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# Greenery as a mitigation and adaptation strategy to urban heat

*Nyuk Hien Wong*[1], *Chun Liang Tan*[2✉], *Dionysia Denia Kolokotsa*[3] and *Hideki Takebayashi*[4]

Abstract | The absence of vegetation in urban areas contributes to the establishment of the urban heat island, markedly increasing thermal stress for residents, driving morbidity and mortality. Mitigation strategies are, therefore, needed to reduce urban heat, particularly against a background of urbanization, anthropogenic warming and increasing frequency and intensity of heatwaves. In this Review, we evaluate the potential of green infrastructure as a mitigation strategy, focusing on greenery on the ground (parks) and greenery on buildings (green roofs and green walls). Green infrastructure acts to cool the urban environment through shade provision and evapotranspiration. Typically, greenery on the ground reduces peak surface temperature by 2–9 °C, while green roofs and green walls reduce surface temperature by ~17 °C, also providing added thermal insulation for the building envelope. However, the cooling potential varies markedly, depending on the scale of interest (city or building level), greenery extent (park shape and size), plant selection and plant placement. Urban planners must, therefore, optimize design to maximize mitigation benefits, for example, by interspersing parks throughout a city, allocating more trees than lawn space and using multiple strategies in areas where most cooling is required. To do so, improved translation of scientific understanding to practical design guidelines is needed.

Sensible heat
Heat transfer that results in a change in temperature between objects, without changing the volume or pressure.

The urban heat island (UHI) effect describes an increase in temperature of dense urban areas compared with their suburban or rural surroundings[1,2] (FIG. 1a). The UHI arises through shifts in energy fluxes associated with land use change — specifically, an increase in solar absorption, sensible heat and heat trapping[3], and a corresponding reduction in evapotranspiration — as well as increased anthropogenic heat from buildings and vehicles[4] (FIG. 1b). UHI intensity typically varies between 0.4 °C and 11 °C (REF.[5]), and is more pronounced at night[6], exposing residents to higher thermal stress.

Such exposure can have adverse impacts for human health, producing increased mortality and morbidity, especially amongst low-income and vulnerable populations, such as the elderly[7,8]. These impacts are heightened during heatwave events when temperatures are already amplified[9,10]. For example, during the 2003 European heatwave, it is estimated that the UHI contributed to 50% of the total deaths in the West Midlands, UK[11]. The same heatwave also caused an estimated 70,000 excess deaths across Europe[12], most prominent in urban locations such as Paris, France[13]. Analyses in various other global cities also indicate greater mortality in urban regions during heatwaves owing to the UHI effect, including Shanghai[14], Hong Kong[15], Ho Chi Minh[16], Athens[17] and London[18].

Accordingly, there is an urgent need to mitigate urban warming and its deleterious impacts, especially against a background of increased urbanization and anthropogenic warming. Urbanization, for example, is widely regarded to increase local temperatures, and, thus, UHI intensity, in the future[19,20]. While the impacts of climate change are more variable — for instance, increasing UHI intensities in Chicago[21], Beijing[22] and Melbourne[23], but decreasing them in Paris[24] and Brussels[25] — the combined impact of both factors is anticipated to exacerbate the UHI effect[26,27] and, thereby, UHI-related mortality[11,28]. Moreover, given that heatwaves interact non-linearly with UHIs to amplify urban heat stress in the present climate[29], projected increases in heatwave frequency and intensity might similarly magnify heat stress further in the future[30,31].

Government sectors and policymakers have, thus, considered several active and passive strategies to address the UHI effect. These methods include: reducing shortwave and longwave absorption by modifying the reflectance properties of urban surfaces — increasing the albedo of building materials and surfaces (particularly roofs)[32,33]; designing urban geometry to minimize heat gain and facilitate the release of stored heat and dissipation via urban ventilation[34,35]; lessening anthropogenic heat creation by increasing energy efficiency and reducing vehicle use[36]; expanding blue spaces such as lakes

[1]Department of Building, National University of Singapore, Singapore, Singapore.
[2]Department of Architecture, National University of Singapore, Singapore, Singapore.
[3]School of Environmental Engineering, Technical University of Crete, Chania, Crete, Greece.
[4]Department of Architecture, Kobe University, Kobe, Japan.
✉e-mail: tcl@u.nus.edu
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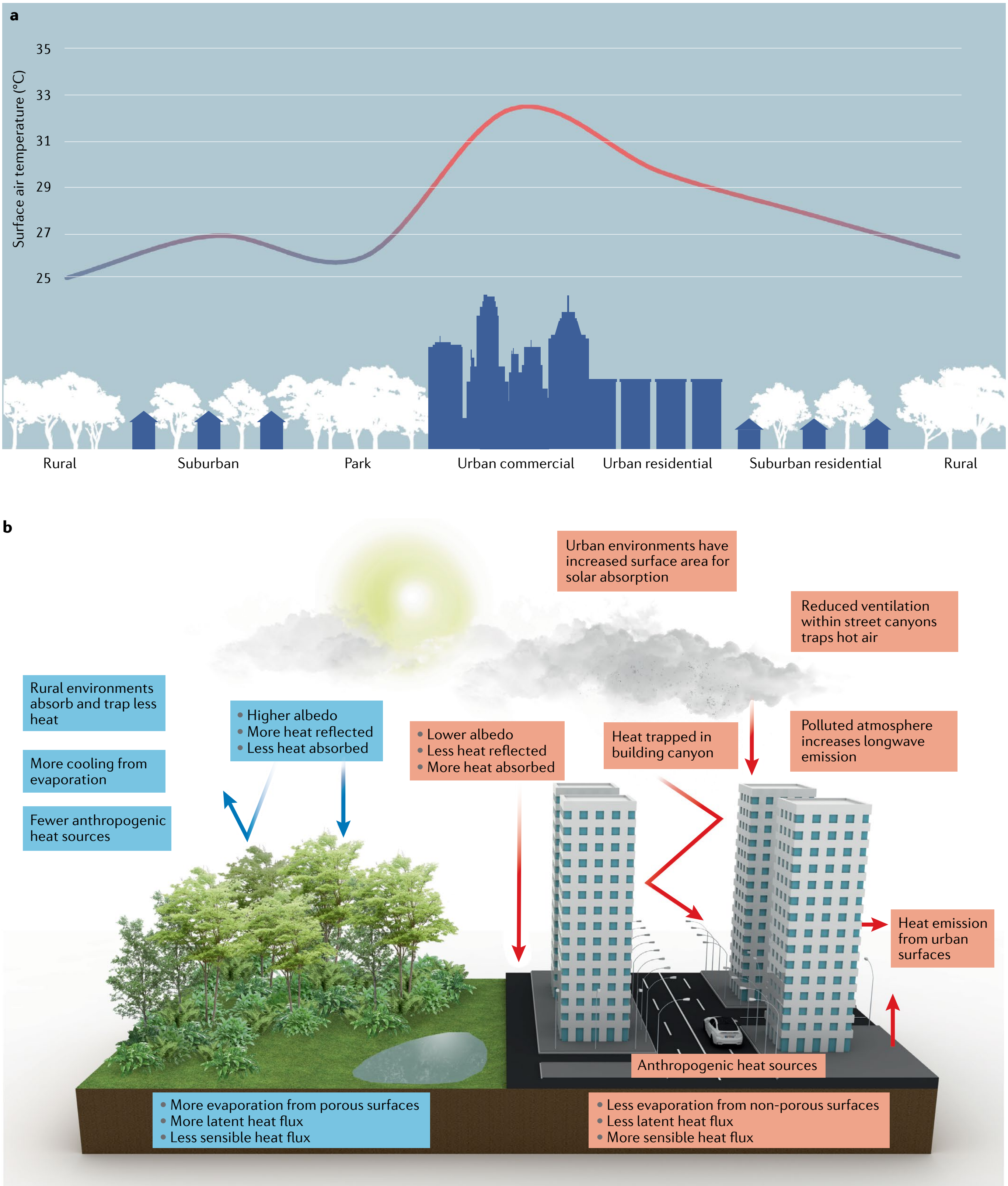



and rivers[37]; and promoting cooling via evapotranspiration with urban greening. Indeed, green infrastructure — encompassing green roofs, green facades and parkland expansion — has been regarded as an effective mitigation strategy for urban heat[38,39], and, at the same time, brings ecosystem services and co-benefits in terms of carbon sequestration[40], phytoremediation[41], improved air quality[42] and promoting biodiversity[43,44].

