greenspace: 3.58°C • directly below the tree: 15.6 °C **Air temperature:** • hot-humid (one single tree): 0.6–2.8 °C • hot-dry (urban wooded sites with a width of 20 to 60 m): 2.8 °C **Human thermal comfort:** • 3.9–16 °C (PET) • 4.23°C (mean radiant temperature)	**Surrounding surface temperature:** • tree-covered greenspace: 145 m **Air temperature:** • hot-dry (urban wooded sites with a width of 20 to 60 m): 100 m **Human thermal comfort:** *no results found*	Abreu-Harbich *et al.* (2015), Cheung & Jim (2018), Richards & Edwards (2018), Santamouris *et al.* (2018), Shashua-Bar & Hoffman (2000), Ziter *et al.* (2019), Jia & Wang (2021)
Littoral/riparian vegetation	**Surface temperature:** *no results found* **Air temperature:** *no results found* **Human thermal comfort:** • 1.4 °C (apparent temperature)	**Surrounding surface temperature:** *no results found* **Air temperature:** *no results found* **Human thermal comfort:** • 10–20 m from the waterfront	Gupta *et al.* (2019), Hu & Li (2020), Manteghi *et al.* (2015), Xu *et al.* (2010)
Urban parks	**Air temperature:** • day (average): 0.94–5.7 °C, (peak): 9 °C (depends on the type of park) • night: 1.15–2.4 °C	**Air temperature:** • small park (0.1 ha): 100 m • bigger park: several 100 m, about one park width	Bowler *et al.* (2010), Hamada & Ohta (2010), Jamei *et al.* (2020), Oliveira *et al.* (2011), Spronken-Smith & Oke (1998), Zoulia *et al.* (2009), Wong *et al.* (2021)
Vertical greenery systems	**Surface temperature:** • day: 7–17 °C **Air temperature:** • 0.96–3.33 °C (max. when irrigated)	**Surrounding surface temperature:** *no results found* **Air temperature:** • maximum effect: 0.15 m • cooling effect diminishes within 0.6 m	Akbari & Kolokotsa (2016), Jamei & Tapper (2019), Wong *et al.* (2010), Cameron *et al.* (2014), Wong *et al.* (2021)
Green roofs	**Surface temperature:** • day (average): 10–17 °C, (peak): 25 °C compared to a conventional roof: • day: 20.5 °C • night: −7.1 °C (warming)	**Surrounding surface temperature:** *no results found* **Air temperature:** • 40 m	Block *et al.* (2012), Jamei & Tapper (2019), Peng & Jim (2013), Santamouris (2014), Sieker *et al.* (2019), Berardi (2016), Blanusa *et al.* (2013), Li Bou-Zeid & Oppenheimer (2014), MacIvor *et al.* (2016), Scherba *et al.* (2011),

(*Continued.*)

Table 3 | Continued

Mitigation measure	Reported temperature reductions	Area of influence	References
	Air temperature: • above the roof: –0.2–1.5 °C (warming possible) • at pedestrian level: 0.4–1.7 °C (low-rise building) • when implemented at city scale: 0.3–3 °C		Solcerova *et al.* (2017), Wong *et al.* (2021)
Vegetated swales and bioretention systems	**Surface temperature:** *no results found* **Air temperature:** • 16:00: 1.3 °C	**Surrounding surface temperature:** *no results found* **Air temperature:** *no results found*	An *et al.* (2015)

cumulative cooling effect (Richards *et al.* 2020). Furthermore, understanding diurnal variability of the cooling potential of different types of short vegetation can improve targeted planning of urban *greenery* (e.g., in particularly vulnerable residential districts).

3.2.2. Trees

Trees are among the most studied types of *greenery* for heat mitigation (Shashua-Bar & Hoffman 2000; Santamouris *et al.* 2017; Sieker *et al.* 2019; Tiwari *et al.* 2021) and literature agrees on their efficacy in hot-humid, hot-dry and warm-temperate climates (Jamei & Tapper 2019). Street trees significantly cool urban areas during the day through shading and ET (Jamei *et al.* 2016; Taleghani 2018), thus they are particularly beneficial in environments with high midday pedestrian traffic (e.g., business districts). Shashua-Bar & Hoffman (2000) demonstrated that approximately 60% coverage was sufficient to offset vehicle heat emissions at street level (Tel Aviv, hot-dry summers) and that urban wooded area reduced air temperature by 2.8 °C with a zone of influence up to 100 m. Cooling is more effective in open spaces where direct solar radiation would otherwise reach the ground for most of the day and less pronounced in urban canyons because of shading from buildings (Santamouris *et al.* 2018). Water availability within the soil allows roots to access moisture for tree health. In dry regions, this is particularly challenging, so in these regions, trees are often combined with vegetated infiltration swales (or other systems) to retain stormwater (Sieker *et al.* 2019).

Despite the considerable number of studies on the impact of trees on urban heat mitigation, only a few consider the combination of trees and other cooling solutions such as short vegetation. Adequate mitigation strategies should adopt a holistic view and leverage the combination of cooling mechanisms to achieve maximum daytime temperature reduction (like shading) and fast radiative cooling of vegetation at night. Space and water availability, as well as spatial configuration of trees combined with other cooling solutions and integrated urban planning should be factored into future research to optimise their cooling potential throughout the day and night and maximise the impact of ventilation corridors.

3.2.3. Littoral/riparian vegetation

Shoreline *greenery* along ponded (i.e., littoral) or flowing *water bodies* (i.e., riparian) decreases the *water bodies*' night-time warming effect (Climatelier 2016; Gunawardena *et al.* 2017; Hu & Li 2020), reduces heat exposure and increases human thermal comfort along waterfronts (Xu *et al.* 2010; Hathway & Sharples 2012; Gupta *et al.* 2019). Field measurements (Xu *et al.* 2010) found that *greenery* along waterfronts improved the perception of thermal comfort up to an additional 6 m away. Configuration of such vegetation is important. If the canopy is too dense, ventilation and night-time cooling may become inhibited (Gunawardena *et al.* 2017). Simulations showed that the daytime PET during a heat wave could be reduced up to 10 °C by increasing waterfront *greenery* (i.e., trees) as well as other design interventions (e.g., unobstructed airflow, mist sprays, fountains and direct water access) (Climatelier 2016; Jacobs *et al.* 2020).

The synergistic effects of *greenery* and *water bodies* have only recently been examined. Hu & Li (2020) found that their combined influence on the annual mean daytime apparent temperature (considering air temperature, relative humidity and wind speed) was more than the sum of its parts (also: Jacobs *et al.* 2020). However, it remains unclear how this synergistic cooling works, how plants best adapt to high water availability and to what extent *greenery* can reduce the nocturnal warming effects of *water bodies*. Considering that many cities have historically been founded near *water bodies,* this understanding could prove widely applicable and address an essential gap in quantifying the impact that interconnected and interacting *Blue Green Systems* have on the thermal environment of cities.

