What we know and don't know about the cooling benefits of urban trees

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Abstract

The cooling provided by urban trees can be separated into three distinct benefits: locally trees cool people and cool buildings largely by shading them; and regionally they reduce the urban heat island largely by evapotranspiring. Experimental and modeling studies on local cooling have provided consistent results. The effective temperature of people, as measured by PET or globe temperatures can be reduced by 7-15 °C by tree shade, depending on climate; modelling tends to give a higher figure. Tree shade can also reduce air conditioning costs of buildings by 20-50% providing suitable tree placement. However, air conditioning is rare in Northern Europe, so research is instead urgently needed on the effect of trees on reducing internal room temperatures and hence PET within houses.

Research on regional cooling benefits has been more fragmented because it is hard to scale up local measurements to the whole city. Research that has compared the air temperatures within urban parks with built-up areas unfortunately confounds local and regional effects and cannot be meaningfully used to determine the overall effect of the urban forest. More useful estimates of regional cooling can be determined by averaging surface temperatures or integrating evapotranspirational water loss over the city. More research is needed to transfer the results of experimental investigations on the cooling effect of trees into regional climate models.

For all three benefits we also need to further investigate the effects of tree species, size and growing conditions, and the weather on the cooling effectiveness of individual trees, and to test the theory that the cooling benefits of trees are directly proportional to their growth.

Introduction

It is well known that urban trees provide cooling benefits, both locally and regionally (Ennos, 2010). They cool people down on hot sunny days, shade buildings from the sun and reduce the intensity of the urban heat island. However, few people are completely clear about how trees provide these benefits, know how great the benefits are and how they are measured, or appreciate what we don't know about them.

How Trees Provide Cooling Benefits

Though there is some evidence that surface cover can affect the development of boundary-layer clouds (Ek and Holtslag, 2003; Vila et al, 2012), in general the vegetation covering a city is unlikely to have much impact on the cloud cover overhead. Therefore the cooling benefits of trees are *not* caused by them changing the incoming solar radiation. Neither do plants and built surfaces differ greatly in how much of the incoming solar radiation they absorb; plants typically reflect slightly more of the short wave solar radiation back up towards the sky than dark materials such as tarmac and brick, but they reflect *less* than pale materials such as concrete.

In fact, the cooling benefits of trees are caused by two main factors. First, the canopies of trees provides shade, reducing the input of short wave radiation to ground level, particularly in the summer when deciduous trees are in leaf; at this time of year their canopy can reduce the amount of short wave radiation reaching ground level by up to 90% (Heisler, 1986; Zhang et al., 2013). Second, trees, like all plants, use a large percentage of the radiation that they intercept to evaporate water from within their leaves (Monteith and Unsworth, 1990). This process, known as evapotranspiration, cools them down and reduces the amount of heat available to warm the air around them.

Shading and transpiration have very different effects on local and regional cooling. The two local effects - cooling people and cooling buildings - are both largely mediated by tree shading. People feel cooler under the canopy of trees because they receive less direct or reflected short wave radiation and less long wave radiation from the cool surfaces of the leaves or their shaded surroundings. Buildings are cooled because shade reduces the amount of short wave radiation heating the external walls and roofs and penetrating their windows. Both effects peak in the middle of the day when sunlight is strongest. Though transpiration also increases to a maximum in the middle of the day, its effect on cooling the surrounding air actually has little influence on either how warm people feel or how much buildings heat up.

In contrast, the regional cooling effect of reducing the urban heat island is largely unaffected by shading – similar amounts of short wave radiation are absorbed by trees, or grass, even though they intercept it at different heights. Instead this effect is caused by the transpiration, which cools both the canopies of trees and swards of grass, reducing the convective heating and hence air temperature of vegetated areas. Subsequent mixing results in a lower mean air temperature, though there are differences in urban microclimates between cooler parks and warmer built up streets. Unlike the local effects, the regional effects of vegetation on air temperatures are greater at night, because of reduced convection in the calmer conditions, which means less mixing of air between cooler and warmer areas.

The considerations of scale complicate the research. To determine the cooling benefits of trees, researchers need first to determine which of the three benefits they are trying to measure, and consider the physics of the situation. Only then can they choose the appropriate equipment to use and the right scale at which to undertake a survey, or to decide on the appropriate modelling tools to use to simulate the situation.

The main section of this review aims to clarify this complicated topic, by explicitly describing the mechanisms by which trees provide each of their three main cooling benefits. The review will then introduce the physics of each process and describe how the effects of trees have been investigated and the results that have been obtained. It will end up by summarizing what we know and don't know about the benefits of trees, and make suggestions for further research that is needed. Of course, this is an extremely broad topic and one which in recent years has been subjected to an exponentially increasing amount of research. No one researcher can keep up to date with all the papers in this area, particularly in the regional benefits of trees and their reduction of the urban heat island. For this reason, this review is geographically confined to northern temperate areas, particularly North West Europe, though the physics of course applies to all regions. Neither will the review probe the nuances of the subject. Rather it seeks to present user groups such as planners, engineers and arboriculturists with the information they need to understand the issues involved, and the progress that has been made and which still needs to be made to develop a good understanding of how much benefit trees provide us. It seeks to give to researchers an overview of what to study, how to study it, and most usefully, how *not* to study it.

1. The Local Cooling Benefit

i. The Effect on Human Comfort

Theoretical Considerations

To maintain healthy physiology a person has to keep a core temperature of around 37°C, maintaining a balance between energy input and output. The hat balance of a person can be given by the following equation.

$$M + R_S = R_L + C + E$$

A person at rest produces metabolic heat, M, at a rate of around 60-80 W m^{-2} of body surface. In full sunlight people also receive the additional input of short wave radiation, R_S, either directly from the sun, scattered by the sky, or reflected off surrounding surfaces. This can peak at 1000 W m^{-2} midday in mid latitudes (Monteith and Unsworth, 1990). This energy input must be balanced by energy loss. The main mechanism is usually by exchanging long wave radiation, R_L, with surrounding surfaces; we lose heat at a rate of about 6 W m^{-2} for every 1 °C temperature difference between the skin (usually at around 33°C) and surrounding surfaces. Compared with radiation loss, people lose relatively little heat by convection, C; around a third of that lost by radiation, at least at low wind speeds (Oke, 1989; Ennos, 2010). Heat losses by radiation and convection become inadequate to keep us cool in hot weather, and when people are standing in the sun. The person becomes uncomfortable and has to lose heat actively by sweating, E, the sweat evaporating from the skin, and providing 4.2 kJ of cooling per gramme of water evaporated. In hot sunny weather people feel more comfortable when under the shade of a tree canopy largely because they receive little direct short wave radiation input. Moreover, because they are surrounded by cooler, shaded and vegetated surfaces, their radiative heat losses are increased.

