Forestry Commission

Research Note

The role of urban trees and greenspaces in reducing urban air temperatures

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Cities and towns are often affected by the urban heat island effect, whereby air temperatures are higher than those in surrounding rural environments. This Research Note describes the negative impact that elevated urban temperatures can have on human thermal comfort and health and how urban green infrastructure can help lessen this impact. Drawing on recent research, two particular aspects of green infrastructure are explored. Firstly, the cooling effectiveness of urban greenspaces is examined. Secondly, the role urban trees play in providing cooling and the factors that may influence this benefit are highlighted. This Note gives examples of how the urban environment can limit cooling from vegetation, and provides guidance as to how these limitations can be reduced. Current scientific knowledge of strategies to maximise cooling and the extent to which this knowledge is being translated into practice are discussed as are the measures which have been adopted to help value this benefit. In light of climate change, the need for cooling by trees and greenspaces is expected to increase even in temperate climates such as that of the UK. Green infrastructure planning and development should embrace greenspace design and tree placement that facilitate such cooling, as well as include tree species with high cooling ability and ensure they are provided with enough space and resource to grow and function. Further research on the design strategies that lead to maximum cooling is required. Communication between researchers, practitioners and policymakers should be strengthened.

Forest Research

The urban climate and its implications for human health

Many cities and towns across the world experience higher air temperatures than surrounding rural areas. This effect is named the urban heat island (UHI) and it varies with season, time of day, weather conditions, city size and characteristics (Oke, 1987). In temperate climates, the UHI is particularly noticeable on clear, calm, warm nights (Oke, 1982). For example, night-time urban air temperatures which were 7 and 10 °C higher than in adjacent rural areas have been recorded in Birmingham (Zhang, Cai and Thornes, 2014) and London (Doick, Peace and Hutchings, 2014), respectively.

The UHI effect is caused by a combination of factors linked to urbanisation. Urban areas are largely covered by human-made materials, not vegetation. Vegetated areas lose much of the energy they receive from solar and long-wave radiation through evapotranspiration (termed 'latent heat[1] loss'), which can reduce the temperatures of their leaves and adjacent air (Gill *et al*., 2007). In contrast, built-up non-vegetated areas store the energy they receive and release it as long-wave radiation and sensible heat[2], thereby warming the local environment (Grimmond, 2007). The energy stored by different surfaces is mostly released after sunset; however, in built-up areas this takes place slowly as the buildings create barriers that receive, absorb and re-release the energy, preventing direct escape to the atmosphere (Oke, 1982; Grimmond, 2007). Thus the difference between urban and rural temperatures is accentuated at night.

Urban areas are also more densely populated than rural ones. In 2014, 83% of England's population was living in urban areas (Defra, 2018). The fuel and energy consumption taking place within cities and towns for activities such as transport, manufacturing, heating and cooling produces large amounts of heat, increasing the urban warming effect (Grimmond, 2007; Rizwan, Dennis and Liu, 2008), and releases pollutants which accumulate in the atmosphere. These airborne pollutants absorb some of the emitted long-wave radiation and redirect it back to the urban area (Rizwan, Dennis and Liu, 2008), further increasing the amount of energy circulating therein.

During a heatwave, air temperatures are considerably higher than normal for an extended period, which along with changes in the local humidity, light wind conditions, and the increased solar radiation can substantially reduce human thermal comfort. High air temperatures can further directly aggravate cardiovascular, respiratory and renal conditions, which lead to increased illness, hospital admission and death in the most vulnerable, especially young children and the elderly (Kovats, Hajat and Wilkinson, 2004; Hajat, Kovats and Lachowycz, 2007). In addition, high air temperatures can exacerbate air pollution (Papanastasiou, Melas and Kambezidis, 2015), which may also contribute to poor health. For example, ozone formed at ground level is detrimental to human health (Wang *et al*., 2003) and its formation increases with higher air temperatures (Levy *et al*., 2001). High air temperatures are also known to increase the number of deaths associated with the intake of particulate matter ≤ 10 µm (PM_{10}) (Qian *et al*., 2008). The risk of illness or mortality during hot periods is therefore intensified in urban areas that are affected by the UHI effect (Tan *et al*., 2010) and areas that have higher concentrations of airborne pollutants (Mayer, 1999).

Climate change projections for the temperate zone, including parts of Europe, North America and northern Asia, forecast that heatwaves will become more frequent and severe in future decades (Meehl and Tebaldi, 2004; Wang *et al*., 2012; Guerreiro *et al*., 2018). Consequently, the interactions between climate change, the UHI effect and urban air quality will heighten the future public health risk in cities and towns across the temperate region (Harlan and Ruddell, 2011). Mitigating strategies are therefore required to reduce the impact of UHIs and warmer climates on human well-being.

Green infrastructure as a strategy to reduce urban air temperatures

Green infrastructure includes the network of urban trees and woodlands, private and public greenspaces (such as parks, gardens, playing fields, allotments and green corridors), as well as green roofs and walls and vegetated areas associated with water bodies (e.g. wetlands) and provides numerous benefits to urban society (UK National Ecosystem Assessment, 2014). One such benefit is the moderation of local air temperatures (Bowler *et al*., 2010) that occurs in several ways as illustrated in Figure 1.

