



Air temperature regulation by urban trees and green infrastructure

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A well-known effect of urbanisation is the warming of the local climate relative to surrounding rural areas, creating a phenomenon known as the 'urban heat island' (UHI). UHI intensity varies across a city and over time, but temperature differences may reach 9°C in the UK. Factors that contribute to a UHI include the thermal properties, height and spacing of buildings, the production of waste heat, air pollution, and differences in land cover and albedo. The UHI effect is important as heat-related stress accounts for around 1100 premature deaths per year in the UK – increasing noticeably in exceptionally hot years. An estimated 8–11 extra deaths occur each day for each degree increase in air temperature during UK summer heatwaves. As the occurrence and intensity of extreme heat events is set to increase under the changing climate predicted for the UK, there are significant implications for the thermal comfort and health of city dwellers across many parts of the UK. UHI abatement is of significance to those engaged in the development and delivery of climate change adaptation plans, including urban planners, policy makers and health professionals. Urban planning, building design and landscaping can all provide strategies for mitigating the UHI. Vegetation has a key role to play in contributing to the overall temperature regulation of cities. Informed selection and strategic placement of trees and green infrastructure can reduce the UHI and cool the air by between 2°C and 8°C, reducing heat-related stress and premature human deaths during high-temperature events.

Introduction

Cities frequently demonstrate higher mean average temperatures than surrounding rural areas. Described as the 'urban heat island' (UHI), this phenomenon has been reported for cities worldwide. The UHI is an artefact of the complex built environment, the lack of cooling vegetation and the high density of human activities in urban areas, and is a result of differences in the energy balances of urban and rural environments. During the day, cities and the countryside receive energy from the sun and from human activities. This energy is reflected or absorbed and stored for release when the temperature of the surrounding environment drops, most notably at night-time. Differences in where the heat is stored, the amount of heat stored, the rate and extent of energy release and what happens to emitted energy combine to create the UHI.

This Research Note draws together scientific evidence to outline the causes of urban heat islands, the role of trees and wider green infrastructure in combating the phenomenon, and the effects of urban heat islands on health. After providing some background on urban heat islands and their likely intensification in the future as a consequence of human activities, the Note explains how urban climate can be effectively modified by altering the amounts of heat energy absorbed, stored and transferred, and by adopting cooling strategies. Vegetation, and in particular trees, can be very effective as it delivers several mechanisms of cooling simultaneously and in a complementary manner. However, the extent to which vegetation cools the urban climate depends on species selection and strategic placement – putting the right tree in the right place. The final sections summarise some other adaptations which can be used to help mitigate the phenomenon and outline some of the potential conflicts to be avoided in using vegetation to cool the urban environment.

The urban heat island effect

Urban construction materials are often dark in colour with a high specific heat capacity and, hence, have a strong tendency to absorb and store heat energy. After sunset, the energy is released as long-wave radiation. In areas of high building density, the proportion of long-wave radiation lost directly to the atmosphere is less than in rural environments, as the energy radiating to neighbouring buildings is absorbed and re-emitted to the local environment, causing heating. On calm nights, localised warming is accentuated: cooling is inhibited by the lack of ventilation bringing cooler air in from the surroundings and transferring warm air away. Consequently, the maximum intensity of the UHI is typically reached several hours after sunset (Oke, 1987). During the August 2003 heatwave, 9°C

differences in night-time air temperature were observed between London and surrounding areas (Greater London Authority, 2006).

The UHI effect correlates to a city's population size and density: more built-up urban environments have a bigger heat island effect than those with less densely grouped centres, although even small urban centres including some towns demonstrate the phenomenon. UHI extent therefore varies across a city. Heat islands can develop in 'pockets' around single buildings and temperature differences of 4°C have been reported along a single street (Taha *et al.*, 1990). Two urban design factors further contribute to the UHI. Firstly, the height and spacing of buildings and their orientation relative to the prevailing wind restrict airflow and mixing and thus limit cooling. Secondly, in urban areas with deep street canyons (high building height to street width ratio) and high building densities there is a dense input of waste heat from human activities. Heat flux models for Greater Manchester, demonstrated that buildings are the dominant emitter of waste heat energy, contributing some 60% of the total (Smith, Lindley and Levermore, 2009). Road traffic contributed 32% and human metabolic heat emissions 8%. Waste energy constitutes a significant proportion of the total (solar plus anthropogenic) energy input, and contributes between 1 and 3°C to the heat island (Fan and Sailor, 2005). Reductions in its emission will help combat UHI development.