One way to quantify the effect of both short and long wave radiation on the thermal comfort of a person is to determine the mean radiant temperature(T_{mrt}) of their surroundings; this is defined as the uniform temperature of a hypothetical spherical surface surrounding the subject (emissivity ε=1) that would result in the same net radiation energy exchange with the subject as the actual, complex radiative environment (Matzarakis et al., 2007). The two main measures to quantify thermal comfort are the physiologically equivalent temperature (PET), and the index of thermal stress (ITS) (Shashua-Bar et al., 2011). PET combines T_{mrt} with other measurements of the local environment - air temperature T_A, wind speed and relative humidity - to calculate a measure of the temperature that the person feels they are experiencing, which can then be related to human thermal comfort in a specific area (Matzarakis et al., 1999). PET was originally developed to compare outdoor conditions with equivalent indoor conditions and originally made the assumption that internal human heat production was 80 W and heat transfer resistance of human clothing was 0.9 clo (Matzarakis and Mayer, 1996). However, this is not universally acceptable, so often area- and climate-specific PET index values are used to produce better estimates of the cooling benefit of green vegetation in particular urban areas. The other less frequently used method of measuring human comfort, ITS, directly quantifies the net incoming thermal energy from the surroundings, including the effects of short and long wave radiation, convection and the effects of metabolism. This produces the ITS, a figure which rises in proportion to the amount of heat that must be lost by sweating and which is given in Watts (Shashua-Bar et al., 2011). How comfortable people feel is also influenced by recent experience and by psychological factors, so that people adapt to a hot or cold climate, and can feel cooler just by virtue of being under a tree canopy. Therefore the comfort threshold for PET and ITS can vary. Nevertheless, these measures provide useful measurements for the effect of tree shade.

Experimental Studies

Based on these physical considerations, several experimental studies have been performed to investigate the micrometerology and human comfort in urban street canyons in a range of climate zones (Yoshida et al., 1991; Santamouris et al., 1999; Bourbia and Awbi, 2004; Holst and Mayer, 2011), though much less effort has been put into specifically investigating the effect of vegetation on human comfort. Perhaps the most comprehensive method of calculating energy exchanges, and hence PET and ITS, is to use pyranometers and pyrgeometers to determine short-wave and long-wave radiation fluxes respectively. These can be combined with the output of thermometers, anemometers and hygrometers, which measure the temperature, wind speed and relative humidity of the air (Matzarakis et al. 1999; Shashua-Bar et al., 2011; Lee et al. 2013) to calculate PET and ITS. However, T_{mrt} can be much more cheaply and easily calculated using measurements derived from globe thermometers (Thorsson et al., 2007). These are thermometers held within a sphere of copper or acrylic plastic which are mainly affected by the radiant temperature, but cooled to a small extent by convection. As long as the wind speed is also known these can give accurate estimates of T_{mrt}, (Thorsson et al., 2007; Shashua-Bar et al., 2011), and from this estimate, PET can be readily determined if relative humidity is also measured. Globe thermometers can also be used alone (Armson et al. 2012; 2013) to give a rough estimate of PET, though such estimates will miss the effect of humidity.

These techniques have shown that street trees can have large effects on ITS and PET, particularly when they directly shade the area in question. Shashua-Bar et al (2011) showed that tree shade in a courtyard in the Negev region of israel could greatly reduce incoming radiation, lowering peak ITS from around 520 down to 200 W, a much greater effect on ITS than that produced by covering the courtyard with irrigated grass.

Matzarakis et al. (1999) showed that on a single hot summer day in the streets of Freiburg, Germany, tree shaded sites had a T_{mrt} which was about 30 °C lower than sunny sites, while the reduction in PET was in the order of 15 °C. This PET reduction was similar to that shown later by Lee et al. (2013), who compared the effect of tree and building shade, once again in Freiburg, Germany during hot summer days in 2007 and 2008. They compared the T_{mrt} and PET under the shade of a 3-storey building (15m) and a canopy of five small leaved linden trees. They demonstrated that the relative short-wave radiant flux densities are similar under building and tree shade, though shading by tree canopies extended over a longer time period. The incident shortwave radiation through the tree canopy was 4% higher than through the building, so building shade reduced T_{mrt}, and PET by rather more than tree shade. Nevertheless on average the study showed that reducing the sky view factor by 10% through tree shading led to a lowering of T_A by 0.2 °C, T_{mrt} by 3.8 °C, and PET by 1.4 °C between 10.00 and 16.00 hrs. Using these figures one might expect a 100% reduction in sky view (a continuous tree canopy) would give rise to a PET reduction of 14 °C. However, the results are likely to be smaller because humidity would be likely to be increased and wind speed reduced. Working in the Northern German town of Oberhausen, Muller et al, (2014) found a reduction in PET at midday under a dense tree canopy of rather less, 4-7 °C compared with open areas. Similarly, the reduction in globe temperatures due to tree shading recorded by Armson et al. (2012; 2013) in Manchester, UK, were 5 – 7 °C beneath a row of trees and 3.8 °C to 4.6 °C beneath small street trees. These effects were probably smaller than those recorded in Freiburg in both these cities because they are located further north, so short wave radiation from the sun would not have been so intense.

Modelling Studies

As an alternative to empirical studies, several modellers have used micrometeorological models (e.g. RayMan, ENVI-met, Green CTTC and SOLWEIG) to quantify the impact of street design and vegetation on the thermal conditions in street canyons (Ali-Toudert and

Mayer, 2006; Johansson and Emmanuel, 2006; Kuttler, 2011; Herrmann and Matzarakis, 2012), and simulate T_{mrt} and PET.

