General Certificate of Education
Advanced Level Examination
June 2012

Science in Society SCIS4/PM

Unit 4 Case Study

Preliminary Material

- This Source Material should be opened and issued to candidates on or after 1 May 2012.
- A clean copy of the Pre-released Source Material will be provided at the start of the Unit 4 examination.

Information

- This case study source material consists of extracts from five sources (**A-E**) on the subject of trees and air temperature.
- This material is being given to you in advance of the Unit 4 examination to enable you to study the content of each extract in preparation for questions based on the material in the examination. Consider the scientific explanations and the ideas about how science works that are involved, as well as the issues raised in the sources.
- You may write notes on this copy of the case study source material, but you will not be allowed to bring this copy, or any other notes you may have made, into the examination room. You will be provided with a clean copy of this case study source material, together with one additional source: **Source F**, at the start of the Unit 4 examination.
- You are not required to carry out any further study of the topic than is necessary for you to gain an understanding of the ideas described and to consider the issues raised. You are not required to understand any detailed **science explanations** beyond those outlined in **Sources A-E** and those in the *Science in Society* specification.
- It is suggested that a minimum of three hours detailed study is spent on this pre-release material.

Source A

Extract of article from *The Daily Mail*, 14 July 2010.

Roasting temperatures blamed for spike in death rates as heatwave continues to bake South-East

Britain faced more sweltering temperatures today amid health warnings about the heatwave gripping the South-East.

The hottest temperature today was reached in Norfolk and some other parts of East Anglia at 31 °C. The hottest day of the year so far was on Friday when 31.7 °C was recorded in Gravesend, Kent.

Temperatures hovered around 20 °C in London and in the high teens in large towns and cities overnight - with many suffering an uncomfortable and restless sleep.

An official heat-health alert remained in place with reminders the roasting weather posed a risk to the elderly and vulnerable.

The Health Protection Agency said there had been a rise in deaths over the past two weeks, according to its analysis of government data on death rates. Preliminary figures show that hundreds more people may have died as a result of the hot weather - which shows no signs of abating.

Heat can be particularly dangerous for the elderly, young children and those with serious illnesses.

Yvonne Doyle, regional director of public health and heatwave adviser to the Government, said: ‘Younger people see the hot weather as a cause for celebration, tanning and barbecues, but for older people and those with long-term health problems it can be very serious and cause unnecessary deaths. If you have elderly neighbours or relatives, check on them and make sure they’re prepared and can manage. Keep curtains and windows closed during the day, when the outside temperature is hotter than indoors. Plenty of cool drinks are important for everyone - water is best, and avoid excess alcohol or hot drinks.’

The Met Office’s heat warning is level two on its four level warning scale. It relates to how likely temperatures are to exceed ‘threshold’ levels that trigger health concerns - typically 30 °C during the day and 15 °C at night.

Breakdowns also increase in hot weather and the AA today reminded motorists to check their car’s cooling system. Steve Dewey, AA road operations director, said: ‘For every degree above 23 °C there is a noticeable increase in our breakdown workload, so very warm weather like this can sometimes double it. Overheating is a big risk, especially if you encounter any slow-moving traffic.’

Source B

Extract from web article on Guardian.co.uk, 2 September 2010

Green roofs offer antidote to urban heat island effect, say researchers

Researchers at Columbia University have demonstrated that a layer of plants and earth can cut the rate of heat absorption through the roof of a building in summer by 84%.

Green roofs benefit more than just their owners, according to Stuart Gaffin, a researcher at Columbia University. “They are a win-win on so many fronts,” he said.

Perhaps the greatest overall benefit of green roofs comes in tackling the “urban heat island” effect, which Gaffin suggests is responsible for two-thirds of New York’s localized warming over the last century. The conventional black rooftops that he calls “tar beaches” are major contributors to this phenomenon, absorbing and re-radiating the Sun’s energy as heat. “We’re going to want to cool regional climate down, especially where people are living,” Gaffin noted. “So we’re going to have to confront the urban heat island effect.”

While conventional roofs can reach temperatures of 80 °C at 1.00 p.m. even outside of high summer, green roofs always stay closer to ambient temperatures. “These [conventional roofs] are almost dangerously hot spaces,” Gaffin told environmentalresearchweb. “That’s a huge heat load that we can get rid of.”