3.2.4. Urban parks

Local cooling is greater if *greenery* is implemented in targeted configurations, e.g., large urban parks, rather than small and dispersed green areas (e.g., Santamouris *et al.* 2018; Ortega-Rosas *et al.* 2020). Often known as the Park Cool Island (PCI) effect, according to some authors (e.g., Ortega-Rosas *et al.* 2020), day- and night-time air temperatures in urban parks are generally cooler than in surrounding urban areas. Contrary, other studies such as Spronken-Smith & Oke (1998) have shown that PCI are either cooler during daytime or at night. A park's cooling performance and its radius of influence depend on the integrated *Blue Green Systems* (i.e., wooded sites, grassland or mixed-use parks) and, consequently, their dominant cooling mechanisms and configuration (Spronken-Smith & Oke 1998; Zoulia *et al.* 2009; Hamada & Ohta 2010).

Cooling extends beyond park boundaries (Saaroni & Ziv 2003; Oliveira *et al.* 2011; Žuvela-Aloise *et al.* 2016), depending on size (Jamei *et al.* 2020; Yao *et al.* 2022): up to 100 m for a small park (width: 20–60 m) (Shashua-Bar & Hoffman 2000) and several hundred metres for larger green areas (Spronken-Smith & Oke 1998; Hamada & Ohta 2010; Santamouris *et al.* 2018). Cooling decreases logarithmically with decreasing park size (Yang *et al.* 2020), indicating that small increases in park size could significantly extend its cooling radius. Moreover, other authors refer that park shape has the impact of urban park cooling potential; however, the findings are in some cases contradictory. For example, Li & Yu (2014) state that round-shaped parks have more impact on cooling the areas around the parks, whereas Yao *et al.* (2022) argue that parks with more complex shapes can have greater cooling impacts. This indicates an area requiring further clarification.

Air temperatures within and surrounding parks depend on the adjacent urban fabric (e.g., street orientation relative to wind direction, density of buildings, anthropogenic heat emissions) (Zoulia *et al.* 2009). These temperatures are highest in densely built-up areas, except during the evening (Žuvela-Aloise *et al.* 2016). However, any perceivable cooling effect beyond park borders is reduced if the surrounding urban area exhibits heavy anthropogenic heat emissions (Zoulia *et al.* 2009). As such, to be part of a city-wide heat mitigation system, parks should be connected to other *Blue Green Systems* in their surroundings (e.g., street trees). Studies about the city-wide impact of parks and their potential when combined with other *Blue Green Systems* are, however, still scarce, and tangible guidelines for their optimal design and distribution within cities absent.

3.2.5. Vertical greenery systems

The three basic components for designing vertical greenery systems (VGS) constitute plants, growth medium and irrigation (National Parks Board Singapore 2020). VGS can be integrated into urban landscapes as green walls or green façades. Green walls incorporate multiple 'containerised' plantings to create vegetation cover, whereas green façades rely on a small variety of plants that climb and spread (State of Victoria 2014). VGS absorb incident solar radiation and release this energy as ET, decreasing air temperature at the pedestrian level (Wong *et al.* 2010; Cameron *et al.* 2014; Peng *et al.* 2020c), increasing human thermal comfort in urban canyons (Jamei & Tapper 2019) and reducing building cooling or heating demand by blocking incident radiation and increasing insulation (Wong *et al.* 2010; Cameron *et al.* 2014; Peng *et al.* 2020c).

Achievable surface and air temperature reductions from VGS depend on plant species (Cameron *et al.* 2014), urban density (Cameron *et al.* 2014; Ruefenacht & Acero 2017; Jamei & Tapper 2019) and irrigation water availability (*et al.* 2014). Dense planting exhibits the largest decrease in building surface temperature as it more effectively blocks incident radiation (Cameron *et al.* 2014). However, VGS only influence the thermal environment in close proximity to the system (Block *et al.* 2012). Wong *et al.* (2010) measured a 3.3 °C reduction of ambient air temperature at 0.15 m from an irrigated green wall in a hot-humid climate with lower reductions already at 0.6 m. This implies that the application of VGS for outdoor heat mitigation will be limited to medium- and high-density urban areas (Santamouris *et al.* 2018; Peng *et al.* 2020c). Ideally, for neighbourhood or city-wide cooling, VGS should be installed at regular intervals and connected to other ground- or roof-based *Blue Green Systems* to maximise cooling potential. Significant irrigation is crucial to sustaining plant health. As such, the coupling with alternative water source provision (i.e., rainwater, greywater) is currently a topic of further investigation (e.g., Prodanovic *et al.* 2019, 2020). In addition to the potential of directly cooling the outdoor urban environment, VGS also positively influence indoor microclimate, which will indirectly reduce the generation of anthropogenic heat from air conditioning.

3.2.6. Green roofs

Green roofs potentially reduce peak sensible heat fluxes by approximately 70% and total daily sensible heat fluxes by 50–60% compared to conventional black roofs (Takebayashi & Moriyama 2007; Scherba *et al.* 2011). Composed of vegetation, engineered substrate and a waterproof membrane, such roofs reflect more solar radiation when compared to bare roofs and emit more energy as latent heat, ultimately reducing sensible heat and surface temperatures. Performance highly depends on soil moisture content (Djedjig *et al.* 2012), green roof type (i.e., extensive vs. intensive), climate and time of day (Morakinyo *et al.* 2017). When soils are dry, the fraction of sensible heat released can be up to three times greater than the fraction of latent heat (Tabares-Velasco 2009), thus resulting in occasional increases in daytime and nocturnal air temperatures above the surface by 0.2 °C (Morakinyo *et al.* 2017; Broadbent *et al.* 2018c).

Few have evaluated whether green roofs can lower the ambient temperature at the city scale or reduce local heat stress at the pedestrian level. Applying green roofs at the city scale could reduce the average ambient temperature between 0.3 and 3 °C (Santamouris 2014). Well-irrigated green roofs would need to make up nearly all rooftops in order to reduce daily maximum air temperature (at 2 m) by 0.5 °C (Li *et al.* 2014). In medium- and high-rise neighbourhoods, the cooling effect at the pedestrian level is negligible (Ng *et al.* 2012; Berardi 2016). Nonetheless, potential air temperature reductions within the urban canyons in low-rise neighbourhoods (<30 m) are achievable (Peng & Jim 2013; An *et al.* 2015). Green roofs can effectively mitigate urban heat, especially when they replace dark roof surfaces but are not necessarily superior to white or reflective roofs (Scherba *et al.* 2011). Continuous irrigation (Coutts *et al.* 2013a; Li *et al.* 2014) and dense planting with a mixture of plants that actively transpire (Coutts *et al.* 2013b; Jamei & Tapper 2019) are key design considerations. Understanding how green roofs can be designed, not only for their impact on urban temperature but also their multifunctional potential in managing stormwater runoff (Zhang *et al.* 2020), contribution to increased urban biodiversity and increased solar panel energy production (Cook & Larsen 2020) will support their broader adoption.