Some studies produce results that are broadly similar to empirical ones. Using the Green CTTC model, Shashua-Bar et al. (2012) estimated that in the streets of Athens, local tree shade would reduce the maximum value of PET to 36 °C, a 10 °C reduction from the sunny side of the street where PET was close to 46 °C. Increasing tree canopy coverage from 7.8% up to 50% was the most effective way of reducing discomfort further, lowering average midday PET by around 8 °C.

Other modelling studies give much larger estimates for the cooling effect of trees than empirical studies or Shashua-Bar et al's (2012) study. A modelling study in Stuttgart, Germany (Ketterer and Matzarakis, 2014) estimated that maximum PET would be around 10 °C lower under trees (35°C) compared to green areas (45 °C) and 18°C lower than over sealed areas (53°C). Ali-Toudert and Mayer (2006) using ENVI-met 3.0, a three-dimensional numerical model (Bruse and Fleer, 1998), simulated different street canyon design under hot summer conditions in Freiburg, Germany. They found a PET value decrease on the order of 20 °C under the tree canopy for both E-W and N-S oriented streets compared with bare asphalt, whereas the reduction in air temperature was only in the order of 1.5 °C. Muller et al (2014) found maximum temperature reductions of PET under trees of over 24°C.

Discussion

Despite shading being an obvious benefit of urban trees it is clear that relatively little research has actually quantified the effect that this has on people, though it must often reduce thermal discomfort (Wilson et al. 2008). There have been some experimental studies, in Northern Europe but few in the UK, with reductions in PET recorded in the order of 5-10°C depending on the latitude. Similarly, there have been few modelling studies and these have often come up with rather different estimates of the effectiveness of cooling, giving much greater temperature reductions of 10-25°C than have been found experimentally. This is probably due to the difficulties of modelling a link with the boundary layer. Consequently the volume of air considered in the models will be too small, resulting in overestimates in changes in temperature. Nevertheless, the results obtained within each technique have been consistent and shown large local effects on PET and hence human comfort. The potential negative effects of urban trees on PET – an increase in humidity and reductions in wind speed – have not been found to have a major impact; the shading effects far outweigh them.

However, very few of the studies have considered differences between trees; they have failed to compare how well trees perform depending on their species, size, growing conditions or placement within the urban canyon. One would expect fast growing trees with a denser canopy to be more effective, while trees placed in such ways to allow breezes to flow between them would give adequate shading while allowing air cooling. One study that did examine the effect of species (Armson et al. 2013), reported that globe temperatures underneath *Crataegus laevigata,* which had a high canopy density (and hence leaf area index LAI) and lower canopy aspect ratio, were significantly lower than under *Prunus* 'Umineko' which had a lower canopy density and higher canopy aspect ratio. Clearly, this is just a start; far more research needs to be carried out to determine how to optimize the use of trees to cool people.

What is Known

1) Trees improve human comfort primarily by their shading effect.
2) Shading cools people by reducing T_{mrt}, which can be lowered by 25 °C or more.
3) Experimental studies suggest that people's physiologically equivalent temperature (PET) can be reduced by 5-15 °C and energy load by over 300 W due to tree shading, the effect being greater in cities with a warmer climate.
4) Modelling predicts a larger effect: that PET can be reduced by 10-25 °C, depending on the city.

What is Not Known

1) Little is known about the effect of the size of trees
2) Little is known about the effect of the species of trees
3) Little is known about the effect of the growing conditions of trees
4) Little is known about the effects of raising tree cover generally.

What needs to be Done

1) More experimental work is needed to investigate the effect of tree cover and position on cooling.
2) More experimental work is needed to compare the benefits of trees of different species, size and of trees planted in different arrangements.
3) More simulations and experimental investigations are needed to quantify the cooling effects of trees in the UK .

ii. __The Effect on Building Energy Use__

Theoretical Considerations

Just like people, buildings suffer from heat stress, heating up during warm summer days, mainly because the short wave radiation from the sun heats up their walls and roofs and enters the building directly through their windows. Many buildings, particularly in areas with a warm summer climate are cooled by air conditioning, which is particularly common in public buildings. However, air conditioning uses energy and adds to the urban heat island. Consequently researchers such as Akbari et al. (2001) have shown that in the US, peak urban electric demand rises by 2–4% for each 1°C rise in daily maximum temperature above a threshold of 15 to 20°C, largely due to the added costs of air conditioning buildings. There are basically two ways in which trees can reduce air conditioning costs for a building: by reducing the local air temperature; and to a much greater extent by shading the building from the sun, thereby reducing its surface temperature, and reducing the influx of sunlight through the windows. Many researchers have therefore focused on the energy-saving benefits of vegetation to offset a building's demand for energy intensive indoor cooling, carrying out both experimental and modelling studies. Of course, trees also cast shade on buildings during the winter months, reducing short wave energy uptake, so they can also *increase* demand for heating energy in the winter months. However, in mid-latitude cities, demand for light in winter usually means that most street trees are deciduous. Consequently, reductions in electricity demand resulting from tree shade during the summer usually far outweigh any increase in demand for winter heating (McPherson and Rowntree, 1993; Arboit et al., 2008), and sheltering of buildings from the wind can also reduce winter heating costs..

Experimental Studies

Because it is extremely hard to find buildings which are identical, except for the distribution of trees around them, few experimental studies have been carried out to assess the effects of tree shading on their energy performance; most researchers have instead mostly carried out modelling studies to quantify the effect. However, Parker (1981) measured the cooling-energy consumption of a temporary building in Florida, USA before and after adding trees. Akbari et al. (1997) also monitored the peak energy savings from shade trees during the summer of 1992 in two houses in Sacramento, California. They collected data on air-conditioning electricity use, indoor and outdoor dry-bulb temperatures and humidities, roof and ceiling surface temperatures, inside and outside wall temperatures, insolation, and wind speed and direction to estimate the energy savings per household. To evaluate the effect of tree shade on built surface temperatures Millward et al. (2014) carried out an experiment at the centre of Toronto, Canada for six months during the summer of 2008, investigating the effects of species-specific characteristics (i.e., size, leaf area), optimal placement (orientation and proximity to buildings), and the most effective planting patterns (individual trees vs clusters). They installed a total of 13 pairs of temperature loggers on the surfaces of eight buildings in and out of tree shade.