Plants in green roofs regulate their temperatures through evapotranspiration. “They evaporate copious amounts of water,” Gaffin explained. “That takes a lot of energy and means it’s a great way to stay cool.” Eliminating extreme temperature cycles allows green roofs to be designed as relatively low maintenance options. They experience less thermal expansion and contraction stress, leading to predictions of at least a doubling of lifespan compared to black roofs.

The urban heat island effect is often used by critics of climate research to suggest that measured temperature rises don’t indicate global warming. “Generally the climate research community avoids even using urban weather stations, or attempts to make corrections, because you know that’s a warming bias,” Gaffin explained.

The Columbia team is considering whether meteorological stations on green roofs might provide improved measurements for urban studies, however – although even this wouldn’t enable them to assess climate change. The US National Weather Service recommends placing sensors at least 100 feet from paved or concrete surfaces. “One of the major restrictions says ‘don’t put them near black asphalt rooftops’,” Gaffin explained. “When you put green roofs up, they are like meadows in the sky.”

White is another roof colour used to fight both the urban heat island effect and global warming in general, by simply reflecting light back into space. This offers cheaper installation than green roofs, but needs special maintenance to prevent dirt reducing its effectiveness. Together, Gaffin expects green and white to replace black roofs. “I think the way we’re going to cool things down in cities is going to be a combination of vegetation and brighter surfaces,” Gaffin said. “There’s going to be a contribution from both.”

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Source C

Adapted from Reuters.com, 23 September 2010.

Air conditioning drives down hospitalizations

By Adam Marcus

Air conditioning not only keeps you cool during the summer heat, it may also keep you alive.

A new study of California residents suggests that people with air conditioners at home are less likely than their neighbours without the technology to develop serious heat-related illnesses – including pneumonia, cardiac disease and heat stroke – during temperature spikes.

Although the differences were generally small, for large populations the public health effects of air conditioning could be substantial, the researchers say.

Policies designed to encourage the use of air conditioning at home, particularly central systems, might reduce illnesses and death linked to heat, said study co-author Dr. Rupa Basu.

“We don’t want to say that (more air conditioning) is all we need,” said Dr. Basu, who noted that greater use of ACs could strain the electrical supply to the point of being harmful. “But I think that it would be beneficial to have this as at least one of the ways of minimizing temperature effects.”

In addition to causing heat stroke, high temperatures can aggravate breathing problems, such as asthma and pneumonia, and force the heart to work harder as the body tries to cool itself by moving blood nearer to the skin.

Heat waves are well known to increase rates of death in stricken areas.

In this study, the researchers compared hospitalization rates and the use of air conditioning in California between 1999 and 2005. They estimated use – as opposed to prevalence – of air conditioners through a detailed 2004 state survey of household appliances.

To account for California’s widely variable climate – which ranges from scorching Death Valley to the snowy peaks of the Sierras – and the effects of geography on local temperature the researchers divided their study population into more than 100 zones.

As in an earlier study, they found that every 10-degree Farenheit rise in temperature on a given day was associated with higher rates of hospitalizations for pneumonia, stroke, diabetes, heat stroke and many other conditions. But use of AC reduced the chances of ending up in the hospital.

For some conditions, such as respiratory ailments, the protection was relatively modest, with hospitalizations dropping half a percent for every 10-percent increase in AC use. But for heat stroke, every 10-percent rise in AC use led to nearly a 15-percent decrease in hospitalizations.

Source D

Extract of article in *Physics World*, 2 August 2010.

Urban Cool

Summer in the city can be stifling, with heat rising from tarmac and air-conditioners pumping out stuffy air. But appropriate surfaces and vegetation can make the urban environment a cooler, cheaper and greener place to live, says Roland Ennos.