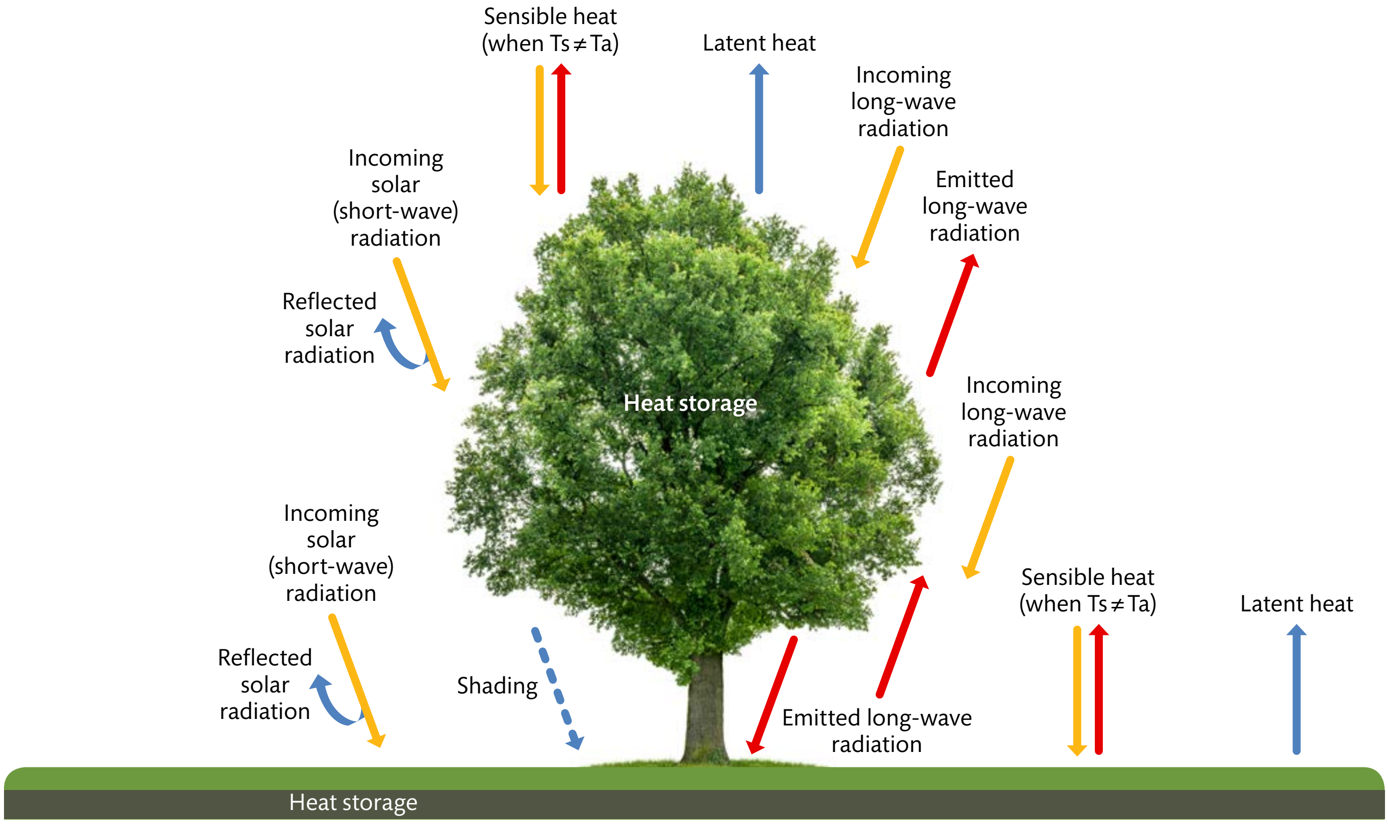
How green infrastructure reduces urban air temperatures

Through evapotranspiration

Through this process, some of the energy absorbed by plants evaporates water within their leaves, cooling them. The resultant water vapour is then transpired through the leaf pores (stomata) into the air without warming the air around them.

1. Latent heat is the energy needed to change the state of a solid, liquid or gas without changing the substance's temperature. When water evaporates in the soil, from a water surface or within leaves, this process uses some of the energy stored by the surface and cools it. Conversely, latent heat can be released back to the surface through water condensation.
2. Sensible heat is the heat that we can feel and that warms surfaces and air. When two surfaces are in direct contact or when a surface is in contact with air, heat is conducted or convected from a warmer to a cooler place.

Figure 1. Energy balance of green infrastructure.



Note: the arrows represent energy sources and energy losses. Orange arrows are energy sources towards green infrastructure: incoming solar (short-wave) radiation, incoming long-wave radiation and sensible heat gain (heat transferred when the air temperature, Ta, is higher than the surface temperature, Ts). Latent heat gain through condensation of water is assumed to be minimal and is not shown. Red arrows are energy losses from green infrastructure that lead to an increase in local air temperatures: emitted long-wave radiation and sensible heat transfer (when Ta is lower than Ts). Blue arrows are energy losses from green infrastructure that can lead to reduced local air temperatures: latent heat release (evapotranspiration) and reflected solar radiation. The broken blue arrow is shading which contributes to reducing surface temperatures by reducing the amount of radiation received.