The studies all showed that trees have large effects. Parker (1981) found that trees conferred cooling electricity savings of up to 50%, while Akbari et al. (1997) showed that the shading effects of the trees gave cooling energy savings of around 30%, corresponding to average savings of 3.6 and 4.8 kWh/day. Millward et al. (2014) showed that tree shading reduced the building surface temperature by as much as 11.7 °C, an effect that lasted up to 10–12 hours. Moreover, trees planted on the west-facing aspect of built structures provided the greatest temperature reduction, with maximum benefit occurring mid to late afternoon when ambient air temperature in Toronto was usually close to its maximum. In addition, the authors also showed that solitary mature trees within 5 m of building provided the maximum surface temperature reduction.

Modelling

Several modeling techniques have been used to investigate the effect of trees on building energy use. Akbari and Taha (1992) investigated the potential of using vegetation and high-albedo materials in Toronto, Edmonton, Montreal, and Vancouver, Canada on residential buildings using the DOE-2.1D building energy analysis program. DOE-2.1D is a public domain program developed under the leadership of the Lawrence Berkeley Laboratory, University of California, USA. The authors assumed that any given vegetative cover would be uniformly distributed in all orientations. This is a conservative assumption since tree shade can be optimized to maximize energy savings by positioning the trees on the east and west sides of buildings.

McPherson (1994) used the Micropas and the Shadow Pattern Simulator (SPS) computer programs to investigate the effects of trees on the heating and cooling energy use in the city of Chicago, USA. Micropas provided hour-by-hour estimates of building energy use based on the building's thermal characteristics, occupant behaviour, and specific weather data (Nittler and Novotny 1983). Based on their simulation studies, researchers (David Nowak, Daniel Crane and Patrick McHale) from the USDA's Northern Research Station, developed the Urban Forest Effects (UFORE) model, which later evolved into the i-Tree Eco software application (https://www.itreetools.org/index.php). This application quantifies the effect of individual trees on building energy use and calculates the reductions in carbon dioxide emissions using average US building prototypes, the energy use of buildings, the size, distance and orientation of the trees planted, and weather conditions. Similarly a team of researchers at the USDA Forest Service, Pacific Southwest Research Station namely Greg McPherson, Scott Maco, and Jim Simpson developed the Tree Resource Assessment Tool for Urban forest Managers (STRATUM), which later evolved as the i-Tree Streets software application. Based on the species, DBH, site and management data, i-Tree Streets quantifies the ecosystem services including energy conservation provided by a municipality's street tree population and puts a monetary value on it.

More recently, Sawka et al. (2013) adapted SMUD's (Sacramento Municipal Utility District's) Tree Benefits Estimator, originally designed to quantify the energy conservation benefits of a utility-sponsored shade-tree-planting programme in California, for application to 787 trees, planted on 254 residential properties in Toronto, Canada. Solar gain reduction data obtained from an SPS model was used in Micropas (version 4.01) energy simulation software.

The results from these studies have been fairly consistent., Akbari and Taha (1992) showed that tree shading alone can reduce the energy use up to 24% for a single-storey building with 30% increase in tree cover (corresponding to 3 trees per house). Similarly parametric computer simulations of three trees around an unshaded well-insulated house in Chicago (McPherson, 1994) showed that shade alone reduced annual and peak cooling energy use by 31% (583 kWh) and 21% (0.67 kW), similar to the experimental figures given by Akbari et al. (1997). On a per tree basis, energy simulations from 12 U.S. cities found that annual energy savings for cooling from a well-placed 7.6 m tall deciduous tree ranged from 100 to 400 kWh (10 to 15%) (McPherson and Rowntree, 1993).

In another study conducted in Toronto, Canada, Akbari and Konopacki (2004) analysed the cooling energy benefits of fully grown shade trees planted around residential buildings using the DOE-2.1E model. They showed that four mature trees can give annual cooling energy savings of 165 kWh and 246 kWh, depending on the building vintage, with a greater benefit for older buildings. In comparison, Sawka et al. (2013) showed that energy savings from a single tree can be between 0 to 172 kWh (at 25 years post-planting) and between 0 and 237 kWh (at 40 years post-planting). Along with other researchers such as Donovan and Butry (2009), and Simpson and McPherson (1996), Sawka et al. (2013) also reported that the trees located on the west side of a residential building reduce indoor cooling demand the most. Trees planted on the west side provide lengthened shadows in the late afternoon when ambient air temperature is at a maximum. Trees on the east side of a building have the second most significant impact on reducing energy demand; they cast shadows during the morning hours. However, trees on the north do not significantly reduce air conditioning demand (Akbari et al., 1997; McPherson and Simpson, 2003) and trees on the south provide limited shade in the afternoon, thus reducing the energy saving potential at the peak time.

Discussion

The evidence base for the cooling benefits of trees on buildings seems to be strong; there is good agreement between experimental and modelling studies of the shading benefits of trees in reducing air conditioning costs in North America and this has been converted into usable models such as i-Tree eco and i-Tree streets. Of course the shading benefits of trees increase with their size, and depend on their proximity to and placement relative to buildings. Therefore knowing tree cover alone is not enough to calculate the cooling benefits; the position and size of each tree must be determined before their benefits can be calculated. Nevertheless, at least for North America the benefits are clear, though in most cases the physical characteristics of the trees such as variability in crown shape and leaf density is not taken into consideration (Sawka et al., 2013).

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In contrast to North America, little research has been carried out in Europe and particularly in the UK on this benefit. This benefit of trees is omitted from European versions of i-Tree eco, largely because air conditioning is much rarer in this part of the world, and building typologies are very different. In Northern Europe, trees are also often positioned further away from buildings, especially homes, because of the need felt by residents to maximise light. Therefore though i-Tree is being enthusiastically taken up in Europe, there seems little prospect that the building cooling benefit it calculates would be quantifiable, or even relevant to housing in Northern Europe, at least with our current housing stock and before substantial climate change and modification of housing occurs.