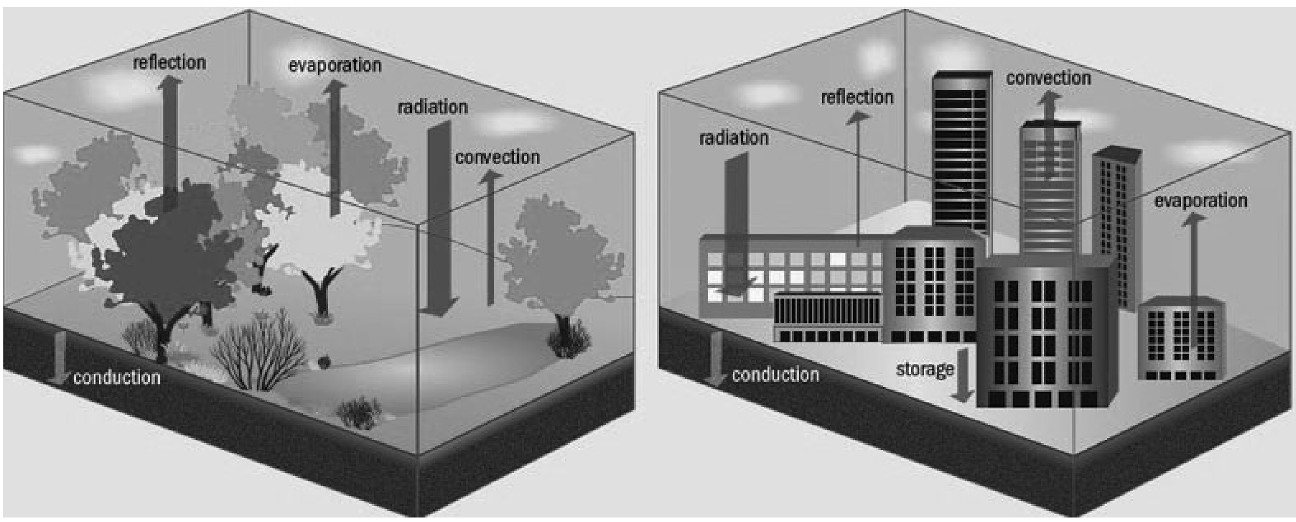
The picture-perfect summer for many involves dipping toes into the water's edge on a sandy beach, strolling through a park licking an ice cream or cracking open a bottle of cold beer as gorgeous smells waft from a barbecue nearby. But if you live in a city – and over half the world's population now do – your enjoyment of the summer is probably reduced by your surroundings. Cities are hot, noisy places with poor air quality that are prone to flash flooding during storms. In cities we are guilty of using huge amounts of energy for cooling in summer, heating in winter and transport the whole year round. Making cities more pleasant and sustainable places in which to live is therefore one of the key goals of environmental research, and it is one that physicists are ideally suited to contribute to, since most urban environmental problems are best understood in physical terms.

Physicists across the world, particularly those working in environmental physics and meteorology, are now collaborating with scientists from other disciplines to study the environmental performance of cities and establish how "green" these urban environments are. One particularly important environmental characteristic of cities is the "urban heat island", whereby urban areas are hotter than their surrounding countryside. This is a real problem, which will be made even worse by climate change. It has therefore become a prime focus of research.

The urban heat island

Cities are typically about 4 °C hotter than the surrounding countryside and the larger they are, the bigger the difference. To understand why, we must consider the energy balance of the two areas as shown in **Figure 1**.

Figure 1



Although heating, air-conditioning and transport all produce energy in cities, this is a surprisingly small component of their heat balance – only about $50\,W\,m^{-2}$. Except for in winter, this is dwarfed by the energy we receive from the Sun, which even in the UK peaks at more than $800\,W\,m^{-2}$. The difference between temperatures in a city and the surrounding countryside is therefore mostly due to what happens to the Sun's energy in the two environments.

In rural areas, vegetation reflects about a quarter of the incoming short-wave radiation (visible light or shorter wavelengths). Of the three-quarters that is absorbed, much of the energy is used to evaporate water from leaves – a process known as "evapotranspiration". This cools the vegetation, which therefore radiates little long-wave radiation (infrared), and even less energy remains to heat the air by convection and to heat the soil by conduction.

In cities, where vegetation has largely been replaced by buildings and roads, the energy balance is dramatically altered. Dark, artificial materials reflect less – and absorb more – radiation than vegetation. This lower "albedo" means that only about 10% of the Sun's radiation is reflected; this figure is even lower in high-rise cities where light is reflected down into urban "canyons". Almost all of this energy goes into heating the dry roads and roofs, where it is either stored in bricks and mortar or heats the air above, thus raising daytime surface and air temperatures well above those of the surrounding countryside.

At night the difference in temperature between the countryside and the urban heat island can become even more pronounced. Cities cool down more slowly because there is more heat stored in its buildings, which continues to dissipate into the night; there is more pollution to trap long-wave radiation; and within urban canyons less of the cool sky is visible, so less radiation can escape.