In this Review, we examine urban greenery as a mechanism to mitigate urban heat. We begin by outlining the

Fig. 1 | **The urban heat island effect. a** | A typical urban heat island profile, showing higher air temperature in built-up areas and lower temperature in rural areas with more greenery coverage. **b** | Factors contributing to the urban heat island effect, highlighting significant changes in heat and air movement when rural land is urbanized. Red boxes indicate warming mechanisms and blue boxes indicate cooling mechanisms.

physical mechanisms through which greenery contributes to cooling, followed by a discussion of the different forms of greenery — green parks, green roofs and green walls — and their cooling potential. The implications for planning and design of buildings and cities are subsequently considered, followed by the future needs and priorities of the research community.

## Mechanisms of greenery-related cooling

Regardless of the specific approach adopted, green infrastructure acts to cool urban environments through various mechanisms: evapotranspiration[45], shade provision[46] and increased albedo[32,47], the combination of which reduces the thermal load on the built environment and its inhabitants (FIG. 2).

Heat flux interception from the plant canopy (and, thus, provision of shade) is one of the most direct and effective means of cooling the urban microclimate[48,49], dominating the cooling potential of green infrastructure. Depending on the density of their canopies, plants are able intercept 70–90% of incoming solar radiation[50,51], still reaching 50% for deciduous trees during winter when leaf counts are substantially lowered[52]. This reduction in both shortwave and longwave radiation substantially cools urban surfaces such as buildings, roads and pavements, in turn, reducing the mean air temperature of surroundings. Shade from green infrastructure can also lower energy requirements for cooling, reducing anthropogenic heat sources and potentially reducing energy savings by 20–80%[53–55].

Vegetation further allows evapotranspiration. Evapotranspiration uses solar energy to convert liquid water into water vapour, thereby, replacing sensible heat with latent heat[56–58]. Thus, compared with impervious urban environments where sensible heat gain occurs owing to an absence of water, this evaporative cooling effect provides the important function of lowering the Bowen ratio and temperature of surrounding landscapes[59]. The reduction in sensible heat gain also acts to lower plant canopy surface temperature and decrease longwave emission to surroundings[45].

The presence of greenery can further enhance the albedo of highly urbanized environments. For example, the albedo of built-up areas varies from ~0.1 to 0.2 (REFS[60,61]), whereas the albedo of plants can reach close to 0.3 (REF.[62]). Raising the albedo increases the proportion of incoming radiation that is reflected, thus, decreasing the component that is absorbed and, therefore, able to increase surface temperatures[32]. Given the limited range of albedo values for plants[63], however, the cooling potential arising from albedo changes is lower than that of shading provision and evaporative cooling.

## Greenery on ground

Retaining or reintroducing green spaces such as gardens or parks offers one such strategy to mitigate the UHI effect. As discussed, shade provision from vegetation canopies blocks shortwave and longwave radiation, while also promoting evapotranspiration, lowering longwave emission and, in the case of large urban parks, minimizing anthropogenic heat sources. Through a combination of these factors, green spaces provide an effective means to lower UHI intensity, as revealed through numerous field measurements[64–69], numerical simulations[70–72] and remote sensing[73–76].

However, while almost all studies reveal temperature reductions owing to the presence of greenery, the magnitude of cooling varies substantially. For instance, a meta-analysis of 24 studies covering tropical and temperate climates indicates air temperature cooling of 0.94 °C (REF.[38]), whereas another based on 89 studies suggests cooling of 1.5–3.5 °C (REF.[77]). Analyses focusing on one city further show even larger temperature reductions, reaching 4.52 °C in Changchun, China[78], and 6.82 °C in Nagoya, Japan[76]. Indeed, compiling 30 published studies spanning diverse geographic regions indicates that green parks act to cool air temperature by an average of ~3 °C, with a range of 2–4 °C (FIG. 3).

When assessing surface temperature (rather than air temperature), the cooling potential of green parks is larger (FIG. 3a), mainly due to better thermal conductivity of solid surfaces compared with air. Remote sensing technologies — which provide estimates of cooling over relatively large (60–120 m) spatial footprints — reveal average surface temperature reductions of 4.2 °C, with a range of 1.9–6.7 °C. By contrast, on-site measurements — which are able to capture temperature changes with higher granularity — document average reductions of 14 °C, with a range of 9.2–19 °C (FIG. 3a).

Thus, while the cooling potential of green parks is clear, so too are the contrasts in quantitative estimates. This variability is linked to the methodologies adopted for measurement (on-site measurements at pedestrian height as compared with remote sensing techniques, which are averaged values over large areas), as well as differences in climate, the size and shape of the park, and plant selection and placement (FIG. 4), as will now be discussed.

### *Climate*

The cooling potential of urban greenery on the ground is influenced by both diurnal[79,80] and seasonal cycles[67,78]. On diurnal timescales, maximum temperature reductions associated with greening tend to occur during the day. In Hong Kong, for example, an urban park was found to be 8 °C cooler than its surroundings in the day, whilst only 2 °C cooler at night[81]. This temporal difference in cooling potential can be attributed to the contrasting diurnal temperature gradients; during the day, exposure to direct solar radiation produces large differences between green and urban spaces, but, by nightfall, heat is emitted back to the atmosphere in urban environments as longwave radiation, minimizing urban–rural contrasts.

Variability in cooling potential is also strongly evident on seasonal timescales, reaching peak amplitude during the summer. For instance, in Nagoya, Japan, park-related cooling was much larger in summer (1.9 °C) compared with winter (0.3 °C)[82] (FIG. 4a). These differences arise

**Evapotranspiration**
The combined processes of evaporation of water from the soil, as well as plant transpiration, where water is transported from the soil through the roots and exits via the leaf stomata and into the atmosphere as water vapour.

**UHI intensity**
The temperature difference between urban and rural areas; either surface or air temperature can be used.

**Albedo**
The ratio of reflected radiation over total incident radiation on a surface, indicating its overall reflecting potential. Albedo values can range from 0 to 1, with 1 meaning all radiation is reflected and 0 indicating that all radiation is being absorbed.

**Latent heat**
Heat transfer that results in a change in state (such as liquid into vapour), without changing the temperature.

**Bowen ratio**
The ratio of sensible heat flux to latent heat flux above a surface that contains moisture. Commonly used in meteorological and hydrological studies, it is an indication of the abundance of water over surfaces, as the presence of moisture will directly influence latent heat flux density.