3.2.7. Vegetated swales and bioretention systems

Bioretention systems (or 'rain gardens') and vegetated swales combine vegetation and engineered soils to temporarily store runoff, remove contaminants and enhance infiltration and ET (Woods-Ballard *et al.* 2007). Although predominantly used for stormwater quantity and quality management, these systems potentially reduce surrounding air temperatures (through ET). To date, no studies have quantified subsequent temperature reductions from these systems alone, but in combination with others (e.g., vegetated swales (Sieker *et al.* 2019)) and in conjunction with stormwater management benefits (Woods-Ballard *et al.* 2007). Various studies found that ET reduced the outflow volume of bioretention systems by 19–84%, therefore significantly altering the water balance (Ebrahimian *et al.* 2019). This varied from 2 to 35%, when infiltration potential was eliminated and water impounded (i.e., evaporation from standing water), reducing overall stormwater attenuation. Current knowledge can only be drawn from related modelling studies on rooftop rain gardens. An *et al.* (2015), for example, found that air temperature above the rooftop rain garden was 0.5 °C cooler than above the green roof without the additional water storage and 1.3 °C cooler than above the bare roof during the hottest time of day. The cooling effect is thus more pronounced when water is available, implying that rain gardens and vegetated infiltration swales may provide no daytime cooling if stormwater and moisture retention are not appropriately accounted for, particularly during a heatwave when cooling is most needed (Gunawardena *et al.* 2017).

To date, we only have an indication that vegetated swales and bioretention systems might reduce adjacent air temperatures. Little is known about their cooling effect and area of influence for altering the urban microclimate, their sensitivity towards water availability and trade-offs associated with prolonged water storage, microclimate and stormwater management objectives.

3.3. Water bodies/features

Water bodies/features are either natural or man-made, ranging from lakes, rivers and constructed urban wetlands to fountains (Ruefenacht & Acero 2017). They also differ in terms of water flow (i.e., stagnant, flowing and dispersed) and provide aesthetic value as well as a variety of ecosystem services to city dwellers, including sustainable drainage (through available stormwater storage) (Gill *et al.* 2007; Kongjian *et al.* 2018) and cooling potential. Yet *water bodies/features* have received less attention in heat mitigation research than *greenery* (Koc *et al.* 2018). Different observational (e.g., Ishii *et al.* 1991; Saaroni & Ziv 2003; Chen *et al.* 2009; Li & Yu 2014; Hu & Li 2020), remote sensing (Gill *et al.* 2007; Gunawardena *et al.* 2017; Kongjian *et al.* 2018) and modelling (e.g., Theeuwes *et al.* 2013; Žuvela-Aloise *et al.* 2016; Zhao & Fong 2017) studies have quantified the cooling effect of *water bodies/features* on their surroundings.

Ongoing debate about (re)integrating water into cities as a viable strategy to reduce heat exposure has likely been caused by confusion between: (1) reducing peak daytime temperatures and (2) reducing night-time urban–rural temperature differences, i.e., mitigating the UHI effect. The specific heat capacity of water is advantageous to daytime cooling; significant downwind cooling of distributed *water bodies* has been reported during the daytime (Broadbent *et al.* 2018c). Conversely, the nocturnal warming potential of open *water bodies* questions its overall effectiveness in urban heat mitigation (e.g., Du *et al.* 2016; Gupta *et al.* 2019; Xue *et al.* 2019; Yang *et al.* 2020). Water surfaces are generally warmer at night than bare soil or vegetation, but there is a dispute as to how this compares with anthropogenic surfaces over the night-time (e.g., Theeuwes *et al.* 2013; Žuvela-Aloise *et al.* 2016; Zhao & Fong 2017). Nocturnal warming effects of *water bodies* on surrounding ambient air temperature are complex and depend on system size, quantity, proximity of warmer regions thereto (Theeuwes *et al.* 2013) and wind patterns (Broadbent *et al.* 2018c). Solcerova *et al.* (2019) showed the warmer upper layers of *water bodies* first conduct heat to the underlying layers and only about 11% of the stored heat is re-emitted as sensible heat to the urban surroundings, thereby increasing ambient air temperatures. Understanding of *water bodies/features*' influence on ambient air temperatures is still insufficient, possibly attributed to the greater focus that LST has been given. Better assessment of daytime and night-time cooling performance and increased comparison of different *water bodies/features* (current known performance summarised in Table 4) is warranted. Furthermore, for planning effective urban heat mitigation strategies, full diurnal assessment and effective combinations with urban *greenery* should be more actively pursued to leverage other functional benefits of *Blue Green Systems* (e.g., biodiversity enhancement, carbon sequestration and stormwater harvesting).

3.3.1. Ponds, lakes and sedimentation basins

Ponds, lakes and sedimentation basins act as thermal buffers within built-up areas (Gunawardena *et al.* 2017; Li *et al.* 2017; Ruefenacht & Acero 2017), reducing the LST of their surroundings up to several hundred meters away from the waterfront (Du *et al.* 2016; Yang *et al.* 2020) and breaking connectivity of urban *heat source* areas (Peng *et al.* 2020a). Such reductions were found to be more effective when combined with *greenery* (Du *et al.* 2016; Gupta *et al.* 2019). These stagnant *water bodies* can delay diurnal peak air temperatures in their proximity by about 1.5 h (Chen *et al.* 2009). Discrepancies arise around their overall influence on air temperature and human thermal comfort especially due to their night-time warming effect and humidity increases (Theeuwes *et al.* 2013; Steeneveld *et al.* 2014; Gunawardena *et al.* 2017; Hu & Li 2020). These are mainly documented for stagnant *water bodies*. For other water forms, such as rivers, constructed urban wetlands, fountains and water sprinklers, further studies may be required as other controlling factors may influence their impact on surrounding air temperature.

The cooling effect along pond/lake shorelines increases with their size (Kleerekoper *et al.* 2012; Sun & Chen 2012; Syafii *et al.* 2017). The relationship between the distance from the water's edge and the cooling effect appears to be logarithmic (Peng *et al.* 2020b). The larger the pond, the more local cooling it provides, but with limited wider spatial impact (Li & Yu 2014; Oke *et al.* 2017). Conversely, smaller, shallower ponds distributed at regular intervals can provide greater benefits at a neighbourhood scale (Robitu *et al.* 2006; Theeuwes *et al.* 2013; Sun *et al.* 2018; Yu *et al.* 2020), especially if located perpendicular to the prevailing wind direction (Broadbent *et al.* 2018c). During extreme heat, even small ponds can cool their surroundings, increasing ambient humidity to a lesser extent and reducing nocturnal warming effects (Jamei & Tapper 2019). However, small stagnant *water bodies* (i.e., waterfront <200 m) have a negligible effect on improving human thermal comfort, irrespective of daytime or nocturnal cooling (Jacobs *et al.* 2020), a topic that warrants more in-depth research. Like urban parks, rounder *water bodies* yield greater air temperature reduction than irregular shapes (Sun & Chen 2012; Li & Yu 2014). These results are somewhat surprising and may require further investigation. A growing body of knowledge is emerging, but more research is encouraged on questioning widespread perceptions (e.g., nocturnal warming effects) and overall design of such water bodies (Solcerova *et al.* 2019).