All this causes major problems for city-dwellers. The rise in urban air temperature above that of the surrounding countryside, which can reach 7 °C in a metropolis like London, makes cities less comfortable places to live in during the summer months. Soaring temperatures increase ill health and can even kill people during heatwaves: it is thought that more than 35 000 people died in Europe as a result of the 2003 heatwave, most of them in towns and cities. The urban heat island also makes cities less sustainable, since it increases the amount of energy used for air-conditioning – energy that is pumped into the open air and just makes the situation worse. Fortunately, physics shows that two very different methods could be used to alleviate the urban heat island: using "cool surfaces"; and using vegetation, or "green infrastructure".

Cool surfaces

Increasing the albedo of buildings and roads so that they reflect more sunlight is an approach that has been used for centuries in the Mediterranean – think of whitewashed villages in Greece, southern Italy and Spain. At the Lawrence Berkeley National Laboratory in California, the effectiveness of this approach has been investigated by the Urban Heat Island Research Group, led by physicist Hashem Akbari. The cooling effect of a roof's surface depends on its reflective and emissive properties – its ability to reflect short wavelengths such as visible light and near-infrared radiation, and to emit thermal radiation in the far infrared. While standard white-painted surfaces are good at keeping cool, it is also possible to make medium-to-dark-coloured cool surfaces, which can look more traditional on roofs. These are created by combining a reflective basecoat, such as white titanium dioxide, with a darker pigment that has moderate visible reflectance, such as iron-oxide red or perylene black. As long ago as 1999, Akbari's group showed that these "cool surfaces" can reduce the peak temperatures of roofs and pavements in California from 50 °C down to about 30 °C.

The same group has also studied the implications of this cooling for individual buildings. First, the researchers compared the thermal performance of conventional buildings with identical ones that had roofs clad in cool surfaces. These tests showed that in summer, cool surfaces typically reduce air-conditioning costs by 20–30%. However, these experiments – by necessity – ignored the cumulative cooling effect that could result from large-scale use of cool materials throughout an entire city.

To study the effect of cool materials on the urban heat island, Akbari's group had to use more indirect methods, as clearly it is not practicable to perform a controlled experimental study comparing two cities that are identical in all respects apart from their surface cover. What the researchers did was simulate air temperatures in the Los Angeles area using complex and computer-intensive regional climate models. The calculations suggested that the urban heat island could be reduced by 2 °C if all buildings and roads were covered by surfaces with an albedo 30% higher than is there now. This would reduce summer air-conditioning costs by a further 2–3%.

Tree-shaded buildings

A potentially even more effective method of preventing the urban heat island than using cool surfaces is to increase both the albedo and evaporative cooling of cities using vegetation and water. Once again, this approach has long been popular in Mediterranean towns, which have cool squares and boulevards shaded by trees and chilled by fountains.

Researchers in the US, such as Akbari's group and the Forest Service of the United States Department of Agriculture (USDA) led by David Nowak, have mostly concentrated on how tree shade can reduce the air-conditioning costs of buildings. Experiments and computer modelling have shown that several large trees strategically planted on the south and west sides of buildings can cut these costs by about 30%. However, the cooling effect of the existing trees in the city they studied – Chicago – is only about 4-5%, due to limited tree cover in the city, particularly in heavily built-up areas.

Researchers in Germany and Canada, meanwhile, have concentrated on the effects of a different approach: incorporating vegetation onto the roofs of buildings to create "green roofs". Studies in 2008 by Brad Bass and his group from the Centre for Environment at the University of Toronto showed that by using green roofs, air-conditioning costs can be reduced by up to 70% in single-storey buildings because the vegetation cools the roof by evapotranspiration and because the soil insulates the rooms below from the heat. However, these savings fall to about 30% and 20% for two- and three-storey buildings, respectively.

Tree-lined streets

It has proved harder to determine how effective vegetation is at cooling a city itself, because of its complexity; vegetation increases both albedo and evaporative cooling, and has lots of layers of leaves, which are hard to represent in regional climate models. One attempt has been made by Limor Shashua-Bar and Milo Hoffman of the Technion Israel Institute of Technology, who found that heavily wooded streets in Tel Aviv could have air temperatures up to 4 °C cooler than their surroundings. However, the researchers had to represent the effect of the trees not by a detailed model but by simply reducing the incoming radiation by 40%. Before we can accurately model the effects of vegetation on the urban heat island, we clearly need to know more.