Water on the surfaces of leaves, water bodies or soil can also evaporate. The total volume of water which evaporates and is transpired depends not only on the water available for evaporation, but also on the characteristics of the leaves and soil, the energy supply (from solar and long-wave radiation), the air temperature, the air vapour pressure deficit (the difference between the amount of moisture in the air and the maximum amount of moisture the air can hold at a particular temperature), and wind conditions.

Through reflecting more solar radiation

Vegetated areas typically reflect more solar radiation away from the surface than dark, artificial surfaces. Consequently, less solar radiation will be absorbed, resulting in vegetated areas having cooler surfaces and lower air temperatures compared with built-up, non-vegetated areas.

Through having lower heat storage capacities and providing shade

Vegetated areas have lower heat storage capacities than many artificial materials and transfer energy rapidly to the air because of their multiple small leaves and branches which facilitate air movement. Consequently, a smaller amount of the energy in the radiation absorbed during the day will be stored by vegetated areas and released to heat the air at night compared with built-up, non-vegetated areas. When trees, shrubs and other vegetation attached to buildings shield other urban surfaces (e.g. soil, pavement and buildings) from radiation, they can also reduce the amount of energy that those surfaces will store and subsequently release.

Through having a more open view of the sky

Greenspaces, including parks, gardens, squares and other spaces covered by low vegetation can have a higher proportion of sky visible (higher sky view factor) compared with built-up areas. This promotes long-wave radiation loss and air circulation and helps dissipate the energy received.

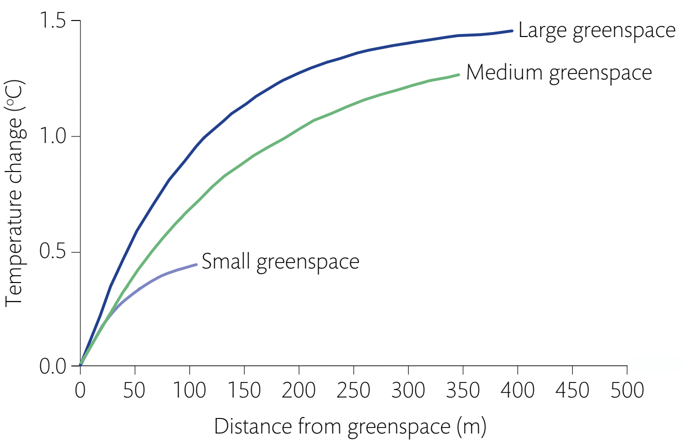
The contribution of urban greenspaces and trees

This Research Note builds on FCRN012 (Doick and Hutchings, 2013) and focuses on the contribution of two important typologies of green infrastructure – urban greenspaces and individual urban trees – for reducing air temperatures in cities and towns within the temperate region.

Factors affecting the cooling effectiveness of urban greenspaces

In temperate climates, the cooling benefits of greenspaces are most noticeable on calm, clear and warm nights when the UHI effect is strongest. During these periods, air temperatures within greenspaces are typically lower than those in surrounding built-up areas and the air temperatures in areas adjacent to the greenspaces are also reduced as cooling extends beyond the greenspaces' boundaries (Upmanis, Eliasson and Lindqvist, 1998; Doick, Peace and Hutchings, 2014). A Forest Research investigation (Doick, Peace and Hutchings, 2014) found that a large park in London had night-time air temperatures which were up to 4 °C lower (average 1.1 °C) than those in built-up areas on this type of night and that cooling extended in a non-linear way up to 440 m (average 125 m) from the greenspace (Figure 2). Moreover, recent studies have also recorded significant greenspace cooling in temperate climates during the day. For instance, this was shown in a monitoring campaign recording daytime air temperatures in and around 62 urban parks and forests in Leipzig, Germany, where greenspaces provided cooling approaching 3 °C (an average of 0.8 °C for forests and 0.5 °C for parks), extending up to 470 m from their boundaries (Jaganmohan *et al.*, 2016).

Figure 2. An example of estimated air temperature increase with increasing distance from greenspaces of different sizes (small: 2.5 ha; medium: 12 ha; large: 111 ha) during selected warm and calm nights up to a distance where the air temperature plateaued.