Table 4 | Reported temperature reductions and area of influence of *water bodies/features*

Mitigation measure	Reported temperature reductions	Area of influence	References
Ponds, lakes and sedimentation basins	**Surface temperature:** Compared to concrete/asphalt: • day: 0–11.1 °C (higher in summer) • night: −0.5 °C (warming) **Air temperature:** • day: 0.6–3 °C (increases with size) • night: up to −3.5 °C (warming) • cooling effect increases during extreme heat events **Human thermal comfort:** • might be negligible	**Surrounding surface temperature:** • 180–900 m (increases with size) **Air temperature:** • 50 m **Human thermal comfort:** • 8–14 m	Broadbent *et al.* (2018c), Gupta *et al.* (2019), Syafii *et al.* (2017), Theeuwes *et al.* (2013), Xu *et al.* (2010), Zhao & Fong (2017), Chen *et al.* (2009), Du *et al.* (2016), Ishii *et al.* (1991), Xue *et al.* (2019), Yang *et al.* (2020), Li & Yu (2014), Saaroni & Ziv (2003), Peng *et al.* (2020b)
Rivers	**Surface temperature:** • 0.75–2.25 °C **Air temperature:** Above the river: • 3–5 °C In the adjacent areas: • 0.31–1.5 °C (max. in spring) **Human thermal comfort:** • might be negligible	**Surrounding surface temperature:** • 300–590 m **Air temperature:** • 250 m **Human thermal comfort:** *no results found*	Du *et al.* (2016), Gupta *et al.* (2019), Han & Huh (2008), Hathway & Sharples (2012), Murakawa *et al.* (1991)
Constructed urban wetlands	**Surface temperature:** • day: up to 11.1 °C **Air temperature:** • 1–2 °C	**Surrounding surface temperature:** *no results found* **Air temperature:** • 50 m	Broadbent *et al.* (2018c), Gupta *et al.* (2019), Manteghi *et al.* (2015)
Fountains and water sprinklers	**Air temperature:** • 1–3 °C **Human thermal comfort:** *no results found*	**Air temperature:** • 30–35 m **Human thermal comfort:** • humidity increase: 10 m	Kleerekoper *et al.* (2012), Nishimura *et al.* (1998), Oke *et al.* (2017)

3.3.2. Rivers

The hypothesis that flowing forms of *water bodies* have a greater cooling effect than stagnant water on the surrounding air temperature has been formulated in different studies (e.g., Kleerekoper *et al.* 2012; Oke *et al.* 2017). A potential explanation is that rivers absorb heat in hotspot areas within cities and release it further downstream (Hathway & Sharples 2012; Kleerekoper *et al.* 2012). Studies that quantify and contrast this effect among different systems (particularly, the alterations on evaporation) are lacking. Cooling of surrounding air appears to depend on characteristics such as changes in solar angle, river water quality (e.g., suspended particles) and albedo of the water surface (Hathway & Sharples 2012). Cooling is further enhanced through lower water temperatures, higher ambient air temperatures, higher levels of solar radiation, the surrounding urban form and increased wind speed (Murakawa *et al.* 1991), reduced relative humidity and a higher fraction of pervious surfaces and vegetation in the riparian zone (Xu *et al.* 2010; Hathway & Sharples 2012; Gupta *et al.* 2019).

The active (re)integration of streams and rivers into the urban fabric as a suitable urban heat mitigation strategy is limited due to space issues and competing water resource needs; yet many cities have historically been built in proximity to surface waters and restoring channelised drains to their natural state are increasingly sought (Han & Huh 2008). An attention shift towards 'how to' maximise cooling potential of flowing rivers through optimal urban design (e.g., impervious areas) and *water body* management (e.g., water quality, protecting riparian vegetation) is needed.

3.3.3. Constructed urban wetlands

Constructed urban wetlands are artificial, water-dominated areas (i.e., along rivers or in deltas) mimicking natural *water bodies* that provide a variety of ecosystem services ranging from stormwater management (Gill *et al.* 2007; Kongjian *et al.* 2018) to local cooling through a mix of dense marshland and open water. These differ significantly in their design from other *water bodies* despite the often-used umbrella term 'urban wetlands', which encompasses all designs of natural and man-made *water bodies/features* in cities (Sun *et al.* 2012; Xue *et al.* 2019).

The heat mitigation benefits of constructed urban wetlands are rarely studied on their own. The additional benefits in terms of cooling compared to other *water bodies/features* remain open and deserve further investigation (Broadbent *et al.* 2018c). An overall assessment of the different ecosystem services provided by urban wetlands should also be pursued, as this type of *Blue Green System* can provide multiple benefits, e.g., wildlife habitat, flood protection, pollutant retention/removal (Hassall 2014).

3.3.4. Fountains and water sprinklers

Fountains disperse water droplets into the air, which evaporate more quickly due to greater air contact with the water surface area, thereby enhancing cooling (Kleerekoper *et al.* 2012; Ballout *et al.* 2015; Oke *et al.* 2017). Available literature indicates that fountains are especially effective in altering their immediate environment through enhanced evaporation. Yet, their cooling effect is rarely investigated. The cooling effect is more pronounced in confined spaces (e.g., courtyards) demonstrating that their spatial impact is limited beyond the microscale (Oke *et al.* 2017). Air temperature reductions up to 35 m downwind of such *water features* (fountains and waterfalls in parks) are achievable (Nishimura *et al.* 1998). Even after the spray was turned off, air temperature near the *water features* remained lower by up to 2 °C. Local humidity increased within a radius of 10 m (up to 5 m when the spray was not running) (Nishimura *et al.* 1998). Fountains and water sprinklers are versatile and can be installed in public spaces, e.g., water jets implemented on a busy urban square turned on during a hot summer day. Despite centuries of use (notably in southern European countries), more insight and research are required on adequate designs and operating conditions to maximise their cooling potential.