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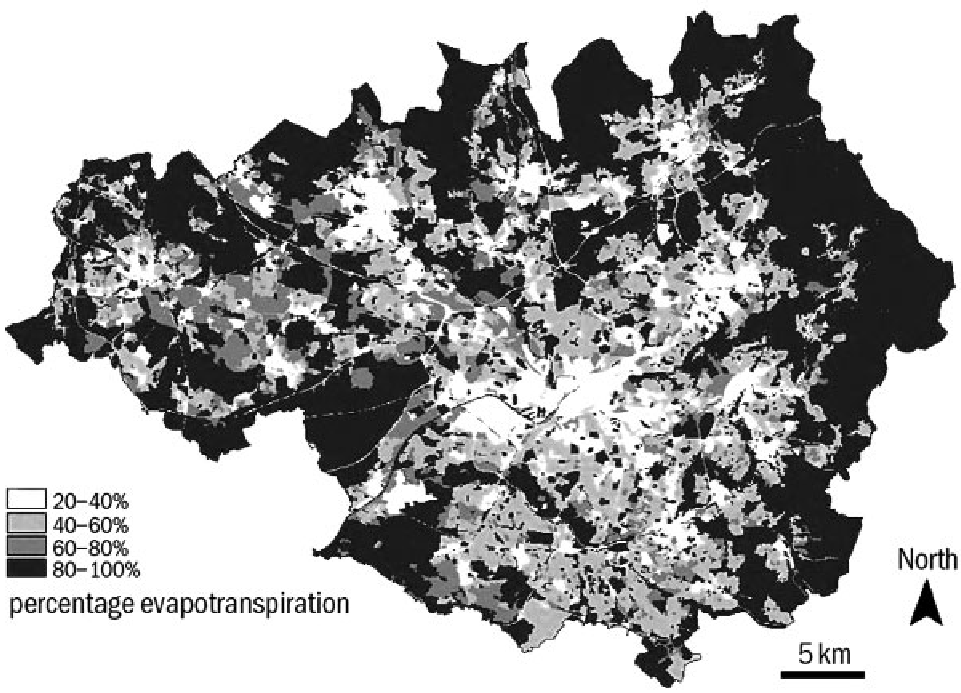
One approach to work out what is happening, taken by a group from the University of Basel, Switzerland, and led by botanist Sebastian Leuzinger and meteorologist Roland Vogt, is to use a high-resolution thermal camera mounted on a helicopter. The researchers measured the surface temperature of parts of Basel on a hot summer's day when the air temperature was 25 °C. They found that streets reached temperatures of 37 °C and roofs 45 °C, whereas the temperatures of trees were on average only 25 °C and of water bodies just 18 °C. Potentially, these figures could be put into a regional climate model to give an indication of the effects of the trees on air temperatures. However, this would ignore the depth of the tree canopy; the lower layers of leaves, being shaded by the top ones, will be cooler than those above. Trees will therefore provide more cooling than would be predicted from thermal-camera measurements.

To solve this problem, my group at the University of Manchester, which includes physicists, biologists and planners, used a simple energy-balance model to calculate the surface temperatures of typical vegetation, buildings and roads (**Figure 1**). Originally developed by Chih Pin Tso, then at the University of Malaya, Kuala Lumpur, in the 1990s, the model suggested that vegetation is more effective than the thermal measurements of Basel would suggest. On hot days, the predicted maximum temperature of woodland was 18-25 °C cooler than that of building and roads.

Our group used the area of Greater Manchester as a case study, which encompasses the city of Manchester and its extended urban sprawl. First, we categorized the area's pattern of vegetation using aerial photography (**Figure 2**) and found that, surprisingly for a built-up industrial area, 59% of Greater Manchester is covered by evapotranspiring vegetation. Of course the vegetation cover, and hence surface temperatures predicted by the model, was not uniform across the area. Built-up areas such as city centres had vegetation cover of less than 30% and were up to 13 °C hotter than green spaces. We also manipulated the green space in the model to perform "experiments" that would normally be impracticable. For instance, we showed that adding 10% tree cover to city centres would reduce maximum surface temperatures by about 4 °C. The results of our study, however, really need to be put into a regional climate model that can calculate air temperatures.

Figure 2



One other thing scientists need to discover is how good trees and grass are at cooling relative to one another. The best way to do this would be to look at the energy balance of the surfaces more directly. Since plants cool themselves by evapotranspiration and the heat of evaporation of water is constant at 2.43 kJ per gram, the cooling provided by a plant is proportional to its rate of water loss. One might expect trees to provide more cooling than grass, since their leaves are held higher up above the ground and so should lose water faster, like washing on a clothes line; on the other hand, trees have to pipe that water up to their leaves against gravity. Environmental physicists and botanists have developed techniques to measure water loss, which will allow us to test these ideas.