An 'urban cool island' is the phenomenon where city temperatures are lower than in the surrounding countryside. Its existence does not undermine the significance of the UHI, they are quite different. An urban cool island may be reported where a comparatively short period of time (a period of a few hours or less) is being reported or where the street canyon effect is particularly pronounced, preventing solar warming. Urban cool islands have also been reported where surface temperatures measured via satellite or aeroplane have been compared to air temperatures measured by thermometer (Leuzinger, Vogt and Körner, 2010). Surface and air temperatures, however, do not correlate well and should be treated separately (Roth and Oke, 1989).

Future intensification of the urban heat island

Global temperatures are set to rise during the foreseeable future as a consequence of human activities (Stern, 2006). Current climate change projections are for the southeastern UK to warm by 2.5–4°C by the 2080s (Defra, 2012), leading to a likely reduction in winter energy demands for heating (Davies, Steadman and Oreszczyn, 2008). Summer months are also projected to be warmer. The Department of Health has identified that temperatures in excess of 23°C are associated with heat-related stress and excess summer deaths (Department

of Health, 2008). The frequency of hot days, with temperatures above this threshold, the prevalence of overheating inside buildings, and UHI-induced heat stress are set to increase under the changing climate predicted for the UK, with significant implications for the thermal comfort and health of city dwellers across much of the UK. While the South East, London, the East and West Midlands, the East of England and the South West are projected to be most vulnerable, excess deaths due to heat are also forecast to increase in Scotland and Wales (Health Protection Agency, 2012). The risks are greatest in large metropolitan areas that can suffer from UHI effects, such as London, Manchester and Birmingham (Defra, 2012).

Positive urban migration continues. The UK urban population grew from 78% of 57.2 million (44.6 million individuals) in 1990 to 79% of 58.9 million (46.5 million individuals) in 2000 and 80% of 62.0 million (49.6 million individuals) in 2010 (United Nations, 2009). This trend is predicted to continue, reaching 83% of 69.3 million (57.5 million individuals) by 2030 and 86% of 72.8 million (62.6 million individuals) by 2050 (United Nations, 2009). Climate change and this population shift will exacerbate both the UHI and its negative impacts.

The Climate Change Act (2008) required the Government to publish a *Climate Change Risk Assessment* (CCRA). Published in 2012, and based on the latest long-range climate projections for the UK (UKCP09 – UK Climate Impacts Programme), the CCRA presents a national overview of potential risks from climate change and informs the development of adaptation plans by the UK Government and the Devolved Administrations. Additionally, the Climate Change Act requires all statutory sectors to have robust adaptation plans in place to build climate change resilience across every sector of UK society. *The Heatwave Plan for England* (Department of Health, 2008), for example, forms part of the health sector's adaptation plans, and *The Draft Climate Change Adaptation Strategy for London* (Greater London Authority, 2010a) provides a framework to identify and prioritise the key climate risks in London.

There is a need to combat the impacts of the UHI, especially in light of a changing climate. While building design is important, urban planning must also consider the strategic use of water features, vegetation and greenspaces within the landscape.

Impact of vegetation

The urban climate can be effectively modified by altering the amounts of heat energy absorbed, stored and transferred, and by adopting cooling strategies. Vegetation can be very effective as it delivers several mechanisms of cooling simultaneously and

in a complementary manner. The mechanisms of cooling are detailed below.

Evaporative cooling and evapotranspiration

Though it is termed 'evaporative cooling' it is not cooling as such, rather 'warming less' (Gill, 2006). Through evaporation, incoming energy is used to convert water into water vapour. Energy is being used to drive the evaporation process rather than being transferred to the sensible heat that we feel, thus air temperatures are lower (Oke, 1987). Where the water is within a plant, on its surfaces or in the soil, the process is termed evapotranspiration. Vegetation is sparser in cities than in the countryside, reducing cooling through evapotranspiration and much of the surface is sealed, reducing cooling through evaporation. This is a primary contributor to the UHI.