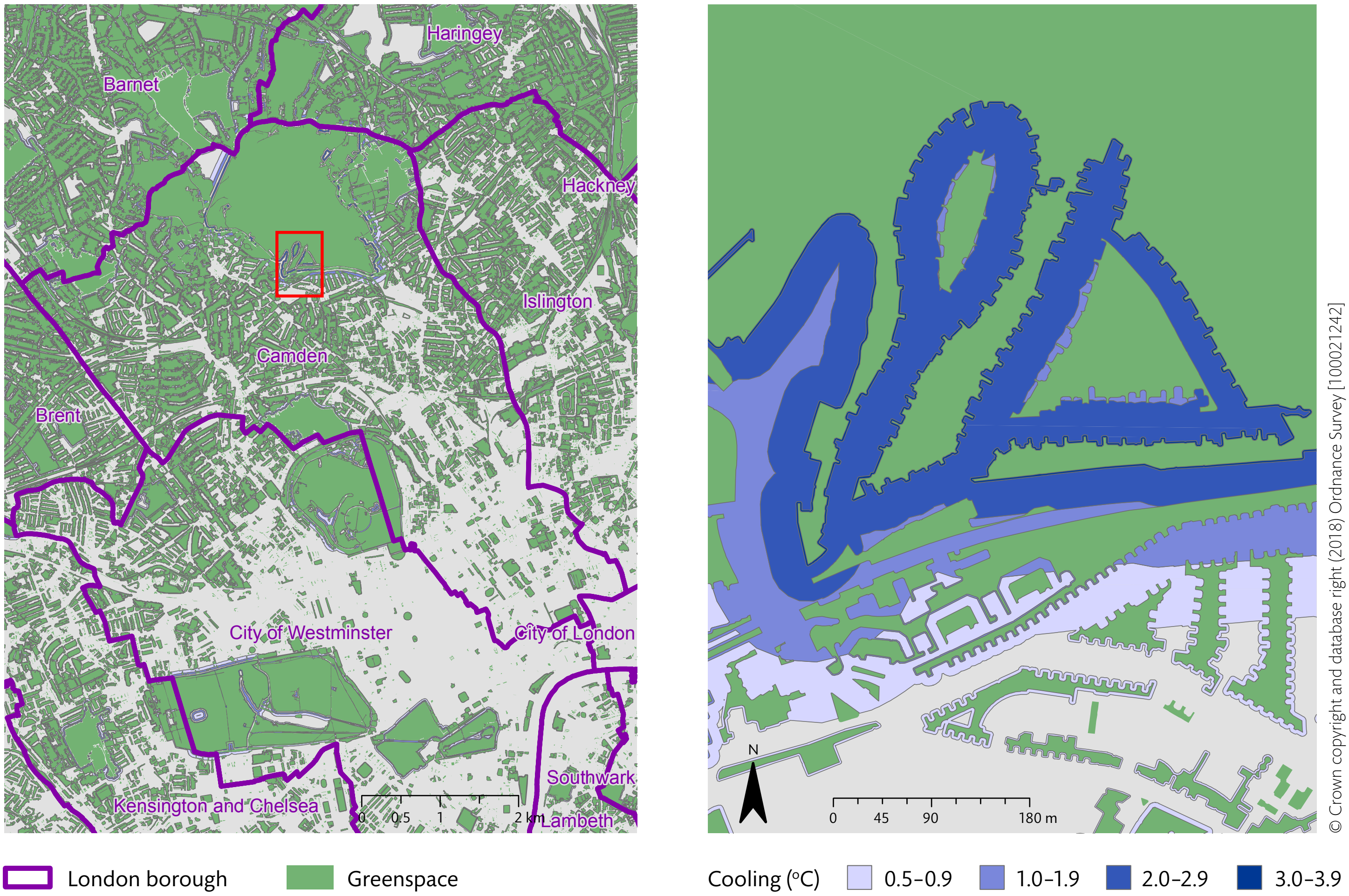
Note: adapted from information provided in Doick, Peace and Hutchings (2014) and Vaz Monteiro *et al.* (2016b).

The maximum cooling intensity and the maximum distance where there is measurable cooling depends on the weather conditions, the characteristics of the greenspace, and those of the surrounding urban area. The size of the greenspace is a key determinant. In London, for example, larger greenspaces provide more cooling than smaller ones (Figure 2; Doick, Peace and Hutchings, 2014; Vaz Monteiro *et al.*, 2016b). On calm, warm nights, mean maximum intensities and distances of cooling provided by small to medium greenspaces (0.5–12 ha) were in the range of 0.4–1 °C and 30–330 m, respectively, although no statistically significant cooling was found for very small greenspaces (<0.5 ha) (Vaz Monteiro *et al.*, 2016b). Based on this evidence, modelling suggested that to achieve cooling of ~0.7 °C across London on warm and calm nights, greenspaces of 3–5 ha would need to be situated ~100–150 m apart (Vaz Monteiro *et al.*, 2016b).

The London borough of Camden was used as a case study to test the spatial implications of achieving such a greenspace network. Camden occupies 2179 ha, and 907 ha (42%) of this is already covered by greenspace (Figure 3). Based on a model developed to map the spatial variation of nocturnal air temperature cooling provided by greenspaces in London (Vaz Monteiro, Handley and Doick, 2017), the current greenspace area in Camden was estimated to provide nocturnal cooling of >0.5 °C to 381 ha of the remaining built-up area (17% of Camden), meaning that greenspaces do not currently affect air temperatures across 891 ha (41% of Camden). To achieve cooling throughout Camden with greenspaces of 3–5 ha, it would be necessary to allocate ~360 ha of land to 120 new 3 ha greenspaces (16% of Camden) or ~320 ha of land to 64 new 5 ha greenspaces (15% of Camden; note that these calculations assume rectangular greenspaces). Clearly there are spatial and economic barriers to achieving such a tight network in highly urbanised areas of cities like London. However, this information may be useful in the design of new towns and housing estates to reduce the development of a UHI. Also, this estimation only takes into account cooling from greenspaces and not the potential cooling offered by other forms of green infrastructure, such as green roofs and walls and street trees.