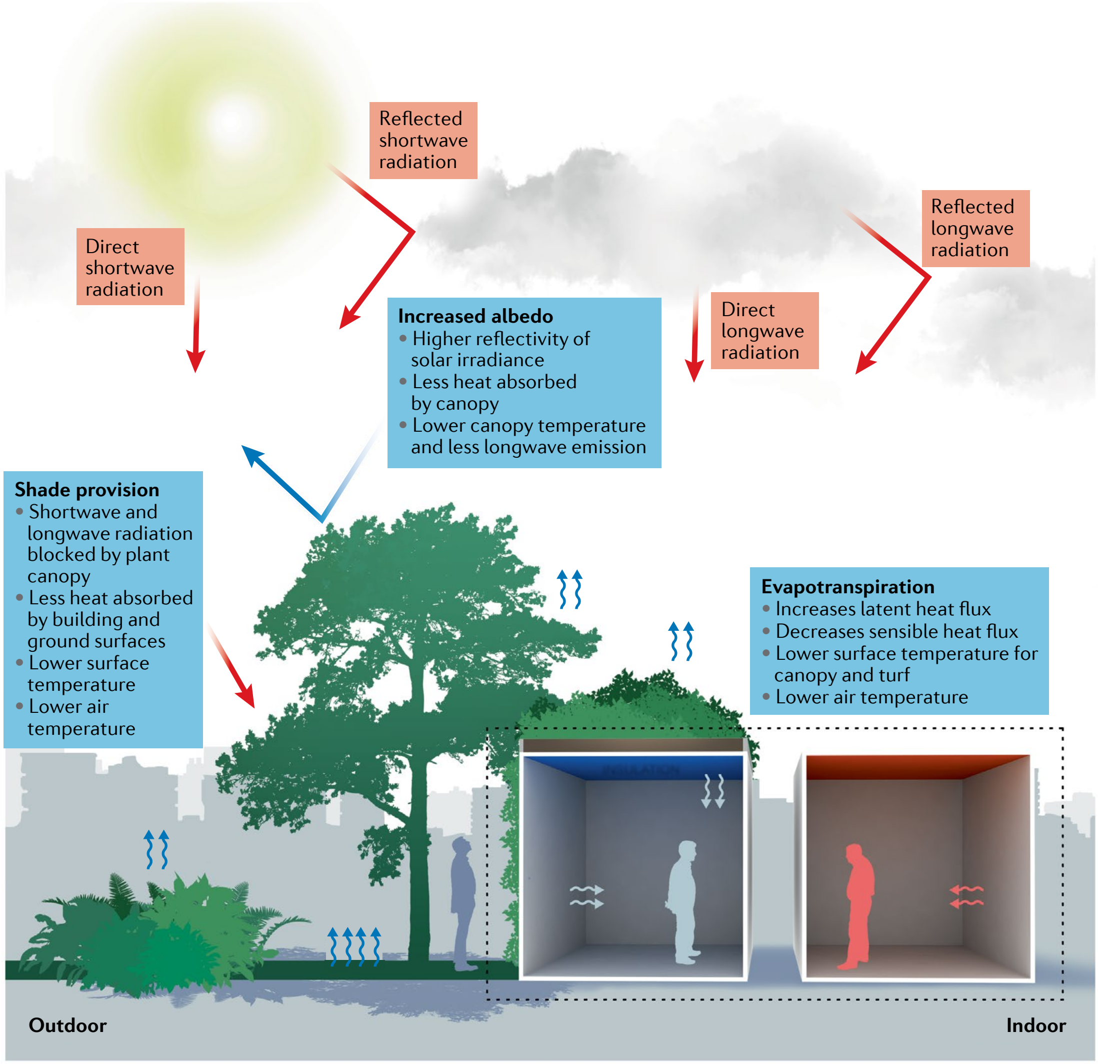



Fig. 2 | **Greenery-related cooling mechanisms in the urban environment.** Urban greenery acts to modify shade provision, evapotranspiration and albedo. The combination of these three mechanisms reduces sensible heat gain, thereby, lowering heat gain and surface temperatures. Red boxes indicate warming mechanisms and blue boxes indicate cooling mechanisms.

through the strong dependence on shade potential and evapotranspiration, which is drastically reduced in autumn and winter when trees shed their leaves and canopy cover is reduced.

While the magnitude of temperature reduction differs between seasons, the temperature reduction differential has no apparent correlation to specific climatic regions[38,77]. Indeed, greenery on the ground has been shown to be effective in providing cooling in tropical[83], subtropical[84] and temperate[85] climates, as well as humid[86] and arid[87] regions. Given the small interquartile range of air temperature reductions across studies (FIG. 3a), greenery on the ground is, therefore, an effective mitigation strategy for urban heat, regardless of the locale.

### *Size and shape of park*

In addition to climate, the size and shape of the green space also exerts a strong influence on the cooling potential of urban parks[88–91]. Larger parks tend to have a more pronounced cooling effect, owing to the net decrease in sensible heat flux and reduced anthropogenic heat sources. For instance, in Suzhou, China, the average cooling effect increases from 1.75 °C for small (<4 ha), 2.66 °C for medium (4–10 ha) to 3.32 °C for large green spaces (>10 ha)[92]. The size at which peak cooling occurs, however, exhibits pronounced variability, owing to the background climate and urban context (FIG. 3a). In Fuzhou, China, for example, the most efficient cooling occurs at ~4.5 ha (REF.[93]), whereas it is 3 ha in Taipei, Taiwan[94], 5.6 ha in Leipzig, Germany[95], and 14 ha in Chongqing, China[96]. The threshold value of efficiency (TVoE) for park size (FIG. 4c) has provided some indicative values of park size to which temperature reduction potential due to park size starts to plateau[97]. The TVoE size can range from 0.5 ha to 0.69 ha in temperate cities such as Copenhagen[98] and Rome[99], to 0.6 ha to 0.95 ha in tropical cities in Asia[100].

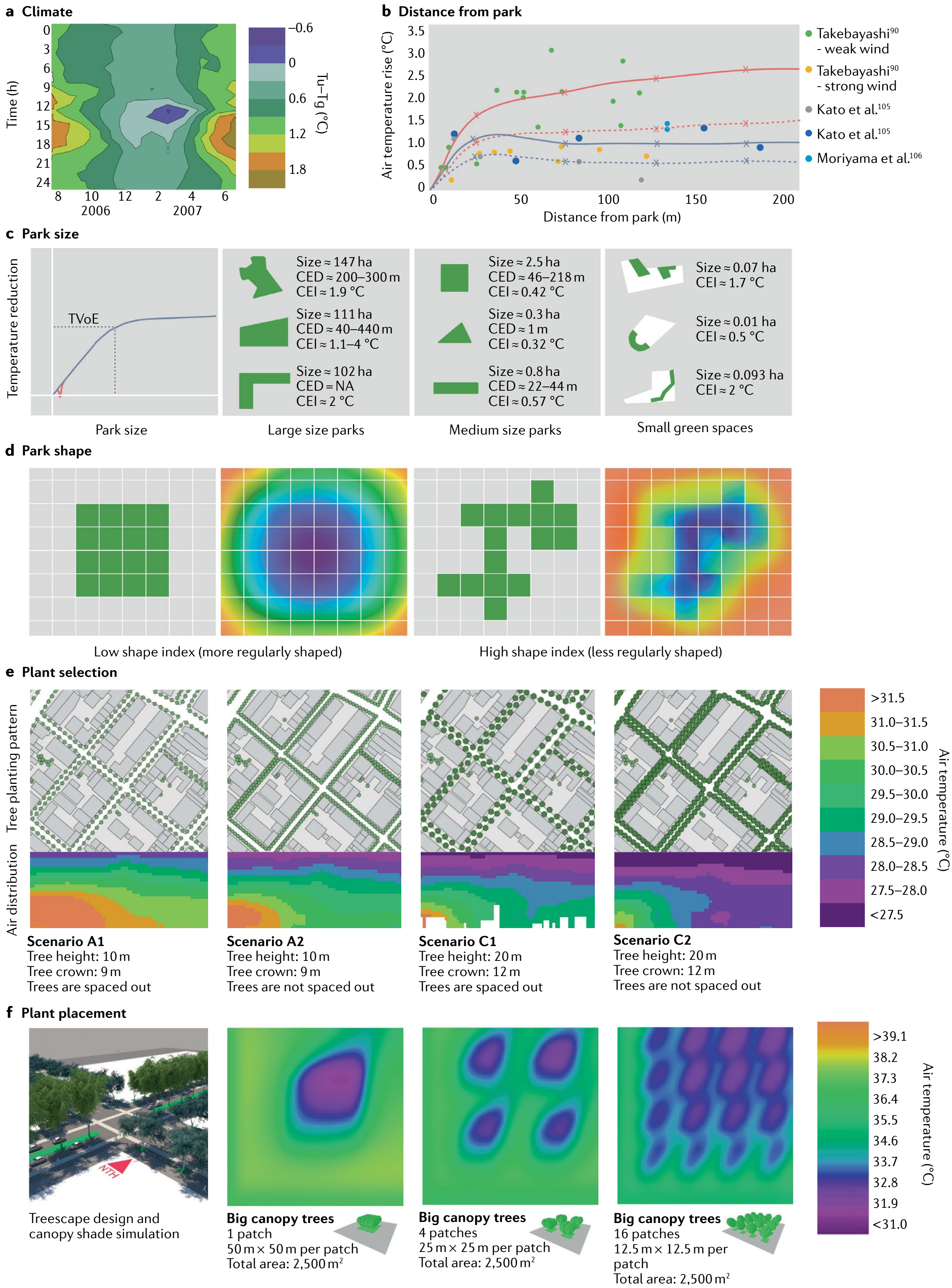
The cooling potential of smaller green spaces is often contradictory. Some research indicates that small green areas have the potential to provide air temperature reductions comparable to large parks[67,77]. However, urban geometry and prevailing wind conditions become

Threshold value of efficiency (TVoE). The value to which an increase in green space ceases to provide substantial cooling.

important factors, and if such conditions are not favourable, small areas can become warmer, not cooler[76,94]. Indeed, such small spaces are often more susceptible to urban and anthropogenic influences, increasing sensible heat gain, for example, through a greater percentage of paved surfaces. Accordingly, 14 of 61 small parks in Taipei were, on average, 0.42 °C hotter than their surroundings[94], and a small 1.5-ha inner-city park in Melbourne also experienced a 0.2 °C increase in air temperature during the early part of the day[101]. The cooling effect beyond park boundaries can also decrease with size. For large parks of more than 100 ha, the cooling effect might extend a few hundred metres beyond the park periphery, whereas the cooling effect of small green spaces (less than 0.1 ha) may not even extend beyond their boundaries (FIG. 4c).