3.4. Hard surfaces

Urban components made of anthropogenic materials (i.e., non-BGI components of the urban fabric) are referred to hereafter as *hard surfaces* and alter the urban microclimate through changes in perviousness or reflectivity. Table 5 summarises reported temperature reductions and improvements to human thermal comfort through altered *hard surfaces*. Although reflective surfaces, also known as cool roofs and cool pavements, were reviewed herein, they are not considered *Blue Green Systems*. Nevertheless, their impact on the urban energy balance warrants discussion and contrast alongside *Blue Green Systems*.

3.4.1. Pervious pavements

Pervious pavements enable infiltration-by-design and alter the urban water balance by reducing surface runoff (Kleerekoper *et al.* 2012; Workman 2018) and retaining stormwater in the urban environment. As such, they disrupt the otherwise linear relationship between increasing daytime air temperature and the percentage of impervious surfaces (Ziter *et al.* 2019). Due to high heat capacity, the stored water is cooler than its concrete matrix, thereby reducing daytime surface temperatures by up to 4 °C (Alves *et al.* 2019) and limiting re-emission of radiation at night (Oswald *et al.* 2012). Underlying soil moisture replenishment enhances evaporation (Gober *et al.* 2009; Hendel 2015), implying that water availability is the key factor for cooling efficiency. Pervious pavements under dry conditions can exhibit even higher temperatures than that of conventional pavements (Ferrari *et al.* 2020). Cooling of pervious pavements is maximised when fully saturated (i.e., after a rain event or surface watering) (Santamouris 2013).

Whilst providing stormwater as a water source is common, even reclaimed wastewater can possibly be used (Yamagata *et al.* 2008), supporting the efficacy of pervious pavements in drier climates or during droughts. Pavement design significantly affects heat mitigation potential (Nwakaire *et al.* 2020). An improved multilayer design of water-holding pavements (comprising an upper layer of porous asphalt or pervious concrete and internal water storage (Nakayama & Fujita 2010; Ferrari *et al.* 2020) can store water for up to three days with significant effects on air temperature above the surface (1–2 °C cooler than above a lawn and 3–5 °C cooler than above concrete) (Nakayama & Fujita 2010). Innovative, evaporation-enhancing permeable pavements (IPP) can reduce overall stormwater volumes by approximately 90% while also significantly reducing surface temperatures (IPP being

Table 5 | Reported temperature reductions and area of influence by altering *hard surfaces*

Mitigation measure	Reported temperature reductions	Area of influence	References
Pervious Pavements	**Surface temperature:** • 4–19 °C • might be higher, compared to concrete, when dry **Air temperature:** • day: linear decrease with increasing pervious cover • 0.8–2.1 °C (max. cooling potential when wet) • 3–5 °C (water-holding pavement) **Human thermal comfort:** • –1–1.2 °C (Universal Thermal Climate Index) (higher, compared to concrete, when dry)	**Surrounding surface temperature:** *no results found* **Air temperature:** *no results found* **Human thermal comfort:** *no results found*	Alves *et al.* (2019), Liu *et al.* (2020), Ziter *et al.* (2019), Ferrari *et al.* (2020)
Reflective Surfaces	**Surface temperature:** • 5–19.3 °C **Air temperature:** Reduction of peak temperature: • cool pavement: 1.9–3 °C per 10% increase in albedo: • cool roof: 0.60 °C • cool pavement: 0.36–0.95 °C **Human thermal comfort:** • –2.9 °C (mean radiant temperature) • –0.2–1.4 °C (Universal Thermal Climate Index)	**Surrounding surface temperature:** *no results found* **Air temperature:** *no results found* **Human thermal comfort:** *no results found*	Carnielo & Zinzi (2013), Santamouris (2013), Santamouris (2014), Taha (2008), Taleghani *et al.* (2014), Jia & Wang (2021)

15.3 °C cooler than concrete pavements) (Liu Li & Yu 2020). In general, they are useful for addressing combined stormwater management and urban heat mitigation goals but require further research to better understand operational conditions (e.g., timing, volume of water input) and performance under extreme heat events across different climates.

3.4.2. Reflective surfaces

As an alternative heat mitigation strategy to *Blue Green Systems*, reflective surfaces on roofs and streets (by increasing surface albedo) absorb less solar radiation and consequently reduce surface temperatures and heat storage in the urban fabric (Taha 2008; Jamei *et al.* 2016). Less heat is re-emitted at night (Zhao *et al.* 2014; Ruefenacht & Acero 2017) resulting in lower diurnal (Santamouris *et al.* 2017) and, to a certain extent, nocturnal canopy layer air temperatures (Taha 2008; Santamouris 2013; Jamei *et al.* 2016). Their impact on human thermal comfort appears considerable (e.g., Santamouris 2013), but is less documented and varies depending on the chosen comfort indices. Furthermore, a higher fraction of re-radiated solar radiation can dazzle pedestrians and adversely affect human thermal comfort (Taleghani *et al.* 2014; Taleghani 2018).

Cooling with reflective surfaces is reportedly lower than cooling achievable with vegetation (Takebayashi & Moriyama 2007; Kleerekoper *et al* 2012) and has no co-benefits for stormwater management (Ha *et al.* 2020). Reflective paint can be feasibly and cost-effectively applied en masse (Santamouris *et al.* 2017) resulting in a greater total influence on urban heat mitigation at the city scale (Kleerekoper *et al.* 2012) so long as background climatic conditions have been accounted for. In the tropics, reflective surfaces can have a year-round positive surface cooling effect (Ruefenacht & Acero 2017; Manoli *et al.* 2019), whereas in temperate regions with distinct seasons, high-albedo surfaces can cause unintended winter cooling (Manoli *et al.* 2019; Ha *et al.* 2020). As summarised in Santamouris *et al.* (2017), various studies based on observation projects indicate that the greatest cooling potential is achieved when reflective surfaces and *Blue Green Systems* are combined (Santamouris *et al.* 2017). Reflective pavements, on their own may achieve a 0.95 °C peak temperature reduction per 10% increase of the albedo but can be combined with *shading*, *greenery* and *water bodies/features* to reach a maximum achievable reported reduction of 1.5 °C. This cumulative effect therefore yields diminishing returns after a certain threshold is reached (Santamouris *et al.* 2018). How *Blue Green Systems* can be combined with other common measures deserves more attention.

3.5. Practices – ensuring space and water availability

Practices do not modify the urban environment, but rather support urban heat mitigation and reinforce the cooling mechanisms of other *Blue Green Systems* through the smart operation of urban water systems, e.g., irrigation, surface watering and through integrated urban planning, e.g., planning of ventilation corridors. *Practices* are holistic in nature (e.g., Climate Sensitive Urban Design – Coutts *et al.* 2013b) and require long-term planning and involvement of multiple stakeholders. A summary is presented in Table 6.