Other characteristics of greenspaces which influence their cooling effectiveness are their shape and density, the types of trees, shrubs and ground cover present in the greenspace, plant arrangement, the percentage of impervious area and topography. The exact role of each of these factors in temperate climates is not yet clear. For example, an increase in the ratio between perimeter and area of a greenspace, which increases the edge effect and the complexity of its shape, reduces the cooling intensity measured during the night (Vaz Monteiro *et al.*, 2016b). This relationship also appears to function during the day, but only for greenspaces with areas

Figure 3. Spatial variation of nocturnal air temperature cooling provided by greenspaces (which include areas predominantly covered by grass and low vegetation or by >30% tree cover, as defined by the UKMap) in the London Borough of Camden, according to the model developed by Vaz Monteiro, Handley and Doick (2017).



<6 ha (Jaganmohan *et al*., 2016). Furthermore, an increase in the density of trees within the greenspace normally leads to more daytime cooling (Jaganmohan *et al*., 2016), but at night dense canopies of trees can hamper heat dissipation and long-wave radiation loss (Gillner *et al*., 2015). However, the negative effect of trees during the night can be minimised by careful tree positioning. For example, Spronken-Smith and Oke (1999) used scale models to examine the nocturnal cooling potential of four parks with different tree arrangements: (1) a grassed park with no trees; (2) a savanna-like park with scattered trees; (3) a tree-bordered park; and (4) a garden-like park with clumps of trees and open patches. They found that, relative to the park with no trees, all model parks with trees had the potential to be cooler at sunset, but not late at night. However, the study did not clarify which design offered the greatest amount of nocturnal cooling and such tree-spacing arrangements have yet to be properly investigated under real-life conditions.

Figure 4 summarises current knowledge on the design strategies which can be deployed to ensure maximum cooling from urban greenspaces. Further investigation into some of the strategies described in Figure 4 is required to provide detailed or quantitative specification.

Factors affecting the cooling effectiveness of urban trees

Tree characteristics

Tree species have different inherent characteristics that control their growth, form, physiology and radiative properties, and lead to some species having greater potential to provide cooling than others. Lin and Lin (2010) investigated the cooling ability of urban trees commonly planted in the sub-tropics and found that the characteristics which made the greatest contribution to reducing under-canopy air temperatures during the day were (in decreasing order of importance) leaf colour, leaf area index (LAI), leaf thickness and leaf roughness. Unfortunately, very little empirical evidence has been collected on the relative importance of different tree characteristics for their cooling capacity in the temperate region.

Figure 4. Current knowledge of design strategies that can lead to maximum greenspace and tree cooling.

Greenspace design

- Adequate size (>0.5 ha) and simple boundary shape
- Short distance between sites (e.g. around 100–150 m for greenspaces with 3–5 ha)
- Sparsely distributed trees[1]

Plant selection

- High typical transpiration rates in the warm season (e.g. species with broad leaves)[2]
- Large stature tree species and those with a wide, dense canopy[2]
- High leaf solar reflectance (e.g. light leaf colour)[2]
- Suitability and adaptability to the site[3]

Site conditions

- Use of vegetated surfaces or permeable/ porous pavements[4]
- Adequate water supply[4]
- Un-compacted and appropriately fertile soil[4]
- Ample rooting space[4]
- Appropriate design of the broader area (leading to sufficient sunlight and non-limiting temperature and vapour pressure deficit conditions)

Maximum cooling benefit

1. Only guideline information is available.
2. See also Factors affecting the cooling effectiveness of urban trees (page 5).
3. Species-specific: In terms of trees, it is important to pick 'the right tree for the right place'. Species selection tools are available online at www.righttrees4cc.org.uk, www.myerscough.ac.uk/media/4052/hirons-and-sjoman-2018-tdag-tree-species-selection-1-1.pdf, www.citree.de/?language=en, www.selectree.calpoly.edu and www.species.itreetools.org.
4. See also Achieving effective cooling from urban vegetation (page 7).

Leaf colour and roughness (often dictated by the presence or absence of hairs or the wax characteristics on the leaf's surface) can influence leaf and air temperatures through their effect on the leaf's ability to reflect radiation (Vaz Monteiro *et al*., 2016a). Leaf roughness, shape and size can further influence the leaf's water supply and energy transfer (Schuepp, 1993; Nicotra *et al*., 2011). By modifying the balance between sensible heat loss and evapotranspiration, these leaf attributes can impact on the amount of air cooling provided. For example, lobed and dissected leaves such as those from many oak and maple species have a thinner leaf boundary layer (the layer of still air adjoining the leaf surface) than similarly sized simple shaped leaves (Schuepp, 1993). A thinner boundary layer results in more effective heat and water vapour transfer from the leaf to the air (Vogel, 1970; Stokes, Morecroft and Morison, 2006). Small leaves such as those from conifers are also effective at losing heat and water vapour (Leuzinger, Vogt and Körner, 2010). In comparison, species with large leaves tend to warm up more, but they often have larger, more numerous and more open stomatal pores, which allow greater latent heat loss when water is available (Leuzinger, Vogt and Körner, 2010; Nicotra *et al*., 2011).