Similar to size, park shape also influences the cooling effect[102]. Regularly shaped parks such as square or circular spaces have been found to exhibit higher cooling efficiency, which drops as the shape gets more complex[75] (FIG. 4d). In addition, the cooling efficiency of parks is maximized when green spaces are polygonal (circular or regular polygons) compared with linear (long and narrow)[103,104]. This difference can partly be attributed to the influence of park shape on plant selection. Linear parks tend to consist of identical tree species and often lack smaller trees and shrubbery. Accordingly, they are prone to heat invasion from areas


Fig. 3 | **Average greenery-related peak temperature reductions.** Maximum recorded air and surface temperature reductions associated with greenery on the ground (panel **a**) and greenery on buildings (panel **b**) from previously published studies (see Supplementary Table 1 for identifier information). Greenery on the ground are separated by studies assessing temperature changes through remote sensing or field measurements and greenery on buildings are grouped by green roofs and green walls. Box and whisker plots on the left are produced from the individual studies shown on the right.


a Climate
Time (h)
0
3
6
9
12
15
18
21
24
8
10
12
2
4
6
2006
2007
−0.6
0
0.6
1.2
1.8
Tu–Tg (°C)
b Distance from park
Air temperature rise (°C)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0
50
100
150
200
Distance from park (m)
Takebayashi[90] - weak wind
Takebayashi[90] - strong wind
Kato et al.[105]
Kato et al.[105]
Moriyama et al.[106]
c Park size
Temperature reduction
TVoE
Park size
Size ≈ 147 ha
CED ≈ 200–300 m
CEI ≈ 1.9 °C
Size ≈ 111 ha
CED ≈ 40–440 m
CEI ≈ 1.1–4 °C
Size ≈ 102 ha
CED = NA
CEI ≈ 2 °C
Large size parks
Size ≈ 2.5 ha
CED ≈ 46–218 m
CEI ≈ 0.42 °C
Size ≈ 0.3 ha
CED ≈ 1 m
CEI ≈ 0.32 °C
Size ≈ 0.8 ha
CED ≈ 22–44 m
CEI ≈ 0.57 °C
Medium size parks
Size ≈ 0.07 ha
CEI ≈ 1.7 °C
Size ≈ 0.01 ha
CEI ≈ 0.5 °C
Size ≈ 0.093 ha
CEI ≈ 2 °C
Small green spaces
d Park shape
Low shape index (more regularly shaped)
High shape index (less regularly shaped)
e Plant selection
Tree planting pattern
Air distribution
Scenario A1
Tree height: 10 m
Tree crown: 9 m
Trees are spaced out
Scenario A2
Tree height: 10 m
Tree crown: 9 m
Trees are not spaced out
Scenario C1
Tree height: 20 m
Tree crown: 12 m
Trees are spaced out
Scenario C2
Tree height: 20 m
Tree crown: 12 m
Trees are not spaced out
>31.5
31.0–31.5
30.5–31.0
30.0–30.5
29.5–30.0
29.0–29.5
28.5–29.0
28.0–28.5
27.5–28.0
<27.5
Air temperature (°C)
f Plant placement
NTH
Treescape design and canopy shade simulation
Big canopy trees
1 patch
50 m × 50 m per patch
Total area: 2,500 m²
Big canopy trees
4 patches
25 m × 25 m per patch
Total area: 2,500 m²
Big canopy trees
16 patches
12.5 m × 12.5 m per patch
Total area: 2,500 m²
>39.1
38.2
37.3
36.4
35.5
34.6
33.7
32.8
31.9
<31.0
Air temperature (°C)

◀ Fig. 4 | **Factors contributing to temperature reduction for ground-level greenery.** **a** | Climate: air temperature difference between urban (Tu) and green (Tg) spaces in Nagoya, central Japan, revealing greater cooling potential in the summer. **b** | Distance from park: in situ (dotted points) and modelled (lines) air temperature rise with distance from the park in several areas of Japan, revealing cooling within 50 m from the green space. Orange lines indicate results from an isotropic diffusion model and blue lines indicate results from an incorporating buoyancy model. Solid and dashed lines indicate model simulations under weak and strong wind conditions, respectively. **c** | Park size: the concept of threshold value of efficiency (TVoE) for park cooling based on size, with indication of possible negative cooling for small parks (red line, left panel). Cooling effect distance (CED) and cooling effect intensity (CEI) for large, medium and small green parks of different shapes, revealing that CED diminishes when park size decreases. **d** | Park shape: illustration of air temperature associated with parks of contrasting shape index, indicating that regularly shaped parks cool a larger area. **e** | Plant selection: cross-sectional air temperatures associated with different model scenarios of tree height, canopy size and planting density in Montreal, revealing greater cooling potential as all three factors increase. **f** | Plant placement: visualization of tree canopy shade and ENVI-met simulation showing the difference in air temperature owing to different tree arrangements, revealing greater cooling potential for multiple, smaller tree patches. Panel **a** is adapted with permission from REF.[82]. Panel **b** is adapted with permission from REF.[90]. Panel **c** is adapted with permission from REF.[186]. Panel **e** is adapted with permission from REF.[187]. Panel **f** is adapted with permission from REFS[154,108].

outside the green spaces and, thus, display lesser overall temperature reduction. Polygonal green spaces, by contrast, tend to trap the cooled air more efficiently via small trees and shrubs, thereby, maintaining a larger temperature differential[103].

### *Cooling effect outside parks*

Although green spaces are cooler than the built environment, they only take up a small portion of the entire urban landscape. Therefore, it is important for the cooler air generated by green spaces to be able to permeate and cool surrounding parts of the built environment, so that cooling benefits are tangible over a larger area, mitigating the UHI. Much effort has, thus, been put into understanding how these spaces can influence their surrounding environments[90,105,106].

How far greening-related temperature reductions permeate varies markedly. In Beijing, China, for example, the cooling effects of 30 urban parks ranges from 2.3 °C to 4.8 °C and extends 35–840 m outside the park, the distance being governed by park size and characteristics of the surrounding environment[73]. An area with high building density, for instance, can impede air movement and hinder the exchange of cooled air from parks to their surroundings. In London, UK, park-related cooling was apparent up to 330 m away from the green space, with the distance of cooling again scaled linearly with green space area, but also tree canopy extent[107]. Cooling is further evident up to 1.1 km for a 156-ha park in Gothenburg, Sweden[79]. Overall, cooling potential is increased under stronger wind conditions, suggesting that the surrounding estate should be designed to maximize ventilation (FIG. 4b).

Thus, although the spatial extent of cooling varies considerably, it is clear that green spaces have the ability to provide cooling not just within the park (FIG. 4c,d) but also outside its boundaries (FIG. 4b), particularly when cooling potential is maximized through arranging parks at a minimum size (at least 1 ha) and placing at appropriate intervals in the urban area (less than 1 km).

Leaf area index
(LAI). Total one-sided leaf area per unit horizontal ground surface.

### *Plant selection and placement*

Size alone does not guarantee maximum temperature reduction, with plant selection and placement also playing a fundamental role in explaining heterogeneous park-related cooling (FIGS 3a,4e,f). For example, owing to their larger canopy (and, hence, shade) and evapotranspiration characteristics, trees provide greater cooling potential in comparison with shrubs and lawns[108,109]. In particular, in situ estimates from Germany indicate mean radiant temperature reductions of 39.1 °C under trees but only 7.5 °C on grassland[110].

The cooling potential of trees themselves, however, varies markedly, owing to contrasting plant functional traits, including canopy size and leaf area, both of which influence shade provision[111–113]. Canopy coverage, as estimated by the leaf area index (LAI), for example, is positively correlated to temperature reduction[114]; the larger the canopy, the larger the cooling (FIG. 4e). Tree species such as *Caesalpinia pluviosa*, with dense canopy and large coverage, can provide more than 90% solar attenuation and are ideal for improving the urban microclimate[115]. Dense canopies have also been shown to maximize cooling[116], reducing radiant exposure at ground level by up to 92% (REF.[117]). Similar to shade provision, plant evapotranspiration is also species-specific[118], with maximum latent heat flux varying by up to ~760 $Wm^{-2}$ (REF.[119]).