For this reason a rather different approach needs to be taken, quite different from the economic approach taken by North American researchers, and illustrated by the i-Tree model. The harm caused in recent European heat waves has largely been to the health of elderly people confined to building that lack air conditioning. Investigations are therefore needed which examine the potential of trees to improve indoor thermal comfort. Experimental studies of the effects of tree shading on building comfort would use similar techniques to those used by Morakinyo et al (2013) on University buildings in Nigeria, to measure the wall and air temperatures inside houses shaded by trees or left exposed, and so calculate PET. Modelling studies could be similar to those already developed, but would calculate internal wall and air temperatures in the absence of air conditioning, rather than measuring the amount of air conditioning needed to maintain a stable internal temperature. Tree shading, occurring as it does, over only part of the day, is likely to be somewhat less effective than using green walls or roofs, though its potential for reducing input of sunlight through windows would improve its performance.

What is Known

1) Trees can reduce air conditioning costs in the US by up to 30-50%, depending on the numbers and placement of trees.

2) Trees positioned on the western side of buildings are most effective, followed by those on the east, south and north.

What is Not Known

1) Very little work has been carried out in the UK or Northern Europe, on the economic benefits of tree shading on buildings, but it is likely that the effects are small and not relevant to the great majority of buildings that lack air conditioning.

What needs to be Done

1) Research in Northern Europe is badly needed to investigate the effect of tree shading on the thermal comfort of people inside buildings that lack air conditioning.

2. The Regional Cooling Benefit

Theoretical Considerations

Though at a local level trees cool people and buildings largely by shading them, their regional cooling effect is due to quite different processes; they change the energy balance of the city by increasing reflection of sunlight, and allowing water to evaporate from their leaves, thereby reducing storage and convection of heat. The heat balance of an area can be given by the following equation (Oke, 1978)

$$R_i = LE + G + S + H$$

During a sunny day with clear skies, incoming radiation to the earth's surface exceeds outgoing radiation, and the surface absorbs net energy, R_i. This energy is used to evaporate water, heat the soil, heat up buildings and heat up the air. It is thus formally distributed over four major categories of energy use: latent heat (LE), ground heat flux (G), heat storage, (S) and sensible heat (H). Vegetation has a higher albedo (typically 0.15 to 0.25) than brick or concrete (typically 0.10 to 0.15) (Oke, 1978), so trees reflect slightly more of the sunlight back upwards, reducing R_i by a small factor. In vegetated areas much of this incoming energy can then be used to evaporate water, both from their leaves (transpiration) and from the soil beneath (evaporation), processes together known as evapotranspiration. This leaves less energy to heat up the soil and the air. Hard landscapes, in contrast, are usually dry, so most of the incoming energy is used to heat the air, or is stored in the bricks and concrete of buildings and roads. The result of the vegetation loss in cities is therefore the build-up of an urban heat island, especially during hot summer weather. The *surface* heat island – the increased temperature of the largely unvegetated urban surface compared with vegetated rural areas – is greatest during the day, when the incoming solar radiation is greatest. However, the *air* heat island can be particularly large – up to 7°C - at night, especially in large high-rise cities because of the lack of convection; the stored heat is reradiated from the buildings and trapped in deep urban canyons (Oke, 1978).

Including trees in towns should increase heat loss by evapotranspiration and so should reduce convection and heat storage. This should lower surface and air temperatures and so reduce the urban heat island, making life more comfortable for the residents, especially at night and during heat waves when excess deaths can occur. Unfortunately, however, the regional cooling effect of a city's trees is much harder to quantify than their local cooling effects because it is virtually impossible to perform controlled experiments at the right scale; there is no way of comparing a city with trees with an identical city without them! To overcome these difficulties, therefore, experimenters have sought to take local measurements and scale them up to level of the whole city and have taken three very different approaches: they have compared air temperatures in areas of cities with and without trees; they have compared the surface temperatures of areas with and without trees; and they have investigated the evapotranspiration of trees.

Quantifying the effect

Approach 1: Air Temperatures

The most obvious way to quantify the cooling effects of urban trees is to do it directly, so many researchers have measured air temperatures within and outside parks or beneath or away from trees, work which has been subjected to a meta-analysis by Bowler et al, (2010). In order to assess the cooling and humidifying effect of 15 plant communities in three public parks in Shenzhen, China, for instance, Zhang et al. (2013) investigated the temperature and relative humidity underneath the tree canopies. The authors took measurements using a portable weather station from November, 2010 to October, 2011. Georgi and Zafiriadis (2006) similarly measured air temperatures, relative humidity percentage and solar radiation at a height of 1.5 m from the ground in the shade of trees and out of the shade under the sun of 294 individual trees of 21 different species of the city of Thessaloniki, Greece.

Zhang et al. (2013) reported that compared to the control sites, the temperature reduction of plant communities ranged from 2.14 °C to 5.15 °C, and the relative humidity increase ranged from 6.21% to 8.30%. The effects on air temperature reduction were most significant at 14:00 – 15:00 h during the day and large in summer and small in winter. Moreover, the authors also showed that multilayer plant communities with higher canopy area and density were the most effective regarding cooling effect. Georgi and Zafiriadis (2006) reported a maximum air temperature reduction of 7.5 °C and maximum relative humidity increase of 41% in the city of Thessaloniki, Greece

Measurements that were carried out in the suburbs of Sacramento, USA with mature trees, showed that the air temperature under the tree foliage was 1.7 − 3.3 °C lower compared with areas with no trees (Taha et al., 1988). Parker (1989) showed an average air temperature reduction of 3.6 °C in the shade of large trees during summer time in Miami, Florida, USA. Souch and Souch (1993) showed a mid-day temperature reduction of 0.7 –1.3 °C underneath the tree canopy compared to non-shaded areas in Bloomington, Indiana, USA. Shashua-Bar et al. (2009) found that the combination of shade trees over grass in the arid Negev Highlands region of southern Israel was the most effective landscape strategy, which could reduce air temperature by 2 °C. Lin and Lin (2010) measured the microclimate conditions under 10 tree species and two bamboo species, and found that tree canopy density, leaf thickness, leaf texture, and leaf colour all had a significant effect on cooling the surrounding air. Armson et al. (2012) found a smaller effect in Manchester, UK; on hot sunny days, park air temperatures were on average only 0.8 °C cooler than the surrounding urban air temperature. Overall, based on their meta-analysis of the results of a wide range of surveys, Bowler et al. (2010) concluded that the effects of trees and parks on local daytime air temperatures are usually small; parks had on average a daytime temperature only 0.94 °C cooler than the surrounding urban temperature, though the differences tended to be greater on hot sunny days when cooling was most needed, so most studies come up with much larger and more impressive maximum figures.