Reflectance

The extent to which solar energy heats the urban environment is linked to surface albedo, or reflectance of radiation. Less reflectance means that more energy is absorbed and stored, to warm the local environment. A lower urban albedo (commonly 15% versus a rural albedo of 20–25%) results in relatively more absorption than in rural surroundings.

Shading

Shading combats the UHI in three complementary and additive ways. Firstly, by limiting solar penetration shading restricts energy storage and the heating of the local environment that subsequently occurs. Secondly, shading reduces the direct gain of energy through windows and the resultant 'internal' greenhouse effect. Lowering air-conditioning demand leads to energy and cost savings and reduces the emission of waste heat energy. Finally, shading shelters people from direct exposure to the sun, which is important as thermal discomfort has been suggested to relate more to higher radiation exposure than higher air temperatures (Emmanuel, 2005).

The magnitude of cooling from a shade tree depends upon crown shape (broad being best) and density. Dense trees block more incoming solar radiation, reducing solar warming, but they also reduce light infiltration. As the use of artificial lighting can lead to localised warming, balance is required. Magnitude of cooling also depends on tree growth rate and longevity, and placement of the tree relative to the building to be shaded. McPherson (1993) calculated the value of shading in Fresno, California, as 2.5 times greater than that of evapotranspiration cooling. However, in temperate climates the role of shading and evapotranspiration are approximately equal.

Spatial scales of cooling

The surface temperature within a greenspace may be 15–20°C lower than that of the surrounding urban area, giving rise to 2–8°C cooler air temperatures and a cooling effect that extends out in to the surrounding area (Taha, Akbari and Rosenfield, 1988; Saito, 1990–91). For example, the cooling impact of the large Chapultepec Park (500 ha) in Mexico City reached a distance of about 2 km, approximately equivalent to the width of the park (Jauregui, 1990–91). With a size of 60 ha, a park can reduce noon-time air temperature by up to 1.5°C for up to 1 km distance, in a leeward breeze (Ca, Asaeda and Abu, 1998). Even for smaller size parks, the cooling band is measurable. The temperature gradient outside the 0.5 ha Benjamin Park in Haifa, Israel, was about 1.5°C and extended up to 150 m (Givoni, 1998). Similarly, a cooling band of 1–2°C extended some 20 m around a small (60 m by 40 m; 0.24 ha) greenspace in Kumamoto City, Japan (Saito, 1990–91). Based upon mathematical models, Honjo and Takakura (1990–91) suggested that a 100 m wide greenspace cools to a distance of 300 m and a 400 m wide greenspace cools to a distance of 400 m. They recommended that greenspaces should be no more than 300 m apart for optimum cooling within a neighbourhood.

In addition to the role of greenspace size, the extent of the cooled area around a greenspace is influenced by the type and composition of vegetation in the greenspace. Potchter, Cohen and Bitan (2006) found that high and wide canopy trees and higher tree/shrub coverage resulted in cooler parks compared to the surroundings. Similarly, Yu and Hien (2006) reported that the ambient temperature in a park was strongly correlated to the density of plants. The relative mix of hard and soft surfaces is also important. While daytime hourly mean air temperatures at 1.2 m height over grass have been reported to be 2°C lower than that over a hard surface (Ca, Asaeda and Abu, 1998), an urban park covered entirely by grass can be warmer than the surrounding built-up area (Potchter, Cohen and Bitan, 2006). Chang, Li and Chang (2007) showed that where paved surfaces are equal or more than 50% of the land coverage parks are on average warmer than their surroundings. Finally, wind strength and direction can affect the size of the cooled area around a greenspace (Yu and Hien, 2006; Zouliia, Santamouris and Dimoudi, 2009).

When arranged throughout a city as street trees, green roofs, gardens and greenspaces, vegetation and water features have a collective net cooling impact on average city-wide temperature (Ca, Asaeda and Abu, 1998; Yu and Hien, 2006). The role of trees is particularly important. Measurements from suburban Sacramento, California, in neighbourhoods with mature canopies indicated daytime air temperatures 1.7–3.3°C lower

than in areas with no trees (Taha, Akbari and Rosenfield, 1988). Analysis of air temperature data collected across the city of Portland, Oregon, showed that the most important urban characteristic separating warmer and cooler regions was tree canopy cover (Hart and Sailor, 2007).