Interactions between vegetation and buildings must also be considered, especially with small parks, given their influence on the urban microclimate. For instance, shade from trees becomes less effective at reducing temperature when they overlap with shade from buildings[120]. Tree or shrub placement can also influence overall ventilation and result in heat or pollutant trapping within urban canyons, with model simulations suggesting up to a 40% increase in pollutant concentration arising from the presence of a dense row of vegetation[121].

Indeed, simulations can be used to understand the impact of plant placement on the microclimate to facilitate planning. The results, however, are often highly contextual and dependent not just on plant attributes but also on the energy exchange characteristics from its surroundings. For instance, while some simulations suggest maximum cooling for trees planted at equal intervals[122], others indicate that a clustered arrangement provided the largest cooling effect[108] (FIG. 4f). Nevertheless, it is clear that the selection and placement of plants must be considered in a manner that optimizes shading and evapotranspiration, and, thereby, cooling (FIG. 4e).

## Greenery on buildings

Modern urban landscapes are characterized by their compact city form, leaving little space for parks and gardens. In this regard, green roofs and vertical greenery (or living walls, green facades) — where vegetation is transplanted onto building surfaces (FIG. 5) — serve as alternatives to traditional landscape, providing environmental benefits to the cityscape, without much demand for ground-level space[123]. Much like greenery on the ground, greenery on buildings acts to cool by modifying evapotranspiration, shade provision and albedo, but also reduces heat transmission into (and out of) the building envelope by enhancing thermal insulation[124] (FIG. 2).

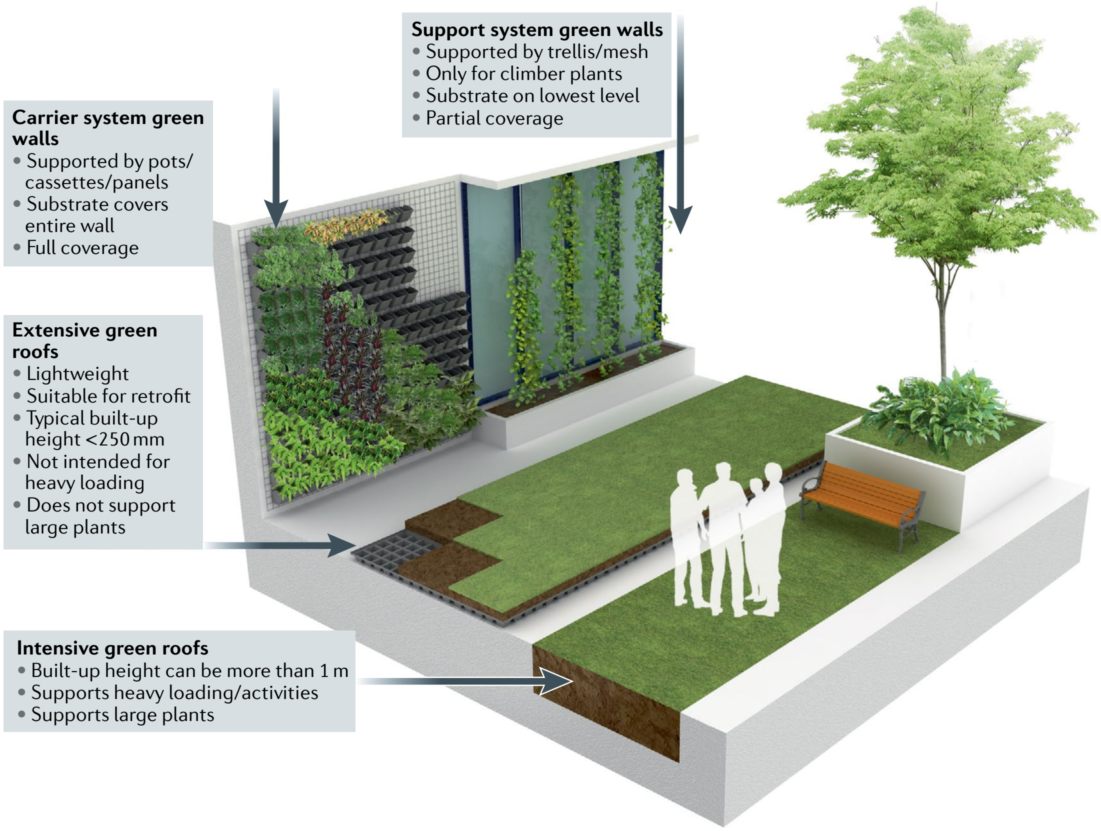



Fig. 5 | **Types of greenery on buildings.** Different options for vertical and rooftop greenery, including support system green walls, carrier system green walls, extensive green roofs and intensive green roofs.

Such greenery strategies can, therefore, feed back to provide energy savings.

Numerous studies have confirmed the cooling effect of vertical and rooftop greenery, in some cases, reporting surface temperatures up to 20 °C (REFS[62,125]) and >10 °C (REFS[39,126,127]) cooler than exposed surfaces, respectively. On average, however, it is estimated that green roofs can reduce peak air temperature by an average of ~3 °C (with a range of 1.5–4.1 °C) and peak surface temperature by an average of ~17 °C (with a range of 11–22.4 °C). Similarly, green walls are able to reduce peak air temperature by an average of ~3 °C (with a range of 2–4 °C) and peak surface temperature by an average of ~16 °C (with a range of 10.7–18.8 °C) (FIG. 3b). As indicated, there are significant differences within these systems that influence cooling potential, as now discussed.

### *Climate*

The magnitude of surface temperature reduction in the presence of vertical and rooftop greenery is highly dependent on prevailing climatic conditions, particularly the season. Typically, both green walls and green roofs are most effective in the summer, when there is higher evapotranspiration and foliage density (thus, shade provision and albedo). For example, green roofs in a Mediterranean climate (Italy) have been shown to reduce peak surface temperature by 20–30 °C in the summer, but only 10–13 °C during winter[128] (FIG. 6a,b), consistent with other analyses in Shanghai[129], Estonia[130] and Michigan[131]. A seasonal analysis for green walls in Italy also shows a similar pattern, wherein reductions in surface temperature peaked at around 6–7 °C in the summer, but only 3.5 °C in winter[132], with similar trends found in the UK[133]. Thus, greenery on building surfaces can act to reduce heat gain in summer and abate heat loss in winter (FIG. 6a,b).

As well as the season, the effectiveness of green facades and green roofs is also strongly influenced by the meteorological conditions. In particular, temperature reduction is most effective in sunny weather, becoming less potent during cloudy or rainy periods[134,135]; in Hong Kong, for instance, green-roof-related maximum surface temperature cooling was 19.8 °C, 7.74 °C and 7.85 °C in sunny, cloudy and rainy weather, respectively[136]. This meteorological sensitivity arises from reduced longwave and shortwave radiation exposure during cloudy periods, curtailing temperature rise and, therefore, cooling potential, and reduced evapotranspiration during periods of high cloud cover or rain, owing to changes in solar irradiance and vapour pressure deficit[119,137]. Indeed, it is thought that a threshold of approximately 300 $Wm^{-2}$ must be crossed before evapotranspiration cooling is activated and becomes evident[138].

### *System selection and placement*

***Intensive green roof versus extensive green roof.*** Green roofs can be intensive or extensive (FIG. 5), respectively encompassing those that are designed for public access

Vapour pressure deficit
The difference between moisture content in in situ air compared with the total moisture the air can hold when it is saturated.

or not, influencing their characteristics; intensive green roofs have deeper soil depths (>250 mm) and can hold large shrubs or small trees[124,139], whereas extensive green roofs have shallow soil depths (~150 mm) and planting palettes limited to succulents and shrubs[140]. Accordingly, intensive systems exhibit greater heat absorption and reduced temperature fluctuations[141]. For example, intensive green roofs have been found to reduce surface temperature by 30 °C, but also provide lower air temperature by up to 4.2 °C at 0.3 m height[125]. In comparison, a separate analysis of a green roof consisting of *Sedum* plants recorded temperature reductions of less than 2 °C (REF.[142]). With careful plant selection, however, it is still possible to achieve peak air temperature cooling of 4.5 °C (REF.[134]).

***Support green wall versus carrier green wall.*** As with green roofs, there are also different types of green walls: carrier system or support system. In the former, the plant substrate is distributed over the entire wall, whereas in the latter, the substrate is limited to the bottom and mesh used to support climber plants (FIG. 5). As such, carrier systems tend to exhibit greater insulation capabilities than support systems, owing to the substructure, air gap, substrate and plant layers[126,143]. In some cases, differences of close to 11 °C have been documented, with carrier systems and support systems promoting surface cooling of 21.5 °C and 10.7 °C, respectively, in Spain[144]. Accordingly, energy savings reached 23% for carrier green walls and 19% for support green walls[144].