The results of simulation studies back up the small effect of trees on air temperature. Shashua-Bar et al. (2010) studied the thermal effect of tree canopy coverage, traffic load, surfaces albedo modification and street canyon geometry using the Green CTTC analytical microclimate model in a suburb area and in the city centre of Athens, Greece. They reported that the average cooling in Athens's streets can be 1.3 °C if the tree coverage in the streets is increased from 7.8 to 50%.

The effects on minimum night time temperatures can be larger than daytime temperatures. Jauregui (1991) measured air temperatures in Chapultepec Park (500 ha) in Mexico City, and found that daily minimum temperature was 3–4 °C cooler in the park. Interestingly he found that influence of the effect of the park on air temperature can be reached a distance about the same as its width (2 km). A similar recent study around Hyde Park in London, UK (Doick et al, 2014) found cooling up to 5°C at night, far more than daytime cooling. The cooling effect extended 400 m away from the park, rather less than the diameter of the park.

In summary the results do show that parks are slightly cooler than urban streets in hot weather, and therefore more pleasant places to be in, but this local effect is shown far more clearly by considering PET and other indices of human comfort as we saw in the first section of this review. The results of this research are also somewhat counterintuitive, showing greater cooling effects at night and smaller ones during the day, when the trees are actively cooling the city. The limited daytime cooling occurs because warm air can be readily blown into parks from the warmer surrounding and the cool air from parks blown out into the surrounding streets. This effect occurs less at night because reduced convection lowers wind speeds (Oke, 1978). The results do show some regional effect of trees, as parks can cool urban streets several hundred metres away, depending on the diameter of the park. In truth, however, air temperature differences such as these cannot tell us much about how much the whole urban canopy reduces the urban heat island; they just show the variability within the urban area. The air temperature beneath a single street tree, for instance, would be identical to that of its surroundings because of the effect of the wind, and this would suggest that the tree had no cooling effect at all. The same would be true for a small park in a steady breeze. Therefore, air temperatures across a heterogeneous landscape can be very homogenous due to the efficient mixing of the air (Brown and Gillespie, 1995). Consequently other methods of integrating the effects of all the small areas of vegetation and single trees over the city are needed to calculate the regional cooling benefits of urban trees.

Approach 2: Surface temperature

An approach that could potentially better identify the combined cooling effect of all the vegetation in a city is to examine surface temperatures. Air will be heated over warm surfaces and cooled over cold ones, so surface and air temperatures should show some similar spatial and temporal patterns (Arnfield, 2003), though surface temperatures will vary more (Lowry, 1988). Averaging surface temperatures over the city should therefore give a reasonable indication of the effect of vegetation on average air temperatures and hence the urban heat island.

Experimental Measurements

The quickest way of surveying surface temperatures over large areas is by remote sensing using satellites (Imhoff et al (2010). However, though this produces reliable maps of surface temperature over cities, the spatial resolution is poor, often as poor as 1 km x 1 km, so it is often impossible to relate surface temperature to the local vegetation cover.

For better resolution, one way is to mount sensing equipment in aircraft. One such study was that of Leuzinger et al. (2010). They scanned the surface temperature of Basel, Switzerland on a hot summer’s day from a helicopter using a high-resolution thermal camera. This enabled them to measure not only ground and roof temperatures but also the tree crown temperatures of 10 commonly planted tree species. They showed that at midday on a hot summer’s day, built surfaces, at 37–60 °C were 12–35 °C warmer than the air, whereas the canopies of trees ranged from 1 °C cooler to 4 °C warmer than air temperature (Leuzinger et al., 2010); the trees with the coolest crowns (and hence with what they assumed was the best cooling performance) were horse chestnuts *Aesculus hippocastanum,* at 24 °C 5 °C cooler than Norway maple *Acer platanoides.*

Hand-held equipment offers even better spatial resolution, but results in other difficulties. For instance using a hand-held infrared thermometer, Armson et al. (2012) were unable to measure crown temperatures but did monitor the surface temperatures of small plots composed of concrete and grass in the presence or absence of tree shading. They reported that permanent tree shade can reduce surface temperature by 15-20 °C, while grass could reduce maximum surface temperatures compared with concrete by up to 24.°C. They also found that the temporary shade of even small street trees can reduce the temperature of concrete by 10-15 °C, trees with a higher leaf area index providing more cooling (Armson et al, 2013).

Modelling

Following the pioneering work of Oke (1978) urban canopy energy budget modelling has received rather more attention (Terjung and Orourke, 1980; Sakakibara, 1996; Arnfield and Grimmond, 1998; Shashua-Bar and Hoffman, 2002, 2003; Whitford et al., 2001; Gill et al., 2007). Whitford et al., (2001) and Gill et al. (2007), for instance, used an energy exchange model to calculate the mean surface temperatures of vegetation, building and roads, using Merseyside and Greater Manchester, UK as case study areas. The model used was a simple 1d model developed from the urban climate model of Tso et al. (1990, 1991). The model solved the surface energy balance of an area and showed as output the surface and soil temperature as a function of time. Gill et al. (2007) predicted a maximum surface temperature difference of 12.8 between the city centre and woodland land uses, with maximum temperatures of 43 °C for non-transpiring surfaces such as concrete, compared to 18 °C for wholly transpiring surfaces such as woodlands and grass. They also showed that increasing the overall surface cover of trees by 10% in city centres would reduce mean maximum surface temperatures by around 4 °C, potentially climate-proofing the city unto the 2080's.