The right tree in the right place

The extent to which vegetation cools the urban climate depends on species selection and strategic placement. This section presents considerations pertinent to selecting species for the greatest impact and locating trees to maximise summer cooling without compromising on solar winter warming. Trees can be very long-lived, so species selection should always consider the projected future climate as well as current climatic conditions.

Tree selection

Not all tree species have the same cooling effect; the lower the foliage temperature the greater the cooling, and canopy size, structure and density also influence the extent of shading. Leaf temperature depends on anatomical (leaf mass, size, shape, angle, reflectance), physical (incoming energy, air temperature, wind) and physiological (transpiration, stomatal conductance) factors (Monteith and Unsworth, 1990), and is intimately coupled with the water status of the plant. Leuzinger, Vogt and Körner (2010) demonstrated that trees responded differently to extremes in temperature but, generally, small-leaved species (e.g. *Robinia pseudoacacia* and *Pinus sylvestris*) tended to be more effective at cooling by maintaining lower crown temperatures than those of larger-leaved species.

Trees with larger canopies tend to cast more shade and deliver greater rainwater management and biodiversity benefits than smaller ornamental species. Health and vitality, however, are critical to ongoing delivery of cooling benefit. Species selection should therefore consider the following:

- Heat tolerance (especially at extreme ambient temperatures): species coolest at 25°C are not necessarily coolest at 35°C (Leuzinger, Vogt and Körner, 2010).
- Drought tolerance: different tree species, varieties, cultivars and provenances can vary in their water demand and tolerance to drought (Niinemets and Valladares, 2006).
- Pest, disease and pollution tolerance: tree species and varieties vary in the pests and diseases that they host. Moreover, reduced vigour caused by urban environment stresses (such as air pollution and moisture deficit) can predispose trees to additional health problems, particularly insect infestation (Mattson and Haack, 1987).
- Rooting zone availability and sensitivity to compaction: root

zone suitability is critical to a young tree's longevity. In dense urban environments, adequate soil for growth, available rooting space, moisture, oxygen and nutrient availability to a large extent determine the size that a tree will reach over its lifespan (Urban, 2008).

All these factors will also be influenced by changes in the future climate.

Species thus vary in their suitability to cool the local environment under different conditions and the critical role of species selection is to identify a suitable match for the site conditions, both now and in the future. The Right Trees for a Changing Climate portal (www.righttree4cc.org.uk) provides a searchable database and guidance on selecting suitable tree species to plant in urban areas in a changing climate.

Tree location

Trees placed close enough to directly shade buildings (termed shade-effect trees) can lower summertime energy demand to cool the building's indoor climate. Reviewing the literature, Meier (1990-91), for example, reported that vegetation can lower wall surface temperatures by 17°C, noon indoor air temperatures by 0.5°C and air-conditioning costs by 25-80%.

Size is important: smaller trees casting less summertime shade cool less (McPherson, 1993). However, effects are also tempered by building size, vegetation type, spacing and position relative to the building. The positioning of shade trees is particularly important in cool and cold climates, as shade cast by branches can reduce solar radiation penetration to such an extent that increases in winter heating demand outweigh any savings from reduced summertime cooling. Reviewing the literature, Hutchison *et al.* (1983) reported reductions of winter insolation by deciduous trees of 26-60% in America. Tree placement for shading benefit is also affected by latitude, as this influences the extent of shade cast (Heisler, 1986). At UK latitudes, trees on the west-facing side of a building provide good amounts of shade in summer and comparatively little in winter. Identical trees positioned on the south-facing side of a building cast relatively more shade in winter, a trend contrary to that required to reduce energy consumption. However, a taller tree in the same 'south' location with lower limbs pruned will cast relatively more shade on the building in summer and relatively less shade in winter than an unpruned specimen. Figure 1 shows how tree placement has the potential to affect solar heating of differently orientated buildings. As improperly placed trees are likely to have the greatest impact on energy cost in cool and cold climates, judicious pruning should be considered to promote energy savings.

Figure 1 Tree placement has the potential to affect solar heating of differently orientated buildings.