***System placement.*** The ability of green walls and green roofs to reduce temperature in the urban environment is contingent upon several morphological factors, such as wall size and shape, as well as conditions of their immediate surroundings. Plant cooling potential from shade and evapotranspiration can be severely undermined when shade is already provided by adjacent buildings or when lack of access to sunlight impedes the evapotranspiration process (transpiration is a light-dependent process)[145]. Given that green roofs are typically located high on buildings, the chances of overshadowing from taller structures is often small.

Green walls, by contrast, are often influenced by their placement, specifically, through self-shading and overshadowing from other buildings. In one instance, green-wall-related temperature reductions have dropped from 16 °C to 2 °C as a result of self-shading, illustrating the dependence of time of day on cooling potential[127]. Similarly, the orientation of green walls is also important (FIG. 6c,d): east-facing and west-facing walls typically experience maximum cooling potential at different times of the day, owing to the direction exposure of the rising and setting sun, in one instance, lowering peak surface temperatures by 15 °C and 16.4 °C at around 12:00 and 19:00, respectively[146]. The south-facing facade, by contrast, recorded its peak temperature reduction of 16 °C at 15:45 (FIG. 6c).

### *Plant selection*

Plant selection further has a direct impact on the cooling potential of both green walls and green roofs. Selecting plants with large foliage will result in higher shade provision and less exposure to both longwave and shortwave radiation, lowering surface and air temperature outdoors, as well as reducing heat transmitted into the building. Green roofs with bigger shrubs and deeper soil depths tend to provide better cooling, as there is more shading from the plant canopy[147,148].

In addition to foliage density, plant functional attributes such as leaf size and colour, as well as evapotranspiration rate, further contribute to temperature reduction. Plants with high LAI, leaf stomatal conductance (indicating transpiration activity), thin and light leaf colour provide better cooling[149]. Specifically, *Stachys byzantina* and *Salvia officinalis*, both tall non-succulent plants with high LAI, can register surface temperature reductions of up to 10 °C. Notably, temperature reduction provided by *Sedum* (succulent, shortest plant and lowest stomatal conductance) was approximately 5 °C.

The holistic approach to plant selection is important, as the cooling potential of plants can vary between species. For instance, plants with high LAI can contribute to higher mean radiant temperature exposure, as larger leaves might get heated up more easily than plants with smaller leaves, as indicated by a 10 °C difference in peak mean radiant temperature between *Phyllanthus cochinchinensis* and *Heliconia* 'American Dwarf'[62] (FIG. 6e). Therefore, it is more appropriate to select plants based on a variety of traits such as plant height, evapotranspiration rate and albedo, instead of focusing solely on foliage density.

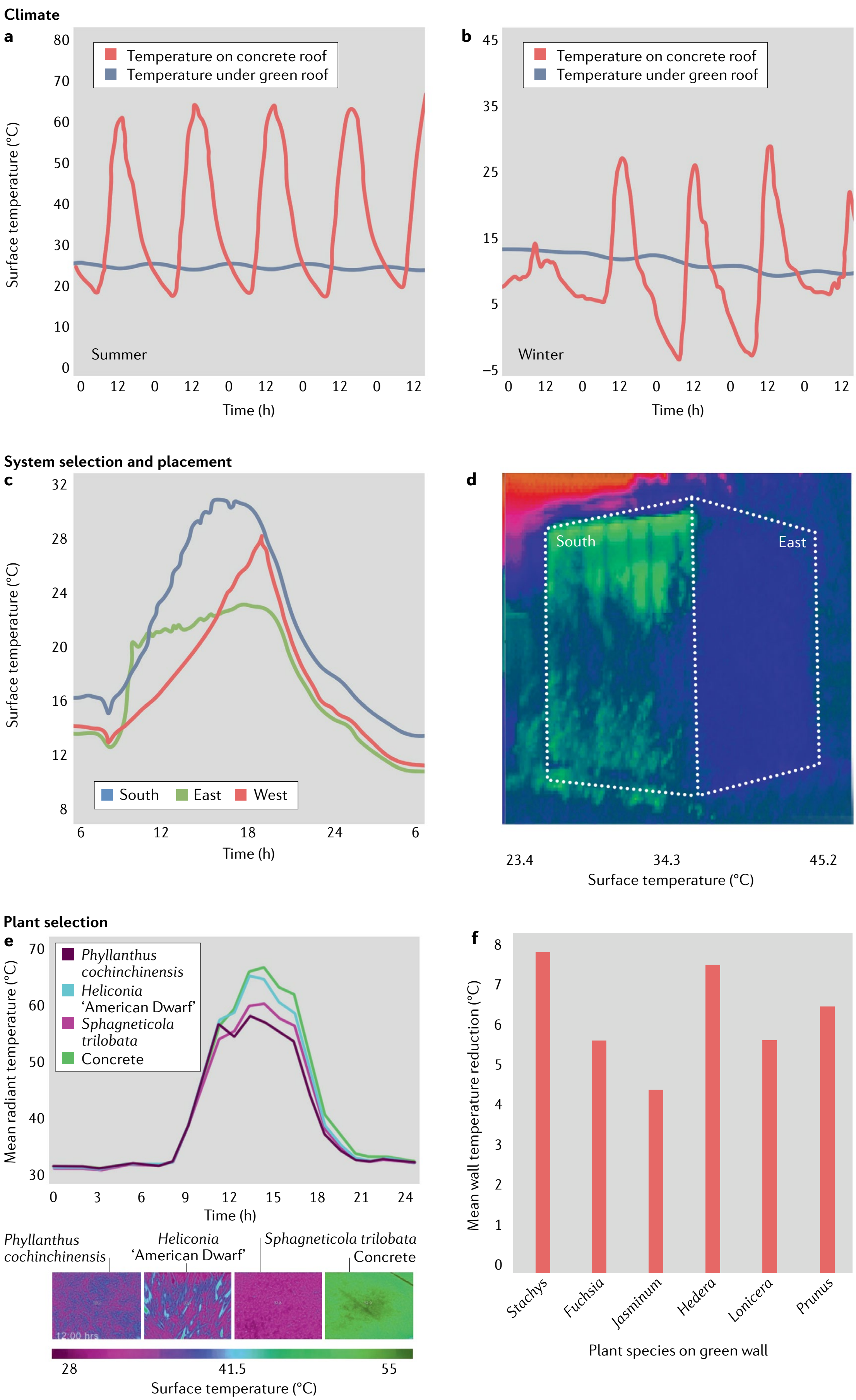
Similar to green roofs, the choice of plants selected will greatly influence the cooling potential of green walls. Variations in plant evapotranspiration and shade provision can account for close to 4 °C in temperature reduction (FIG. 6f). Plants such as *Jasminum officinale* display more cooling due to shade provision, while cooling from *Fuchsia* 'Lady Boothby' can be attributed more to transpiration activity[150].

## Implications for urban design

It is clear that urban greenery is effective in reducing temperature in the built environment: green parks lower air and surface temperatures by an average of 3 °C and 7 °C, respectively, while green walls and green roofs can reduce peak surface temperature by around 17 °C. Moreover, the variability in cooling potential (FIG. 3) implies that simply adding greenery might not instantly cool temperatures. Instead, a more nuanced approach must be adopted when it comes to the selection and placement of greenery, bearing in mind biotic as well as abiotic considerations (FIGS 4,6). While there are no universally accepted guidelines, several key concepts from this Review can be used to help inform urban design and maximize the mitigation potential of urban greenery.