3.5.1. Irrigation

For *greenery* to be effective for urban heat mitigation, particularly under hot-dry climatic conditions, water availability is key (Shashua-Bar *et al.* 2011; Targino *et al.* 2019). Irrigation of *greenery* is not only essential in maintaining vegetation health but enhances ET and maximises cooling (Coutts *et al.* 2013b; Norton *et al.* 2015; Broadbent *et al.* 2018c). A trade-off generally exists between maximum temperature reduction and minimum water use for irrigation (Gober *et al.* 2009; Shashua-Bar *et al.* 2011; Schweitzer & Erell 2014; Meili *et al.* 2019). Availability for alternative water sources for irrigation is often created through the multiple benefits of various *Blue Green Systems* and is a viable opportunity to tackle both flood management and urban heat mitigation challenges simultaneously (Gill *et al.* 2007; Shashua-Bar *et al.* 2011; Schweitzer & Erell 2014; Meili *et al.* 2019). Yet, this involves a balancing act between maximum cooling (saturated soil) and effective runoff reduction (fast infiltration) (Kleerekoper *et al.* 2012; Richards & Edwards 2018).

Irrigation effectiveness depends on timing, volume of water applied and the urban fabric. Research on such aspects (Jamei & Tapper 2019; Wang *et al.* 2019) remains scarce and limited to hot-dry regions. The greatest increase in cooling through irrigation appears to be achievable in least vegetated areas (Gober *et al.* 2009)

Table 6 | Reported temperature reductions and area of influence of different *practices*

Mitigation measure	Reported temperature reductions	Area of influence	References
Irrigation	**Surface temperature:** • day: 8.2 °C (compared to unirrigated grass) and 8.8 °C (compared to bare ground) **Air temperature:** Compared to built-up area: • 0.5–1 °C Compared to dry grass: • day: 0.1 °C per 5% increase in irrigated grass • at 15:00: up to 1.75 °C • night: up to –0.75 °C (warming) • during a heat wave: 2–4 °C	**Surrounding surface temperature:** *no results found* **Air temperature:** *no results found*	Broadbent *et al.* (2018c), Coutts *et al.* (2013b), Block *et al.* (2012), Norton *et al.* (2015), Sieker *et al.* (2019), Spronken-Smith & Oke (1998), Lam Gallant & Tapper (2020)
Surface watering	**Surface temperature:** Water-holding pavement, daytime sprinkling: • day/afternoon: 6–13 °C • night/morning: 2–4 °C **Air temperature:** • height of 2 m: 0.79–1.6 °C • near ground: up to 8 °C	**Surrounding surface temperature:** *no results found* **Air temperature:** *no results found*	Solcerova *et al.* (2018), Yamagata *et al.* (2008), Hendel *et al.* (2014)
Planning of ventilation corridors	**Surface temperature:** *no results found* **Air temperature:** • day: 0.6 °C for a 1 m s^{-1} increase in wind	**Surrounding surface temperature:** *no results found* **Air temperature:** *no results found*	Broadbent *et al.* (2018c)

primarily because it creates evaporation in the absence of vegetation. Irrigation is most effective in the afternoon when temperatures are highest (Broadbent *et al.* 2018c). Although uncertain, nocturnal irrigation only slightly reduced air temperature above short vegetation (Broadbent *et al.* 2018c) implying that it should possibly be avoided since dry parks cool their environment mostly because of the reduced heat conductivity of dry soil in the early morning (Santamouris *et al.* 2018; Spronken-Smith & Oke 1998), as dry soil limits the access to a store of subsurface heat. Conversely, detailed measurements (Lam *et al.* 2020) showed that nocturnal irrigation can promote a residual cooling effect during the day lasting up to 6 h. It is clear that increased ET during the day lowers nocturnal temperatures due to reduced urban heat storage (Gober *et al.* 2009; Jamei & Tapper 2019) and that the overall cooling effect of irrigation increases with the fraction of pervious surfaces (Broadbent *et al.* 2018b). Efficiency of irrigation versus volume of water applied appears to follow a nonlinear relationship until a point of diminishing returns (Gober *et al.* 2009; Broadbent *et al.* 2018b). As such, water demand for irrigation needs to be balanced with other water uses within the urban environment. Potential impact on human thermal comfort due to increased ambient humidity also requires further investigation.

3.5.2. Surface watering

A long-standing summer tradition in Japan is the practice of 'Uchimizu', which involves sprinkling water onto streets to cool the surface and the air above (Yamagata *et al.* 2008; Solcerova *et al.* 2018). This has recently sparked broader interest (Hendel *et al.* 2014; Solcerova *et al.* 2018). Solcerova *et al.* (2018) found that the volume of water applied was a significant factor; water depths greater than 5 mm reduced near-ground air temperature about twice as much as for 1 mm of water. Evidently, water availability is a limiting factor for cooling, warranting optimised, tangible approaches to surface watering (Hendel *et al.* 2014) and the possibility of harvesting and reusing alternative water sources. An optimal watering frequency (to maximise cooling) of every 30 min in direct sunlight and every hour in shaded pavement is suggested (Hendel *et al.* 2014), but transferability of results requires caution due to varying climatic conditions. Particularly interesting, especially in dry climates during droughts, is the demonstration that reclaimed wastewater treated for non-potable uses in urban areas is a viable water source, for example, for surface cooling (Yamagata *et al.* 2008).

Through changes in the perviousness of *hard surfaces,* cooling effects after sprinkling can be prolonged.

Surface temperature of a porous pavement, for example, was reduced by 8 °C after sprinkling during the day with a lasting effect of up to 3 °C into the night (Yamagata *et al.* 2008). As studies on this topic emerge, questions related to water requirements, application frequency and quantity, background climatic influence and effectiveness in different urban settings should be addressed.

3.5.3. Planning of ventilation corridors

Ventilation corridors comprise wedged green spaces or linear parks along rivers that redirect cooler air from the suburbs into the city centre, thereby mitigating urban heat in hotspot areas (Gill *et al.* 2007; Oke *et al.* 2017). Maintaining such corridors is especially important for nocturnal cooling when suburban and rural hinterlands cool faster than city centres. To fully exploit daytime cooling potential of *water bodies/features*, wind sheltering through buildings and dense vegetation in close proximity should be avoided (Peng *et al.* 2020a) as buildings perpendicular to cold air flows can reduce cooling potential (Stadt Zürich 2020). In cities with cold winters, wind sheltering in street canyons can be desirable. Ponds in parallel to wind direction can significantly reduce mean radiant and physiological equivalent temperatures (Syafii *et al.* 2017). However, if *water bodies/features* are oriented perpendicularly to wind flow, greater downwind area cooling is achievable (Broadbent *et al.* 2018c). This aspect certainly deserves further attention in future research.