Though there is reasonable agreement between experimental results and modelling, there are reasons to doubt a close correlation between surface temperature measurements and the heating of air, in particular when it comes to comparing the cooling benefits of different tree species. For a start, trees have many layers of leaves, the highest layers being warmer than the lower ones that they shade. Leaf temperature is also dependent on many anatomical (leaf mass, size, shape, angle, reflectance), physical (incoming energy, air temperature, wind) and physiological (transpiration, stomatal conductance) factors (Monteith and Unsworth, 1990). Leaves absorb radiant energy in proportion to the surface exposed but smaller leaves lose heat relatively faster by convection because they have thinner boundary layers. Small leaves will therefore tend to be cooler than large ones even if they are not transpiring (Knoerr and Gay, 1965; Leuzinger et al., 2010). Therefore, the surface temperature of urban trees is unlikely to be well correlated with their evapotranspirational cooling performance. There has also been a distinct lack of research comparing the surface temperatures of trees growing in different soil conditions, or of trees at different times of day or year. In drought, for instance, tree canopies are likely to be warmer than when the trees are well supplied with water, and so provide less cooling. Therefore at present models are unlikely to accurately predict surface temperatures and the contribution of individual trees.

Approach 3: Measuring Water Loss

A final approach to measure the regional cooling benefit of trees is to measure or model water loss from them, since the latent heat released by a tree or trees (and hence the reduction in convection) can be simply calculated by multiplying the mass flow of evapotranspiration (E) by the latent heat of evaporation of water.

Experimental Measurements

Measuring water loss of individual trees can be performed in several different ways depending on the size and location of trees, the budget and the scale of the study. Water loss from small containerized trees can be simply and cheaply measured using a weighing technique (Miller, 1980; Kjelgren and Montague, 1998), though this is not helpful for the vast majority of urban trees which grow in permanent soil. Perhaps the most accurate method is to use sap flow gauges (Thorpe, 1978; Green, 1993; Barradas, 2000; Pataki et al., 2011; Peters et al., 2011; Shasua-Bar et al, 2011; Rahman et al., 2014a), which measure the flow of water up the trunk of individual trees and integrate over the area of the trunk to calculate instantaneous water loss. Unfortunately, this technique is expensive and is vulnerable to vandalism in areas with public access, making it generally unsuitable for urban areas. A final technique is porometry (Rahman et al., 2011; Rahman et al., 2013; Rahman et al., 2014a; Rahman et al., 2014b), in which the stomatal conductivity and temperature of individual leaves are measured with a clip on device. The advantage is that this method is cheap and safe, but can only be used to find instantaneous flows, making diurnal and seasonal changes hard to follow. Other techniques can be used to calculate evapotranspiration of particular areas of a city: eddy covariance (Grimmond and Oke, 1999; Jacobs et al, 2015), and scintillometry (Jacobs et al, 2015). In all cases, the water loss can be converted to energy loss per unit area simply by multiplying it by the latent heat of vapourisation, which is 2.45 kJ g^{-1}.

The results of experimental studies have shown that trees can produce large effects, but that there is very great variability in evapotranspiration. Barradas (2000), working in Mexico City, showed that during the rainy season evapotranspirational cooling increased in the day up to 184 W m^{-2} and dissipated 60% of the net radiation, similar results to those shown by Thorpe (1978) and Green (1993) while calculating the radiation balance, transpiration rate and photosynthesis of isolated trees in rural areas. However, more recent studies have emphasized the great variability (Pataki et al., 2011, Peters et al., 201)., Peters et al. (2011) showed that conifers had evapotranspiration rates about 50% higher than broadleaved trees, while Pataki et al (2011) found differences in two orders of magnitude between trees in Los Angeles, US. Unfortunately, however, neither of these studies used evapotranspiration to calculate cooling per unit area. Specifically investigating evaporative cooling by trees. Working in Manchester, U.K., Rahman et al. (2011, 2013, 2014a,b) showed that peak midday evaporative cooling by small to medium sized trees can range between 350 W and 7kW or around 100 W m^{-2} to 500 W m^{-2}, but the performance of trees depended greatly on the species and growth conditions. Rahman et al. (2014b) showed that fast growing species such as *Pyrus calleryana,* with their dense and wide canopy can provide cooling up to 2.2 kW $tree^{-1}$, 3-4 times that of the slower growing *Sorbus arnoldiana,* which have a thinner and narrower canopy. Rahman et al. (2011) also investigated *P. calleryana* grown in different soil conditions with different compaction levels. The authors showed that trees in less compacted structural soils had faster growth and had better physiological performances than trees in moderately to highly compacted soil; they provided cooling up to 7kW, 5 times higher than those grown in highly compacted soil, though in all the trees cooling was reduced by over 50% during a spring drought. In a separate study Rahman et al. (2013) showed significant impact of soil sealing on the growth and cooling ability of trees during their establishment period; grown in open cut-pits with less compacted structural soil provided up-to 1 kW of cooling, compared to around 350 and 650 W by the trees grown in small and large covered pits respectively, though once again cooling varied over the year by a factor of two depending on the weather. Finally, Rahman et al. (2014a) showed that *P. calleryana* trees grown in soil whose temperature had been raised by 2-3 °C, simulating urbanization and climate change, provided around 40% more cooling than control trees. In summary faster-growing tree species and trees grown in better growing conditions that allow them to grow faster provide more evaporative cooling. This provides evidence that, as physiological theory suggests (Ennos, 2011; Ennos et al, 2014) the cooling performance of trees should rise directly with their growth rates. Jacobs et al (2015) showed lower mean evapotranspirational cooling rates over a four month period by mature parkland trees in Rotterdam, Netherlands of 21-28 W m^{-2}, though maximum cooling was several times higher, which would result in maximum cooling somewhere between 100 and 200 W m^{-2}.

The results of eddy covariance experiments on forested urban areas agrees fairly well with those from individual trees. Grimmond and Oke (1999) reported average diurnal summer evapotranspirational energy loss of well irrigated urban forest from US cities as 225 W m^{-2}, while in the Netherlands Jacobs et al (2015) found overall mean energy losses over the entire cities of Arnhem and Rotterdam of around 20-25 W m^{-2}, or around 200 W m^{-2} of greenspace, though the greatest rate of water loss occurred just after rain when water was evaporating from the surfaces of leaves, not being transpired.