### *Greenery on ground*

There is evidence to suggest that urban parks should be 0.5–1 ha in size to maximize their cooling potential[97–100]. In addition, they should be regularly shaped to minimize anthropogenic influences and capitalize on the TVoE (FIG. 4c,d). Ideally, these parks should also be evenly interspersed throughout the city with spacing of less than 1 km (REFS[73,107,151]), all to ensure maximum



Climate
a
Temperature on concrete roof
Temperature under green roof
Surface temperature (°C)
80
70
60
50
40
30
20
10
0
Summer
0 12 0 12 0 12 0 12 0 12
Time (h)
b
Temperature on concrete roof
Temperature under green roof
45
35
25
15
5
−5
Winter
0 12 0 12 0 12 0 12 0 12
Time (h)
System selection and placement
c
Surface temperature (°C)
32
28
24
20
16
12
8
South
East
West
6 12 18 24 6
Time (h)
d
South
East
23.4
34.3
45.2
Surface temperature (°C)
Plant selection
e
Mean radiant temperature (°C)
70
60
50
40
30
Phyllanthus cochinchinensis
Heliconia 'American Dwarf'
Sphagneticola trilobata
Concrete
0 3 6 9 12 15 18 21 24
Time (h)
Phyllanthus cochinchinensis
Heliconia 'American Dwarf'
Sphagneticola trilobata
Concrete
28
41.5
55
Surface temperature (°C)
f
Mean wall temperature reduction (°C)
8
7
6
5
4
3
2
1
0
Stachys
Fuchsia
Jasminum
Hedera
Lonicera
Prunus
Plant species on green wall

◀ Fig. 6 | **Factors influencing the cooling potential of vertical and rooftop greenery.** Climate: surface temperature of a green roof (blue) and a concrete roof (red) in summer (panel **a**) and winter (panel **b**) in Italy; note the different scales on the *y* axes. Peak temperatures are reduced to a much larger extent in summer compared with winter, but, in both cases, temperature fluctuations are greatly reduced. System selection and placement: surface temperature profiles associated with green walls on south-facing (blue), east-facing (green) and west-facing (red) surfaces (panel **c**), and an infrared image illustrating the difference between south-facing and east-facing walls (panel **d**). Plant selection: diurnal radiant temperature profiles and corresponding infrared images for three different plant species and concrete (panel **e**), and mean wall surface temperature reduction from six plant species (panel **f**). Panels **a** and **b** are adapted with permission from REF.[128]. Panels **c** and **d** are adapted with permission from REF.[146]. Panel **e** is adapted with permission from REF.[62]. Panel **f** is adapted with permission from REF.[150].

spillover of cooler air temperatures[84,152,153]. As much as possible, it is advisable to allocate more trees than lawn space to block more direct solar radiation[94]. For smaller green spaces to provide effective cooling, plants need to be selected and placed strategically, as informed through the use of simulation tools to visualize cooling effect from trees[108,154] (FIG. 4f).

Pavement or roadside trees are able to reduce surface and air temperature to a lesser degree, but are typically located in close proximity to sources of anthropogenic activity. Their ability to provide cooling is also more susceptible to influences from the urban geometry and climate[155,156], providing opportunities to select vegetation with specific traits, such as choosing trees with larger canopies, so that more shade is provided along pedestrian footpaths during the day[116]. Some examples include *Caesalpinia ferrea* and *Peltophorum pterocarpum* for tropical[119], *Handroanthus chrysotrichus* and *Caesalpinia pluviosa* for subtropical[115], and *Tilia cordata* for temperature regions[111].

Several major cities already have existing directives for park provision per capital[123], as well as urban master plans to gradually increase green cover. In the current London Plan, greenery is a key component in the themes of 'Creating a healthy city' and 'Increase efficiency and resilience'[157]. A target of making more than half of London green by 2050 was set out, with policies implemented to encourage the inclusion of green infrastructure and promote the creation of new publicly accessible green spaces within urban areas, in turn, increasing the city's resilience and adaptation to climate change and the UHI.

### *Greenery on buildings*

Both intensive and extensive green roofs can further help reduce temperature (FIG. 3b). Larger temperature reductions can be expected from intensive green roof systems with deep soil depths and large plants such as *Rhapis excelsa* and *Erythrina fusca*[125,142]. Similarly, green walls provide thermal benefits by shielding wall surfaces from direct sunlight. Carrier systems are more effective than support systems at reducing heat gain through the building facade. For support systems, substantial coverage can also be achieved over time, but climber plants require sufficient time to grow, as well as proper maintenance for thick and even coverage.

It is clear that site conditions must be determined before commissioning a green wall or green roof project. It is recommended that solar simulation be conducted first, with adjacent buildings included to account for possible overshadowing effects. Building walls with high solar insolation are suitable for green wall installation. Green walls can still be installed for well-shaded areas, but their impact on temperature reduction will be diminished.

Next, the type of green wall system should be specified. Carrier systems are preferred for solid walls, as they provide better insulation and provide consistent coverage throughout the green wall. Support systems can be used for glazed facades, but design has to take into account factors such as view, access and maintainability. Designers might opt for smaller gaps between trellises and planting multiple climber plants per trellis to provide thicker and more consistent coverage.

Finally, plants need to be selected for maximizing cooling. Plants with big leaves (high LAI) such as *Aristolochia acuminata* are recommended, as they provide more shade and have less risk of being overcrowded compared with plants with smaller leaves, such as *Selaginella* sp.

The latest Singapore Master Plan has set a target of increasing greenery to ensure thermal comfort in light of climate change[158]. These targets are supported by legislation such as the Landscape Replacement Policy as well as the BCA Green Mark Scheme, which encourages the adoption of sky-rise greenery (green roofs and green walls) with emphasis on shade provision from plants to reduce the UHI. Greenery density is quantified using the green plot ratio (GnPR) — a function of green space area and corresponding LAI[159] — as a more direct translation of academic knowledge of the benefits of high LAI (leading to higher shade provision and more cooling) into practice.

Elsewhere, the promotion of sky-rise greenery in cites is done either through legislation (such as the 2019 Green Roof Act in New York[160], the Biodiversity Act and Green Roof Statement in France[161] and the Tokyo Green Roof Law[162]) or as a criteria in Green Building Rating Tools (GBRTs). Established GBRTs such as LEED (USA) require the installation of extensive or intensive green roofs as part of vegetation provision[163]. In BEAM Plus (Hong Kong), points are allocated for the provision of vegetated building envelope and green roofs to reduce thermal impact[164]. Besides ensuring adequate greenery provision via GnPR quantification, the BCA Green Mark Scheme (Singapore) also awards points for advanced greening efforts, such as having green walls on the east-facing and west-facing facades, to reduce direct solar exposure and minimize heat gain[165].

### *Integration*

When considering the combined effects of greenery, the scale of mitigation benefits must be identified[166] (FIG. 7a). At the city scale, improvement of greenery type for existing parks takes priority, while for the installation of new green parks, cooling intensity and cooling effect distance should be quantified using urban spatial modelling tools. At the district scale, street dimension and street canyon characteristics have a major role; street trees and vertical greenery are the most appropriate solutions. At the neighbourhood scale, areas where citizens are exposed