Urban planning and, especially, the maintenance of ventilation corridors connecting urban and rural areas or intra-urban *heat sinks* with downwind areas, is known to be crucial for effective heat mitigation and the extension of *heat sink* areas. Very few studies account for advection (e.g., Syafii *et al.* 2017; Broadbent *et al.* 2018c; Masson *et al.* 2020) and the potential of strategically planned ventilation corridors to enhance the cooling effect of *Blue Green Systems* beyond the microscale. City-wide heat mitigation plans, which account for wind corridors are scarce, yet essential if the full cooling potential of *Blue Green Systems* is to be realised.

4. FURTHER DISCUSSION AND RESEARCH GAPS

4.1. Do Blue Green Systems work for urban heat mitigation?

Blue Green Systems seem to have, in general, a positive impact on reducing urban heat effects. Their influence can be explained by their dominant cooling mechanisms and the magnitude of their influence varies depending on the specific *System* design, specificities of the urban area and background climatic conditions. At the local scale, road surface temperature can be reduced significantly by replacing conventional *hard surfaces* with pervious or reflective pavements. Furthermore, heat storage reduction in the urban fabric, which is most relevant for nocturnal heat mitigation, can be achieved by adding *greenery* (e.g., green roofs, green walls, short vegetation on the ground, especially when irrigated). Beyond the heat storage reduction, these measures ultimately contribute to reducing air temperature and improving human thermal comfort. However, their influence depends on the time of day and morphological and climatic factors. Improvement of daytime pedestrian thermal comfort can also be achieved by designing and ensuring ventilation corridors. Trees, when optimally positioned in urban street canyon, have been shown to have a significant impact in increasing human thermal comfort. Despite the usefulness of shading, particularly when space constraints inhibit the broader adoption of *greenery* and *water bodies*, detailed studies on adequate shading design are lacking. *Water bodies/features* can also have a positive impact in mitigating urban heat, especially during the day. The cooling potential of some stormwater-related *Blue Green Systems*, e.g., constructed urban wetlands, vegetated swales and bioretention systems, is, however, not yet fully understood and requires further investigation.

To extend the cooling effects of *Blue Green Systems* beyond the microscale, they should be distributed at regular intervals (Zhou *et al*. 2011; Coutts *et al.* 2013b; Gunawardena *et al*. 2017; Zhang *et al*. 2017). Existing infrastructure like private gardens, road traffic islands and grass verges (Charlesworth 2010), reclaimed parking lots and new public open spaces (City of Melbourne 2020) can help to create a dense network. However, only a few studies (Ng *et al.* 2012; Santamouris 2014; Wang *et al*. 2016; Ziter *et al.* 2019) have presented hypothetical scenarios for city-wide cooling effects. *Blue Green Systems* connectivity could increase the city-wide daytime cooling effect by 11–19% considering the LST and reduce the diurnal variability of the LST (Li *et al.* 2017; Sun *et al*. 2018). These results are, however, conceptual and do not provide tangible design guidelines for practitioners or specific recommendations on the most effective configurations of *Blue Green Systems* – knowledge hereof still remains scarce.

Most of the reviewed studies focus on individual heat mitigation measures and evaluate their performance with respect to only one objective (e.g., achieved LST reductions, improvement of human thermal comfort). It is noteworthy that when considering the cooling effect of various *Systems*, their impact is not simply the sum of the individual parts, as trade-offs need to be considered when designing and planning urban heat mitigation solutions for a specific context. For example, trees, providing cooling by shading, can block wind flow, which is, in turn, disadvantageous for human thermal comfort. Consequently, trees might be more suitable in open spaces, whereas shading in narrow urban canyons is provided by the buildings themselves. Another example is related to the various potential impacts of *water bodies/features* on urban heat and human thermal comfort. *Water bodies/features* contribution to daytime temperature reductions may need to be balanced against air humidity increases due to enhanced evaporation and nocturnal warming effects. More research is required to evaluate the optimal design of *water bodies/features*, especially their littoral/riparian zones, in a specific context (Jamei *et al.* 2020).

The combination of *water bodies/features* and *greenery* can have co-benefits for the healthy growth of vegetation, as water availability for *greenery* could hence be ensured. Nevertheless, potential synergies need to be thoroughly investigated as they may lead to undesirable trade-offs, such as the competing goals of urban water management and urban heat mitigation when *water bodies/features* are considered. Stormwater management is mainly focused on maximising local retention and infiltration to prevent flooding, whereas the presence of water on the surface, or the maintenance of high soil moisture content by limiting infiltration, enhances urban heat mitigation. Also, combining strategies like grass and shading with trees leverages synergistic effects with respect to thermal comfort as well as water use efficiency (Shashua-Bar *et al*. 2011). Regulating ponds or stormwater harvesting systems can nourish vegetation to sustain a healthy canopy and enhance ET (He *et al.* 2019). To take these and other goals, e.g., biodiversity conservation, amenity, air quality improvement, carbon sequestration (Nowak & Crane 2002; Hamer & McDonnell 2008; Sörensen *et al.* 2016; Villa & Bernal 2018; Design Singapore Council 2020), into account when designing urban heat mitigation measures, one should consider multi-objective optimisation methods (Wang *et al.* 2020).

4.2. Prioritisation for targeted interventions with Blue Green Systems

While the literature agrees that cities need to adapt in order to counteract the negative effects of urbanisation and climate change (e.g., Charlesworth 2010; Block *et al.* 2012), space restrictions and other challenges mean that the implementation of *Blue Green Systems* requires a quantitative assessment methodology that allows the prioritisation of these measures in critical areas. Densely built-up areas, which are often located in the city centre or industrial districts with a high percentage of impervious surfaces, are hotspots for day- and night-time urban heat. Implementing *Blue Green Systems* (i.e., increasing pervious surfaces, introducing *greenery*, retaining water and/or irrigating) results in the largest thermal comfort gain in such dense areas (Gill *et al.* 2007; Gober *et al.* 2009; Žuvela-Aloise *et al.* 2016). This is because of the nonlinear relationship between the increase in evaporation rate and the cooling effect (as discussed in Section 3.5.1) (Gober *et al.* 2009).

Some argue that heat mitigation should focus on frequently used spaces (He *et al.* 2019) or vulnerable neighbourhoods (Gill *et al.* 2007; Voelkel *et al.* 2016; Ortega-Rosas *et al.* 2020). However, this spatial prioritisation should be made with caution because it is based on a very specific daily movement pattern (i.e., people move between residential bedroom communities and their jobs in central business districts) and does not take alternative daily routines into account. Considering social and demographic factors, high-priority zones within cities to protect the most vulnerable populations (i.e., elderly, children and socio-economically disadvantaged groups) should be explored (Ortega-Rosas *et al.* 2020). Multidisciplinary collaboration thus becomes necessary as it would allow evaluation of how people move within the city (e.g., which outdoor areas are frequented and when), which would determine where outdoor thermal comfort is most important and mitigation measures are best suited. For example, the effectiveness of grass to provide fast night-time cooling in residential areas where people sleep could be investigated. On the other hand, in dense city centres usually frequented during the day, street trees could increase pedestrian thermal comfort through evaporative cooling and shading (Wang *et al.* 2016; Ortega-Rosas *et al.* 2020), allowing pedestrians and cyclists to freely move between buildings during the hottest hours of the day without being exposed to direct solar radiation. Mixed-use parks with lawns, compact tree canopies and playgrounds could also be placed in proximity to schools to provide a local cool island within the urban fabric. Accessibility and connectivity are the important keywords in this context (Design Singapore Council 2020).