Modelling

The usual method to model evapotranspiration of forests and agricultural land is based on the use of the Penmen-Monteith equation (Allen et al, 1998), multiplying potential evapotranspiration by crop coefficients. This approach has also been used to estimate evapotranspiration in urban areas (Huang et al, 1987; Gill et al, 2013; Jacobs et al, 2015). However, this sort of analysis assumes an ample supply of water, favourable conditions, and a large homogenous areas of vegetation (Allen et al., 1998). In the spatially heterogenous city, with its often harsh growing conditions these assumptions are violated most of the time. Having many separate areas of greenspace would be expected to *increase* evapotranspiration (the oasis effect), whereas drought would be expected to *reduce* it. In fact Gill et al. (2013) found that evapotranspiraion of small *Pyrus calleryana* trees, as measured by sap flow gauges, was 10-20% below potential evapotranspiration as estimated by the Penman-Monteith equation. Despite this, most studies have concluded that, though the Penman Monteith equation produces results of the right order of magnitude, the model cannot be expected to produce reliable results and needs proper validation in urban areas; there is an urgent need to compare predictions of evapotranspiration and hence evaporative cooling of several different micro-sites (such as streets with trees, parks, home gardens, lawns etc.) in a city with actual measurements of water loss using the range of experimental techniques described above.

Discussion

Of the three approaches to determine the regional cooling benefits of trees, we have seen that comparing air temperatures of parks and built up areas is conceptually flawed as it mixes up local and regional effects and gives extremely variable results depending on wind speeds. Measuring surface temperatures is preferable as it allows the contribution of individual trees and areas of greenspace to be summed over the entire city, but because of the different levels of coupling of tree canopies and surfaces to the air, the approach is likely to overestimate the cooling effectiveness of trees (Monteith and Unsworth, 1990), especially those with small leaves. Measuring or calculating evapotranspiration is likely to give the best figures for the relative contributions of different species of trees and the effect of different growing regimes, but there is a need to develop models that will relate the overall levels of evapotranspiration to overall temperature reductions. Consequently the results we do have are hard to put into context to give values for health or energy conservation benefits, though Akbari's research suggested a quantifiable effect on building cooling due to reducing the UHI.

There is a big knowledge gap regarding the relative effects of different species; researchers such as Rahman et al. (2014b) have shown that faster growing species can provide more evapotranspirational cooling. Moreover, the effect of growth conditions in terms of cooling effectiveness is also very rarely studied. Researchers such as Rahman et al. (2011); Rahman et al. (2013) have shown that trees in uncompacted and well aerated soil provide more cooling. Pataki et al. (2011) suggested that trees from wetter environment can lose more water through evapotranspiration hence cooling. Finally, very little is known about the effects of time of the day or year on evapotranspirational cooling, but one would expect cooling to be greater earlier in the year and earlier in the day as tree physiology studies have shown that later in the day and during droughts, limits to water uptake cause the stomata to close and photosynthesis to be reduced. There is one simple measure that could be used to estimate the overall evapotranspirational cooling provided by individual trees: growth. Because of the laws of gas exchange, the faster plants photosynthesise and hence take up carbon dioxide through their stomata, the faster they will lose water (Ennos, 2011; Ennos et al, 2014). Therefore one would expect faster-growing trees to provide more evapotranspirational cooling. Though some studies on single species that suggest that this is true (Ennos et al, 2014) more research is needed to test whether this is also true between species and in different habitats.

What we Know

1) Urban trees provide evapotranspirational cooling that reduces their leaf temperature and helps reduce the urban heat island effect.
2) Larger, faster growing trees provide more cooling than smaller, slow-growing ones.
3) The effect of vegetation on the UHI is especially large in the day and in calm weather.

What we don't Know

1) We do not know if the evapotranspirational cooling benefits of trees are the same as those predicted by the Penman-Monteith equation for crops plants.

2) We do not know how evapotranspirational cooling is affected by time of day, time of year or spatial distribution of trees.
3) We do not have a model that can link vegetation structure of a city to its ability to reduce the UHI.
4) We do not know which trees are best in the UK or the best way to plant them

What needs to be Done

1) We need more experimental studies of evapotranspirational cooling by a wider range of species of different sizes, growing in different conditions and at different times of year.
2) There is a need to incorporate evapotranspiration better into neighbourhood and regional climate models.
3) There is a need to test models of cooling against experimental data.
4) There is a need to understand the relationship between tree growth and cooling benefit

Overall Conclusion

Though extensive research has been carried out on the cooling benefits of trees in cities, there is still some confusion about what those benefits are and how they should be measured. Here, we have seen that because of the physics of heat transfer, the local effects of trees in cooling people and buildings are largely caused by shading, whereas the regional cooling effect is caused mainly by evapotranspiration. There are accepted methods of measuring and modelling local cooling which have produced repeatable and reliable estimates of these benefits of trees, though more research still needs to be performed on the effects of the species, size and location of trees on cooling people. More research also needs to be carried out on the effects of tree shading on the internal environment of houses that lack air conditioning.

For regional cooling there is much less agreement about the best methods to use to determine the effects of trees and other greenspace. Unfortunately, much of the research has focused on measuring the effect of trees and parks on local air temperatures. Though this is the most obvious measurement to make, it can tell us little about the effectiveness of trees at reducing the urban heat island; changing wind speeds make the differences between parks and built up areas very variable, and they have little relationship to the overall cooling provided by the entire urban forest. Better methods include measuring or modeling surface temperatures and averaging this figure over the city; and measuring or modeling the evapotranspiration of individual trees or forested areas, and summing this over the entire city. Even in these cases, however, the complexity of air flows over cities is a real problem which prevents us calculating reliable figures for the effect of vegetation on the urban heat island. There is also a need for a much greater amount of research on how the effectiveness of trees depends on their species, size, growing conditions, and the time of day and year.

The one consistent finding over all the research findings in this area, however, is that cooling benefits are maximized in trees that are healthy and fast-growing. One major goal of future research should be not only to fill in the gaps by studying a wider range of trees, but to test the theoretically plausible suggestion (Ennos, 2011; Ennos et al, 2014) that the cooling benefits of trees, especially the regional benefits, rise in direct proportion to their growth rate. If this can be shown, then it would be possible for researchers to provide reasonable estimates of the benefits of the urban forest simply by performing conventional surveys on the size and growth rates of the trees of which it is composed.

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