Water loss from grass is best measured by mounting turf onto a sensitive balance and monitoring weight loss throughout the day. Water loss from trees is measured using sap-flow meters: an electrically heated collar that applies bursts of heat is attached to the trunk of the tree to warm the sap within. Apparatus higher up the trunk monitors the temperature there, allowing the velocity and hence volume flow of water up the trunk to be calculated. Using these techniques, many studies by foresters and agronomists have found that forests and grasslands both give evaporative cooling of 100–200 $\mathrm{W\,m^{-2}}$. But there is little of this information available for urban grass and trees – and we have no idea how their cooling effectiveness might be limited by drought – so experimental work is urgently needed.

Respite from the Sun

A final climatic benefit of vegetation is to provide cool oases for recreation. Many studies have therefore compared air temperatures in parks with those in surrounding roads, only to find that, except on really windless days, the differences are rather small – usually less than 1 °C – because warm air is blown into the park from the surroundings. So why do we feel cooler in parks, and what effect does tree shading have?

To answer these questions we have to consider the heat balance of a person. At rest, a person's body produces heat at a rate of about 60 $\mathrm{W\,m^{-2}}$ of our body surface. How hot we feel depends on how readily we can lose that heat to our surroundings. Surprisingly, except in very high winds, we lose very little heat by convection – only about 9 $\mathrm{W\,m^{-2}}$ – and about 15 $\mathrm{W\,m^{-2}}$ by evaporation from our breath. However, all bodies emit far-infrared radiation at a rate proportional to the fourth power of their temperature, but also absorb such radiation from their surroundings. Therefore, if our surroundings are cooler than 37 °C, we have a net radiative heat loss.

Outside in a shady park we feel comfortable because we are surrounded by cool leaves. On an open street, in contrast, we feel hotter for two reasons: first, we are receiving an additional input of up to 120 $\mathrm{Wm^{-2}}$ of shortwave radiation from the Sun; second, the surrounding tarmac is also warmer, reducing radiative heat loss by about 6 $\mathrm{W\,m^{-2}}$ for every temperature increase of 1 °C. In such conditions we may have to sweat to get rid of the additional heat burden.

To investigate the relative importance of the Sun versus shade on the temperature of the surroundings, we carried out a simple experiment in summer 2009. This involved monitoring the radiant temperatures above grass and concrete plots, which were either in permanent sunlight or in the permanent shade of trees. We did this using a globe thermometer, which is basically a thermometer mounted inside a grey plastic sphere. Held at a height of 1.1 m, this mimics the thermal properties of an adult dressed in a suit. We found that being above grass or concrete had little effect on the radiant temperatures; these were far more influenced by shading, which reduced maximum radiant temperatures by up to 9 °C, from 35 °C to 26 °C. Since people tend to feel uncomfortable at radiant temperatures above 24 °C, it is clear that shading can have a large effect on people's sense of

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well-being, thereby confirming the importance of trees in urban areas.

Influencing policy

All this research is building up a picture of how we can improve cities: trees have the most potential to improve street environments, whereas cool surfaces, green roofs and even "living walls" can improve the environmental performance of individual buildings. In addition, green infrastructure has other benefits, such as a reduction in flash flooding and particulate air pollution. Even so, there is clearly still a vast amount of research to do. We do not know which species of trees might be the best to cool cities and catch pollution particles, whether a single large tree is better than many small ones, or whether deciduous trees are better than evergreens. Nor do we know how the effectiveness of different types of vegetation will alter with climate change.

Nevertheless, we do now know enough to influence policy. The scientists of the USDA Forest Service, for instance, have collaborated with economists to estimate the monetary benefits of planting street trees, from reducing energy costs to reducing the health costs of air pollution. The economic model they have produced – the iTree model –shows that for every dollar put into planting and maintaining street trees, five dollars are saved. In New York, this knowledge, combined with the backing of Mayor Michael Bloomberg, has driven the planting of 20 000 extra street trees a year, while the Mayor of London, Boris Johnson, has also committed to planting 10 000 extra street trees during his term of office. As well as trees, the physical and economic case for green roofs means that they are being retrofitted to ever more buildings. It is good to be able to report that physicists are doing their bit to make our cities greener, pleasanter places in which to live.