Other characteristics controlling not only the amount but also the seasonality of a tree's evapotranspiration cooling capacity are drought tolerance, leaf area, leaf habit and wood structure. A study comparing the evapotranspiration and water use efficiency of nursery trees recommended planting a greater proportion of species from dry habitats with dense canopies in streets. Such species may have lower leaf transpiration rates than trees originating from wet environments but they are normally better adapted to drought and so may be able to carry on transpiring for longer during dry periods, offering extended cooling (Stratópoulos *et al*., 2018). Moreover, in a study of water use of urban trees in Minnesota, USA, Peters, McFadden and Montgomery (2010) reported that deciduous diffuse porous genera such as *Tilia* or *Juglans* (where the cells for water transport are created evenly throughout the growing season) consumed more water during June and July than evergreen conifers or deciduous ring porous genera (e.g. *Fraxinus* or *Ulmus* where the cells created at the beginning of the season are larger and can transport more water than those created later). However, the authors also noted that conifers had a higher amount of annual transpiration per unit canopy area as they were actively functioning for longer (eight months instead of four) and had higher LAI and smaller projected canopy areas (Peters, McFadden and Montgomery, 2010). The overall shape of the canopy and the arrangement and density of leaves and branches also influence the amount of shade provided, given that trees which have a wide canopy and high density of leaves and branches project a more effective shadow (Macias and Doick, In press; Sanusi *et al*., 2017).

Several studies have investigated a small number of tree species typically found in temperate urban locations for their ability to provide cooling through evapotranspiration and shade. One study carried out in Dresden, Germany (Gillner *et al*., 2015), showed that *Corylus colurna* and *Tilia cordata* trees have a greater daytime cooling potential than *Ginkgo biloba*, *Liriodendron tulipifera* and *Ulmus* × *hollandica* trees, because of their higher potential evapotranspiration and leaf area. As a consequence, air temperatures around canopies differed by up to ~2 °C on hot summer days (Gillner *et al*., 2015). Another study, in Manchester, UK, showed that young *Pyrus calleryana* and *Crataegus laevigata* trees can provide three to four times more daytime cooling than *Sorbus arnoldiana* and *Prunus* 'Umineko' trees of a similar age, either due to their high evapotranspiration rates or their wide canopy and high LAI (Rahman, Armson and Ennos, 2015). Trees may also carry on transpiring into the early hours of the night (Dawson *et al*.,

2007) and may, therefore, continue to provide some additional cooling. This was demonstrated in Gothenburg, Sweden where night-time transpiration from the leaves of *Tilia* × *europaea*, *Quercus robur*, *Betula pendula*, *Acer platanoides*, *Aesculus hippocastanum*, *Fagus sylvatica* and *Prunus serrulata* trees was on average 7% of the value recorded during the day on their sunlit leaves (Konarska *et al*., 2016).

The impact that the radiative properties of different tree species may have on urban thermal conditions in temperate climates has been less studied. Nevertheless, leaves from trees commonly found in temperate cities and towns are known to differ significantly in their solar radiation reflectance, particularly in the near infrared band (Chung *et al*., 2015). How these differences translate into local temperature differences is the subject of ongoing research (Chung *et al*., 2015).

Given the lack of information regarding the tree characteristics which most influence cooling in temperate climates, Smithers *et al*. (2018) proposed three simple equations to assess the potential cooling ability of different tree species, one each for transpiration, reflection and shading. The equations used tree height, crown diameter, canopy aspect ratio, LAI, growth rate and reflectance. Of these factors, leaf area (determined from crown diameter and LAI) was shown to be important for all three cooling mechanisms.

Site condition

The amount of cooling provided by a tree is not just a consequence of its characteristics but also the type of pavement surrounding it, soil type and condition, amount of accessible water, local air temperature, vapour pressure deficit and crown exposure to radiation (Figure 4).

Trees typically respond to water stress conditions by closing their stomata to reduce water loss. For example, *Tilia* trees found in streets or in a paved square (with soils that frequently hold low amounts of water) in Gothenburg, Sweden and Munich, Germany have been shown to transpire nearly half the amount of *Tilia* trees found in a park or in a square with grass (Konarska *et al*., 2016; Rahman *et al*., 2017). If, however, trees planted in paved areas have sufficient access to water, then their evapotranspiration can be increased by the warm microclimate and will be higher than that recorded in trees planted in vegetated areas. This was shown by Kjelgren and Montague (1998), who noted that containerised *Pyrus calleryana* trees placed over asphalt in Carbondale, Illinois, USA lost ~30% more water (expressed per unit leaf area) than those over grass because they received more long-wave radiation from the asphalt. However, the evapotranspiration demand created by the microclimate conditions can be so high that it can cause trees to close their stomata and suppress water loss even when they are well-watered (Whitlow, Bassuk and Reichert, 1992).