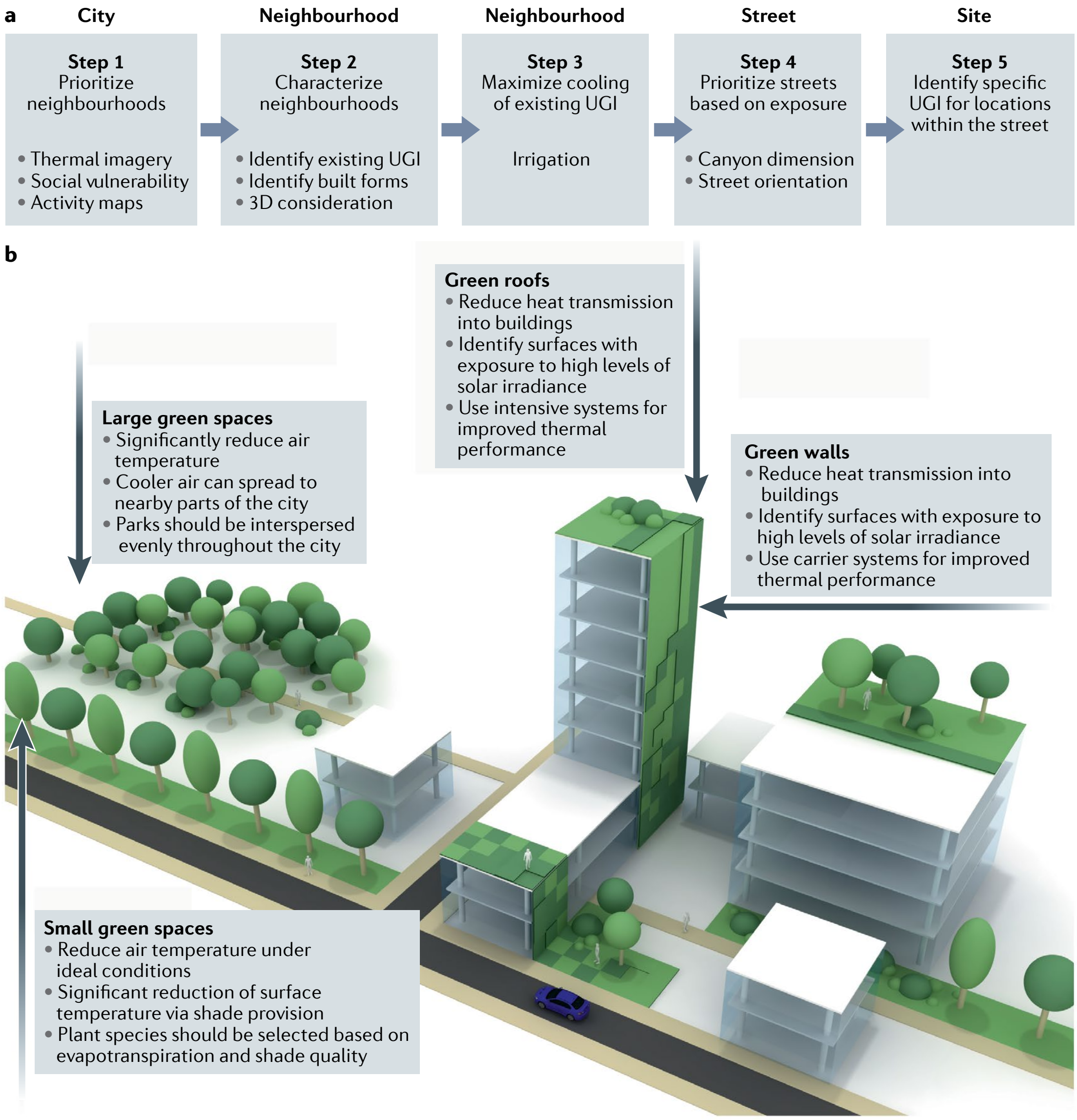



Fig. 7 | **Translation of greenery research into design. a** | Proposed framework for implementing greenery at different scales. **b** | A summary of cooling benefits of urban greenery. UGI, urban green infrastructure. Panel **a** is adapted with permission from REF.[166].

to high mortality and morbidity due to excess heat should be identified. Pocket parks, small green spaces and vertical greenery are the first to be considered, especially if the identified neighbourhoods are densely built and populated.

To better mitigate urban heat, it is advisable to employ a combination of parks, tree and shrub plantings, and vertical and rooftop greenery, situated at areas where building occupants and pedestrians can benefit most from their cooling benefits (FIG. 7b). The different forms of greenery occupy different spaces in the built environment, so they are not mutually exclusive. It is important for the planning of greenery provision to commence at the design stage and not as an afterthought.

Simulation of solar exposure should be conducted for all surfaces (including ground level, as well as the building envelope) for the purpose of identifying areas of high solar insolation, where the addition of greenery should be prioritized. This addition could be selecting trees with large canopies to shade main pedestrian paths or assigning green walls for facades with high solar exposure. Solar exposure is highly contextual and dependent on the local climate. Therefore, adjacent buildings should also be modelled and appropriate weather files be used for simulating conditions for the entire year. Once vulnerable areas have been identified, designers can start to select the appropriate plant species or greenery systems. After designing with the solar simulation results, architects can conduct iterative simulation studies to determine the impact of their greenery design schemes on thermal comfort and energy savings. This process can be repeated until the desired outcome is achieved. Urban planners can adopt a similar methodology for park design. Green spaces should be evenly interspersed throughout the city, so that cooling from parks can be more widespread. Care should be taken to have less convoluted site plans and to maximize tree canopy coverage.

## Summary and future perspectives

Peak UHI intensities can reach 10 °C (REFS[5,167]). This Review has shown that greenery, in all its forms, can be used strategically to alleviate heat gain, reduce thermal stress and, thereby, morbidity and mortality. Indeed, through shade provision and evapotranspiration, greenery on the ground and greenery on buildings can reduce air temperatures by ~3 °C (FIG. 3). However, the cooling benefits of urban greenery, be it greenery on the ground or on buildings, is not homogeneous, and is influenced by climate, plant selection and placement, as well as size and shape for green parks (FIGS 4,6). When rightly translated into design guidelines, scientific understanding of urban greenery can, thus, inform future urban design, which is vital, given anthropogenic climate change and the rising incidence of heatwaves. However, future research is required to maximize the potential of urban vegetation as a mitigation tool, including the following.

### *Plant functional traits database*

While the cooling benefits of different forms of greenery have been widely established, many studies point to the lack of specific data to make informed choices when deciding on the size and shape of green spaces, or when specifying plants for enhancing cooling; that is, there has not been a coordinated effort to come up with a comprehensive database of plant functional trait values at the species level. This database could include growth performance of plants to facilitate green wall coverage[168], to information on drought tolerance of trees for resilient streetscapes in light of changing weather patterns and water availability[119].

Owing to the lack of complete information, urban designers are not able to actively select plants that can provide more cooling. More importantly, this absence of information can lead to inaccuracies when simulating the cooling effects of greenery, as input factors such as LAI, evapotranspiration and vegetation coverage[169,170] are inadvertently generalized[171]. By having a consolidated database, researchers can build on existing knowledge and minimize testing plant species that have already been tested in previous studies. To ensure robustness of results, standards for setting up experiments can also be recommended, including minimum measurement periods, data logging frequency and specifications for sensor quality. Replicability of tests, which is a critical indication of reliability of methodology but often overlooked in this field of study[172,173], can ensue. This can range from growth performance of plants to facilitate green wall coverage[168] to information on drought tolerance of trees for resilient streetscapes in light of changing weather patterns and water availability[119].

### *Thermal comfort*

While much emphasis has been placed on understanding temperature reduction associated with urban greenery, future research must also prioritize expanding knowledge of thermal comfort — a combination of microclimatic factors such as air temperature, mean radiant temperature, air velocity and relative humidity[174,175]. A single tree, for example, has been found to be able to reduce the physiological equivalent temperature by up to 11 °C, but with marked variability owing to myriad factors, including time of day, surrounding vegetation, urban geometry and prevailing wind flow near the measurement spot[176]. Thus, although greenery can significantly improve thermal comfort by reducing the mean radiant temperature through shade provision and evapotranspiration, it is equally possible that trees or tall shrubs impede wind flow, leading to overall thermal discomfort[177]. Indeed, other studies have gone further to show that inappropriate tree placement can be highly detrimental to the outdoor environment, hindering anthropogenic heat and pollutant dispersion in the urban environment[178,179].

To address these issues, computational fluid dynamics (CFD) simulations can be used to provide some understanding on how placement of vegetation, especially for trees and tall shrubs, can complement prevailing wind conditions[71,180]. However, given the complexity and computing resources required, understanding of greenery impacts on wind flow using CFD is in its infancy and a resource ready to be fully utilized.

### *Translation into design guidelines*

Much as research is crucial to understanding the cooling benefits of greenery, it is equally important to translate what is known into practical design. These guidelines can range from simple rules such as prioritizing east–west orientations for green wall facings to maximizing heat reduction for the building[146], selecting trees with high canopy density[172], to complex frameworks that take into consideration surrounding built morphology and macroscale and microscale variables[166]. Different modes of greenery infrastructure can be recommended based on the corresponding scale of intervention, with consideration of other mitigating factors, such as urban geometry and climate (FIG. 7a). Through this method, specific greenery needs of the site can be addressed adequately and comprehensively in a 'right tree, right place' approach[154,181]. This performance-based (or translational) approach can further look into pedestrian comfort at predefined routes and examine how canopy shapes and tree placement can maximize shade provision, leading to improved thermal comfort.

Besides reducing temperature, the presence of greenery can also improve air quality[182], promote urban biodiversity[183] and stimulate mental as well as physiological well-being[184]. As an ecosystem service, greenery, therefore, offers a plethora of benefits to the urban environment, the information of which must be available to maximize greenery benefits. In addition, these design frameworks provide the opportunity for designers to couple other forms of climate regulation services into their design schema, from blue infrastructure (waterways)[37], cool materials (cool roofs and cool pavements)[33], to retroreflective facades[185]. Such efforts are key to encouraging the industry to adopt greening practices and improving thermal conditions of the urban environment.

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Physiological equivalent temperature
Air temperature at which, in a typical indoor setting, the heat balance of the human body is maintained with core and skin temperatures equal to those under the conditions being assessed. It provides an indication of thermal comfort, applicable for both indoors and outdoors.

Computational fluid dynamics
(CFD). Quantitative modelling of fluid flow based on the laws of mass, momentum and energy conservation that govern fluid motion.

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