Trees located such that they do not provide shade but close enough to influence the local microclimate are termed climate-effect trees. These trees cool the local microclimate through evapotranspiration, leading to summertime air-conditioning energy savings. Climate-effect trees, particularly evergreen species, can also reduce heat loss from buildings in winter by reducing wind speed and, thus, air infiltration. Air infiltration is the phenomenon of air exchange between the inside and outside of a building through fissures in the exterior shell; it is caused by pressure differentials arising from wind speed and air temperature and can be particularly pronounced in poorly insulated buildings. As climate-effect trees do not cast shade over a building, they may be strategically placed to the north, south, east or west, as required for greatest effect on the prevailing wind direction.

East and west-facing windows experience low-level sun: small trees prove useful for shading. Locate trees further from the building to improve light penetration. McPherson and Simpson (2003) used computer simulations to test the relative importance of shade-effect, climate-effect and tree position for the 11 climate zones of California (including coastal, valley, desert and mountain). While the direction of impact (warming versus cooling) is likely to be correct, model uncertainty is unknown and the actual extent is likely to differ from that computed. Results are predicted to hold true for use outside California. Thus, shade-effect trees are important where solar radiation is high, climates are hot and arid and building energy use is predominantly for cooling (McPherson, 1993), and these trees provide greatest net energy benefit positioned on the west-facing side of a building wall. In colder climates, where the dominant energy use is for heating, it is important to optimise wind speed reductions and, therefore, climate-effect trees are relatively more important. Locating trees for summer shade seems to be less important than affecting wind speed and ensuring that trees do not obstruct winter irradiance from the south. In the UK, energy has been predominantly used for winter heating, but this is starting to change. Collectively, the UHI effect and climate change are leading to increased energy demands to cool and ventilate buildings and a reduction in winter heating demand. Informed species selection and appropriate positioning of urban trees for shade-effect is thus becoming increasingly important.

Human health impacts

Heat has a direct impact on human health. Heat-related stress currently accounts for some 1100 premature deaths and an estimated 100 000 plus hospital patient-days per year in the UK. These figures can increase noticeably for prolonged periods of high temperatures. The heatwave of 2003, for example, has

been estimated to have led to more than 15 000 additional deaths in the UK and France (Department of Health, 2008). Of these, 310 additional deaths were reported for England and Wales between 11 and 15 July as temperatures built from 22 to 30 °C (equivalent to 7.8 extra deaths each day for each degree in temperature above 22 °C). Later the same year, 676 extra deaths were reported in London alone as temperatures rose from 22 to 29 °C between 4 and 13 August (equivalent to 9.6 extra deaths each day per degree temperature increase) (Johnson *et al.*, 2005). In the summer of 2006, an estimated 10.7 extra deaths per day for each degree of increase in temperature occurred in England (Department of Health, 2008) and the mini heatwave of 30 June to 2 July 2009 led to an estimated 299 excess deaths in England and Wales (Andrews *et al.*, 2010). The Department of Health provides maximum daytime and minimum night-time threshold values for temperatures that could significantly affect health if reached on two consecutive days and the intervening night (Department of Health, 2008). These thresholds vary by region, but an average threshold temperature is 30 °C by day and 15 °C overnight.

The main causes of illness and death during periods of high temperatures are respiratory and cardiovascular diseases. Thus elderly people over 65 (especially those over 75 or living alone), people with compromised health, pregnant women and children up to the age of 4 are particularly at risk. The health effects are most pronounced where night-time temperatures remain high (Department of Health, 2008) and so are exacerbated by the UHI as it limits night-time cooling. Targeting UHI mitigation strategies to locations used by vulnerable groups (such as at hospitals, care homes and nursery schools) and focusing adaptation policies on vulnerable populations and the residents of urban areas will have the greatest impact in supporting adaptation to rising temperatures.

Modelling the impact of climate change on heat-related mortality, the CCRA indicates an approximate 60% increase by the 2020s and a 200% increase by the 2050s (Defra, 2012). These increases were shown to vary with region, partially due to higher population densities in the south, although mainly due to the generally higher temperatures in the more southern regions (see the section on Future intensification of the urban heat island above). Relative to population size, the mortality rate due to heat for London is approximately twice that of the North East of England. The predicted increases are serious and indicate that UHI adaptation is needed to plan for near-term, medium-term and longer-term climate changes.