Poor quality urban soils and the widespread use of impermeable pavements can further intensify stress to urban trees and hinder their growth. Impervious surfaces impede water infiltration to the soil and direct storm water to the surface drainage network (Coutts *et al*., 2013) resulting in low availability of water within the soil for plants. Furthermore, many urban soils are severely compacted inhibiting both water penetration and soil aeration and thus root expansion (Craul, 1985). They can also lack the organic matter and nutrients needed to support plant growth (Craul, 1985; van Herwijnen, Hutchings and Doick, 2014). Tree and canopy size usually decrease in situations where there is a large percentage of impermeable paved area surrounding a tree (Day and Amateis, 2011). Yet the restrictions to growth created by the pavement can be attenuated if the quality of planting medium is adequate. Assessing *Prunus serrulata* and *Ulmus parvifolia* trees growing in similar sized pits but with different rooting media, Smiley *et al*. (2006) showed that trees growing in non-compacted soils below suspended pavement were larger, provided more shade and looked healthier after 14 months than those growing in pits filled with Stalite (an expanded slate lightweight aggregate).

Achieving effective cooling from urban vegetation

Effective cooling is provided by healthy plants; they have more leaves than stressed plants and provide more shade (Coutts *et al*., 2016). Their leaves are also more physiologically active, so they transpire more. Therefore, to maximise cooling it is necessary to provide growing conditions that promote good plant health and functioning as well as an adequate water supply (Figure 4). If low water availability is recurrent, plants may have reduced growth, they may shed some or all of their leaves or even die. Plant water requirements are likely to be increased in urban areas because of the higher air temperatures, vapour pressure deficits and radiation loads. For example, Zipper *et al*. (2017) recorded a 7% increase in evapotranspiration demand in central Madison, USA, compared with non-urban surrounding areas.

With climate change projections indicating an increase in air temperatures and a reduction of precipitation in the summer in temperate climates (Guerreiro *et al*., 2018; Met Office, 2018), the water supply for urban plants in this region is likely to become limiting. New approaches to urban design, such as those incorporated into sustainable drainage systems (SuDS), can facilitate water recharge to soil and vegetation as well as offer cost-effective solutions to storm water alleviation

(Charlesworth, 2010). These systems include the use of urban rain gardens, wetlands, bioswales (vegetated drainage channels next to roads), green roofs, green walls and non-vegetated means of capturing storm water (e.g. water tanks, water bodies, underground aquifers) (Charlesworth, 2010; Coutts *et al*., 2013).

The use of permeable or porous pavements and appropriately sized tree planting pits can also increase the volume of water reaching the soil (Figure 4). The size of tree pit required is proportional to the canopy projection of the mature tree and information is available to help guide pit design (e.g. Urban, 1992; GreenBlue Urban, 2018). Techniques such as soil profile rebuilding that increase the quality and water-holding capacity of urban soils in planting sites should also be followed as they can considerably accelerate plant establishment and growth (Layman *et al*., 2016) and reduce the need for extra watering. Guidance on soil regeneration in urban brownfield sites for future greenspace creation recommends a minimum organic matter content of 10% in order to support soil moisture retention (van Herwijnen, Hutchings and Doick, 2014). However, species' soil preferences vary and the planting medium must suit the species of choice. For advice on selecting the right tree for the right place refer to the urban tree manual (Forestry Commission England, 2018).

Furthermore, increasing green cover in cities and towns can help ameliorate the restricting urban microclimatic conditions that can cause water stress even when water is available and the planting site is appropriate and, in turn, improve the condition of the existing vegetation. This will help maximise its ability to provide cooling, further assisting in improving thermal comfort of urban citizens and reducing the UHI effect.

Practical applications of urban green infrastructure research

In the UK, the cooling benefits of green infrastructure are now well recognised within research circles and by several environmental organisations, government bodies and professional associations. In a review of grey literature, Sinnett *et al*. (2016) identified a large evidence base demonstrating many of the services provided by green infrastructure, including climate regulation. However, this report highlights that much of the information collated is not reaching planning policy and green infrastructure development. The main reasons for the gap between research, practice and policy were linked to: (1) an overload of information, resulting in practitioners and policymakers not being able to access and/or understand it; (2) a lack of a dialogue among researchers, practitioners and policymakers; and (3) a lack of financial justification for investment in green infrastructure (Sinnett *et al*., 2016).

Even if these issues are addressed, the maximisation of cooling benefits is not seen as a priority in the design and management of green infrastructure. For example, when surveyed about their reasons to invest in green infrastructure, local authorities more often mentioned benefits linked to water management, amenity value or air purification than heat reduction (Davies *et al*., 2017; Schüder, 2017). This is perhaps not surprising given the current temperate climate of the UK and the relatively few occasions when temperatures across the country are high, even in urban areas; but with the climate changing, the need for green infrastructure cooling benefits is likely to increase. Indeed, high air temperatures are recognised as a significant potential risk to human health at both central government (HM Government, 2017) and institutional (Kovats, 2015; Public Health England, 2015) levels in the UK. Projections warn that the number of heat-stress related deaths in the UK could more than double by the mid-century from a baseline of ~2000 per year if action is not taken to reduce building overheating and the UHI effect (Hajat *et al*., 2014; HM Government, 2017).