As mentioned in the previous section, the multi-functionality of *Blue Green Systems* should be incorporated into their implementation, consequentially effecting the spatial planning of those *Systems* and possibly leading to trade-offs and synergies between the different objectives (Bozovic *et al.* 2017; Zhang *et al.* 2020). Interdisciplinary research and stakeholder engagement can support the strategic planning and optimal implementation of *Blue Green Systems* in cities.

4.3. Future research priorities

A major shortcoming of many of the reviewed studies assessing the variability of urban heat is the narrow focus on surface temperature LST (Li *et al.* 2017; Sun *et al.* 2018; Gupta *et al.* 2019; Hou *et al.* 2019; Yue *et al.* 2019; Peng *et al.* 2020a; Yu *et al.* 2020). The differences in intra-urban air temperatures cannot be derived only from the LST because other factors influence air temperature changes, such as wind speed and other meteorological conditions (Tomlinson *et al.* 2012; Broadbent *et al.* 2018b). To deepen our understanding of Blue Green System effectiveness in urban heat mitigation and societal well-being, a shift of focus from air temperature or LST to human thermal comfort indices (e.g., mean radiant temperature, PET) is necessary in future studies. Human thermal comfort indicators are more suitable for evaluating the heat exposure and physiological stress level of city dwellers than LST or air temperature, as they consider the relative humidity, long- and shortwave radiation as well as wind speed (Martilli *et al.* 2020). Meanwhile for other aspects (e.g., ecological impact), these conventional environmental indicators may suffice (Karger *et al.* 2017).

To plan and implement effective *Blue Green Systems,* a better understanding of *heat sources* and *sinks* within cities and local climate zones is required. Future research should focus on the development of high spatial and temporal resolution urban heat maps (Steeneveld *et al.* 2014). This could be achieved by field campaigns with mobile transects (Voelkel *et al.* 2016; Broadbent *et al.* 2018c; Rodríguez *et al.* 2020), with improved microclimate models (Broadbent *et al.* 2018a; Meili *et al.* 2019) or a combination of both (Voelkel *et al.* 2016; Raymond *et al.* 2020). Additionally, such studies should not only account for surface or air temperatures, but also for other meteorological factors. Wind, for example, is a key factor influencing the extent of *heat sources* and *sinks* and consequently air temperature variability (Broadbent *et al.* 2018c) and should therefore not be neglected.

A more holistic approach that goes beyond microscale should be pursued in future research. As discussed in previous sections, new urban microclimate studies should include various disciplines, such as microclimate research, spatial planning, urban hydrology and ecology. This will help develop multicriteria urban development analysis that should be supported by multi-objective optimisation expertise. The comparison of different *Blue Green Systems* and their suitability in a given urban setting requires a better understanding of both their ecosystem services and cooling potential. Researchers should develop comparison frameworks that take into account the different environments and also both observed and modelled results.

Trivially, *Blue Green Systems* can only cool cities if they are implemented. Accordingly, research should also aim to reduce the complexity of urban microclimate science by breaking down knowledge into tangible guidelines for practitioners (Lenzholzer 2015). Some specific recommendations are provided in studies by Shashua-Bar & Hoffman (2000) and Ziter *et al.* (2019) who suggest integrating small gardens of typical apartment building size (0.1 ha) into the urban fabric. For effective city-scale cooling, these green spaces should not be more than 200 m apart (Shashua-Bar & Hoffman 2000).

To transform cities into sustainable and liveable environments for their residents and ensure urban resilience to climate-related hazards like floods and extreme heat, planning strategies need to be re-evaluated. A holistic cooling strategy is comprised of a combination of different *Blue Green Systems* and other climate adaption strategies that align with local conditions. Finally, this requires the involvement and cooperation of scientists, urban planners, (landscape) architects, engineers, social scientists, ecologists and other professional experts, and knowledge transfer between the disciplines.

5. CONCLUSIONS

The progressive increase in climate extremes and a rapidly urbanising world reinforce day- and night-time heat exposure in cities. This study evaluates and discusses the spatio-temporal variability of urban heat, the drivers of *heat source* formation, the cooling mechanisms of *heat sinks* within the urban fabric and the potential effectiveness of *Blue Green Systems* in urban heat mitigation. Five main conclusions can be drawn:

1. The UHI effect is an overused concept that does not account for the temporal and spatial variability of heat within cities. Instead of this comparative metric (urban–rural temperature difference), a more targeted and absolute understanding of urban heat dynamics should be encouraged in research and practice. City centres and their downwind areas are typical *heat source* areas; however, polycentric development and densification expose previously unaffected parts of the city to heat effects. This highlights the need to consider urban heat mitigation in the early planning stages of city development.
2. *Blue Green Systems* have a positive impact in reducing urban heat effects. Their effectiveness is influenced by their specific dominant cooling mechanism (which may change diurnally and seasonally). The magnitude of their influence varies based on the specifics of the surrounding urban areas and on background climatic conditions.
3. Depending on the local climatic conditions and characteristics of *hard surfaces,* water availability in cities may be reduced, possibly limiting cooling potential. Closing urban water cycles by harnessing alternative water sources (i.e., storm-, rain-, greywater, sewer mining) and active adoption of *practices* like irrigation of *greenery* and surface watering can enhance the cooling potential of *Blue Green Systems*.
4. Blue-green connectivity is key in providing cooling and other ecosystem services at neighbourhood and city-scales, as many of these decentralised approaches have a limited area of influence. *Blue Green Systems* promote strategically planned, synergistic networks of *greenery* and *water bodies/features*.
5. The integration and combination of various types of *Blue Green Systems* into the urban fabric should be further explored to possibly (i) increase their impact on mitigating urban heat, and (ii) provide multiple ecosystem services, e.g., increase biodiversity and city amenity, harvest rain- and stormwater, improve air quality and more. These systems are multi-functional elements in the planning of future cities.

In this study, we considered a large toolbox of different *Blue Green Systems*, all of which can mitigate urban heat to some degree and have attempted to provide some clarity in current ambiguity around its terminology to support communication across different disciplines (e.g., urban water management, urban planning, microclimate research, urban ecology). Closer linkage between research and practice, interdisciplinary work and more international exchange on the implementation of *Blue Green Systems* is key to harnessing their potential multi-functionality (and improved feasibility for urban heat mitigation) and to designing more resilient and liveable cities.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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