An estimated 20% of London's land area is under the canopy of trees (Greater London Authority, 2010a) and about 38% of its land area is 'greenspace' (Generalised Land Use Database; 2005 Enhanced Basemap figures; Greater London Authority, 2010b).

While it is not known what proportion of London's population is cooled by these trees and greenspaces, greenspaces are recognised to lower local ambient air temperatures by 2–8 °C (see the section on Spatial scales of cooling above). If it is assumed, therefore, that London's trees and wider green infrastructure are preventing 2 °C of additional UHI warming then the current provision of greenspaces in London may be saving 16–22 lives a day during spells of hot weather. The value of premature death averted in the UK is £1 653 687.00 (2010 value; Department for Transport, 2012). Purely in terms of extra deaths due to heat stress averted, London's greenspaces are collectively valued at £26.4–36.4 million. Any reduction in urban greenspace provision is likely to lead to higher rates of mortality during future heatwaves, while increasing tree and greenspace provision may help prevent unnecessary loss of life in the future. Interestingly, the impact of trees and greenspace on air temperatures in winter is less well understood.

Other adaptations to mitigate UHI

The following section provides a brief overview of other measures that can reduce the UHI. Use of a combination of adaptation measures can enhance effective protection of human health.

Direct heating by solar radiation can raise the temperature of a building's walls and roof to 60–65 °C. Depending on the building's construction material and insulation, this can result in elevated internal temperatures. Vegetation may be used as part of a building's fabric or landscape to reduce direct heating by solar radiation. Green roofs, for example, consist of a vegetated growing medium over a waterproof membrane. Bio-shade is a collective term for shade-casting pot plants and plant-draped pergolas. In both cases, they alter a building's microclimate by providing a surface for evaporative cooling and by limiting solar warming, thereby reducing internal temperatures. Wider benefits include supported biodiversity and improved air quality. They also provide stormwater management, as rainfall interception and the use of permeable surfaces lead to reduced run-off to drains.

Using empirical models, Mentens, Raes and Hermy (2006) showed that greening just 10% of the roofs in Brussels, Belgium, would result in an annual rainfall run-off reduction of 2.7% for the region. In a life-cycle impact assessment, Susca, Gaffin and Dell'Osso (2011) found that substituting one square metre of 'black' roof with a 'white' or 'green' roof in New York City would provide 140 kg or 38 kg savings of CO₂e (carbon dioxide equivalent), respectively, over a 50-year period. Of the three roofs, the green roof required less energy during its construction and less replacement of building materials over its

lifespan. The use of bright coloured paints to help buildings cool is exemplified in the white walls and blue roofs of buildings in many Mediterranean locations.

Modification to the albedo of the walls and windows of buildings, car park surfaces and pavements will also have an impact on the energy balance of a building and the surrounding environment. Surface sealants with a low albedo, such as tarmac, prevent evaporative cooling; they also store and subsequently release heat contributing to the UHI. 'Cool pavements' combine reflective materials and high water permeability to aid cooling through reflectance and evaporation (Davies, Steadman and Oreszczyn, 2008). Their permeability also aids stormwater management and reduces the need to irrigate street trees.

Under prolonged hot and dry conditions, evapotranspiration slows. When the vegetation becomes parched it shuts down, and the cooling effect of vegetation is effectively switched off. Modelling suggests that these conditions will occur more with climate change (Gill, 2006; Defra, 2012). The use of 'cool pavements' will help ensure that evapotranspiration cooling by trees continues without the need for irrigation. The use of highly reflective materials in buildings, pavements and car parks are feasible options to reduce the UHI, yet have seen limited integration in UK cities (Mills, 2005).

Water bodies can have a significant cooling impact, especially on their leeward side (Spronken-Smith and Oke, 1998), as may ornamental water features. Their reflective surface lowers the amount of solar energy retained, and they increase the ratio of energy used in evaporative cooling rather than in warming the air. Water features in Arab and Indian architecture are an example of this heat mitigation strategy (Smith and Levermore, 2008).