Fortunately, technologies and practices that allow vegetation to overcome the constraints created by the urban environment are increasingly being used. Institutions such as the Construction Industry Research and Information Association (CIRIA; www.ciria.org) and the Trees and Design Action Group (TDAG; www.tdag.org.uk) have contributed to the mainstreaming of the use of SuDS and the improvement of urban tree-planting methods. Furthermore, information on the benefits and trade-offs of different permeable pavements is starting to reach practitioners (London Tree Officers Association, 2017); this evidence contributes to more informed pavement selection and application. Although these technologies and practices are not being adopted specifically to maximise plants' cooling effectiveness, they will improve it.

Quantifying and valuing the cooling benefit

Accurate quantification of cooling by urban vegetation (on its own or integrated in greenspaces) is hard to achieve as it is dependent not only on the way plants are growing and functioning, but also on the local climatic conditions, quality of soils, and the design and characteristics of the surrounding area. Nevertheless, models are being developed to estimate current cooling and/or forecast additional cooling provided through an increase in green cover, with or without trees. For example, the current greenspace in Greater London (presently 47% of its area) was estimated to offer air temperature cooling of >0.5 °C on clear, calm and warm nights to 39 725 ha of built-up area surrounding the greenspaces, which is equivalent to 23% of London's area (Vaz Monteiro *et al*., 2017). Also, 20% increase in green cover in the Glasgow and Clyde Valley region was projected to be capable of reducing future average air temperatures in the summer by 0.3 °C, a third of the extra UHI expected for the area in 2050 under current climate change projections (Emmanuel and Loconsole, 2015).

Some studies, particularly in the USA, have placed a monetary value on the cooling benefit achieved by the urban vegetation. At a local scale, trees on the west and south facades of 460 buildings in Sacramento, California were estimated to save each household an average of $25 of summertime electricity use due to shade (Donovan and Butry, 2009). At a regional scale, the population of Californian street trees was predicted to lead to net annual energy savings (cooling and heating) of $101 million (McPherson, van Doorn and de Goede, 2016); and, at the national scale, urban/community forests in the USA were estimated to save $7.8 billion in energy costs per year, $4.7 billion of which was from reduced electricity use (Nowak *et al*., 2017). Similar studies for the UK and other temperate regions are scarce. One recent study attempted to model the evaporative cooling provided by the trees in three UK urban areas (Edinburgh, Wrexham and London) and how this translates into energy savings through increased air-conditioning unit efficiency (Moss *et al*. Forthcoming). This cooling from urban trees was predicted as saving up to £22 million in annual energy consumption across inner London alone (Moss *et al*., Forthcoming). Regardless of the lack of UK studies on the monetary value of cooling by urban vegetation, the UK National House Building Council offers practical guidance on tree placement to reduce solar heating of differently orientated building facades, as previously summarised (Doick and Hutchings, 2013).

These potential financial savings, added to the economic value of other benefits provided by the wider green infrastructure (such as air pollution amelioration, flood management and carbon sequestration) can offset, or even exceed, the costs associated with its expansion and management. Implementation of a cost-benefit analysis is therefore an effective means to justify investment (Vandermeulen *et al*., 2011).

Conclusion

In future decades, warmer climates are expected to aggravate the effects of the UHI across cities and towns in the temperate region. Green infrastructure can play an important role in the reduction of urban air temperatures, lessening their negative impact on human thermal comfort and health. For that to happen, it is important to design new greenspaces and manage established ones in ways that will maximise cooling.

Knowledge of the cooling properties of urban greenspaces and isolated urban trees in temperate climates has advanced considerably in the last few years:

- Greenspaces >0.5 ha can cool local air temperatures.
- Cooling across the entirety of an urban area requires greenspaces to be closely spaced as cooling decreases with distance from the greenspace. For example, modelling suggests that, in temperate urban areas, greenspaces of 3–5 ha need to be placed about 100–150 m apart.
- Greenspaces should be treed, but care is required in the placement of trees as dense uninterrupted canopies can block heat dissipation and long-wave radiation loss at night.
- Some trees are better at cooling the environment than others, not only because of their inherent species' characteristics, but also their shape and size. Trees with high typical transpiration rates, high reflectivity, and with denser and larger canopies, reduce the surrounding temperatures more than others, provided they are healthy and have enough space, soil water and nutrient resources to maintain their growth.
- The tree's aerial and soil environment is as important as the tree itself in determining the amount of cooling it will be able to provide. It is important to pick the right tree for the right place but also to give 'the right conditions to the right tree'. New plantings should be combined with innovative design strategies that lead to greater water availability to trees and the improvement of urban soils and pavements surrounding roots.

There is more to discover about optimum greenspace design and tree placement for achieving maximum cooling, and the cooling ability of different tree species. Despite recent studies, a comparison of the diurnal cooling potential of a large range of tree species commonly planted in temperate urban settings, and the mechanisms through which they provide cooling, is still lacking. Additionally, the impact that local environmental constraints may have on the cooling effectiveness of a particular species requires further investigation so that green infrastructure planning and development can be optimal. Going forward, focus should also be placed on improving knowledge exchange among researchers, practitioners and policymakers, targeting new research towards the needs of policymakers and practitioners, and improving methods to justify investment in green infrastructure.

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