Buildings constructed to recent standards of energy efficiency are well insulated and airtight to limit heat losses in the winter. In warm urban environments and under a changing climate, these measures can contribute to uncomfortably high internal temperatures as they prevent unwanted heat from escaping (NHBC Foundation, 2012). Some glazing materials reduce solar heat transmission by 75% while optimising light infiltration and so prove useful in this regard. Furthermore, shade provision can be engineered into the design and construction of a building, providing the opportunity to reduce sunlight reaching both the streets and entering buildings. Systems need to balance shading with light penetration, as the use of artificial lighting will offset energy savings and lead to localised warming. Selecting the right shade system is linked to orientation of the opening to be protected; guidance on solar shading is provided by the NHBC Foundation (2012). For example, south-facing windows need to be protected from high-level sun and therefore horizontal

brise-soleil prove useful; east and west-facing windows experience low-level sun and therefore vertical shading devices and recessing windows provide effective solar shading. As these may reduce external views and light penetration, external shutters that can be opened on demand provide a feasible alternative as does prudent selection, placement and maintenance of shade-effect trees (see the section on Tree location above). Integrating shade systems into new developments to reduce internal heat gain in summer is important. For older buildings, retro-fitting to reduce winter energy use resulting from their poor insulation and low-efficiency heating and glazing needs to be accelerated.

Air-conditioning reduces a building's internal temperature, restoring comfort levels. However, it also releases carbon dioxide and waste heat to the surrounding environment, intensifies the UHI (Smith and Levermore, 2008) and therefore is not a desirable solution to the UHI. Air-conditioning in cities is partly required because noise and pollution make natural ventilation unfavourable. Davies, Steadman and Oreszczyn (2008) and Smith and Levermore (2008) thus present convincing arguments for increased use of electric cars to help combat the UHI: quiet and less polluting, such vehicles facilitate a shift away from energy-intensive air-conditioning, and they emit less waste heat energy than other cars.

Potential conflicts

Trees have the potential to conserve energy and save money. However, there are potential conflicts to these efficiencies (as listed below) and these need to be considered in order to optimise returns.

- Solar energy collectors: shading reduces efficiency and effectiveness of solar hot water panels and electricity-generating solar photovoltaic cells.
- Winter heating: shading of south-facing walls and windows can increase winter heating costs by reducing the amount of incoming warming radiation.
- Inappropriate position: street trees can conflict with power lines and street lamps above ground, while their roots may interfere with underground cables and services. Trees that are efficient at cooling also tend to have a high water demand, leading to a higher risk of building subsidence if inappropriately located.
- Hazards: roots can make pavements uneven. Fallen leaves and fruit pose a trip hazard and the potential for falling deadwood requires commitment to inspection and maintenance.
- Health effects: the leaves and fruit of some trees are poisonous. Some trees and plants emit volatile organic

compounds (VOC), which are linked to ozone and PM₁₀ particulate pollution. Pollen is an allergen to many people.

- Tree growth demands: water demand and suitability to urban living varies between species. Species selection is important for minimising tree mortality rates and replanting costs.

Conclusions

Cities frequently demonstrate higher mean average temperatures than surrounding rural areas – the so-called 'urban heat island' (UHI) effect. UHI intensity varies across a city and over time and may reach 9°C in some UK cities. Climate change projections indicate a rise in temperatures and an increase in the occurrence and intensity of extreme heat events that will exacerbate the UHI. Prolonged periods of high temperatures can have profound effects on human health and UHI adaptation is needed to plan for near-term, medium-term and longer-term changes. There is compelling evidence that trees, urban greenspaces and wider green infrastructure provide significant reductions in urban temperatures and may help prevent unnecessary loss of life during heatwaves.

Planners and developers can help to combat the UHI and increase urban resilience to the impacts of climate change by making the most of opportunities, afforded through redevelopments, to green the urban environment, with priority planting given to large canopy trees. Trees grown near buildings in order to mitigate the localised impact of the UHI are best placed to the west, southwest or south of buildings in the UK, with small-leafed species likely to offer the greatest impact. Greenspaces and wider green infrastructure should be a minimum of 0.5 ha in order to achieve cooling at significant distances beyond the site boundaries.

What this means for forestry

Guardians of existing large canopy trees in urban areas can help by increasing the priority given to conserving those trees in their care. Their protection will help ensure ongoing delivery of the benefits they already afford and bridge the gap until new plantings mature. With delays of between 15 and 40 years, depending on species, for a tree to grow a sufficiently large canopy to deliver meaningful cooling, rainwater management and biodiversity benefits, planting now will help combat the impacts of the warming climate predicted for the UK.

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