About the author

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Source E

Extract from Bowler et al., *Landscape and Urban Planning*, 97 (2010) 147-155

Urban greening to cool towns and cities: A systematic review of the empirical evidence

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Abstract

'Urban greening' has been proposed as one approach to mitigate the human health consequences of increased temperatures resulting from climate change. We used systematic review methodology to evaluate available evidence on whether greening interventions, such as tree planting or the creation of parks or green roofs, affect the air temperature of an urban area. Most studies investigated the air temperature within parks and beneath trees and are broadly supportive that green sites can be cooler than non-green sites. Meta-analysis was used to synthesize data on the cooling effect of parks and results show that, on average, a park was 0.94 °C cooler in the day. Studies on multiple parks suggest that larger parks and those with trees could be cooler during the day. However, evidence for the cooling effect of green space is mostly based on observational studies of small numbers of green sites. The impact of specific greening interventions on the wider urban area, and whether the effects are due to greening alone, has yet to be demonstrated. The current evidence base does not allow specific recommendations to be made on how best to incorporate greening into an urban area. Further empirical research is necessary in order to efficiently guide the design and planning of urban green space, and specifically to investigate the importance of the abundance, distribution and type of greening. Any urban greening programme implemented would need to be appropriately designed and monitored to continue to evaluate benefit to human health through reducing temperature.

1 Introduction

Climate change has been predicted to have a range of consequences for human health arising from the direct and indirect impacts of changes in temperature and precipitation. One of the primary public health concerns is an increase in the intensity and frequency of heat waves, which have been linked with heat stroke, hyperthermia and increased mortality rates. For instance, an estimated 15 000 excess deaths were attributed to the heat wave event across France in August.

Increased air temperatures can be expected to be particularly problematic in urban areas, where temperatures already tend to be a few degrees warmer than the surrounding countryside. This difference in temperature between urban and rural areas has been called the 'urban heat island effect'. Urbanisation leads to changes in the absorption and reflection of solar radiation, and thus the surface energy balance. These changes arise from multiple factors, including the thermal conductivity and specific heat capacities of materials used in urban areas, surface albedo, the geometry of urban canyons and the input of anthropogenic heat. Increasing temperatures resulting from global climate change may exacerbate the health impacts of the higher temperatures that are already common in urban areas. Thus, there is a pressing need to evaluate strategies that may mitigate against further increases in temperatures in urban areas and the associated negative impacts on human health.

Turn over ▸

An adaptation strategy that has been proposed is to 'green' urban areas, essentially by increasing the abundance and cover of vegetation. Vegetation and urban materials differ in moisture, aerodynamic and thermal properties, and so urban greening could affect temperatures through different processes. A key process is evapotranspiration, which describes the loss of water from a plant as a vapour into the atmosphere. Evapotranspiration consumes energy from solar radiation and increases latent rather than sensible heat, cooling the leaf and the temperature of the air surrounding the leaf. This contrasts with the effect of impervious urban materials such as asphalt and concrete, which do not retain water for evaporation and quickly absorb and retain heat when exposed to solar radiation. In addition to evaporative cooling, shading from trees can act to cool the atmosphere by simply intercepting solar radiation and preventing the warming of the land surface and air. This shading effect may create local cool areas beneath tree canopies, which would be important in otherwise open spaces within an urban area. Finally, vegetation may affect air movements and heat exchange. This effect, however, can be expected to critically depend on the type of vegetation. Tree cover may retain warm air beneath the canopy; in contrast, an open grass field that provides low resistance to air flow may promote cooling by convection.

Some studies have used remote sensing technology to estimate land surface temperature and vegetation cover for a number of different urban localities. Many studies following this approach found a negative correlation between vegetation indices such as NDVI (normalised difference vegetation index) and temperature. This is consistent with the hypothesis that green cover may be effective in reducing temperature. Mathematical models and computer simulations have also been employed to investigate and make predictions on the potential effects of vegetation cover on urban climates. In this review, we focus specifically on empirical data based on temperature measurements collected at ground level, rather than surface temperature measurements from satellite imagery or model predictions. We review studies that measure air temperature within green and non-green sites within an urban area; these studies provide a direct test of the effect of green space on temperature. Green infrastructure may be incorporated in a variety of ways, including the creation of parks, tree planting along streets, and green roofs. To be able to assess the effects of different potential infrastructures rather than green cover per se, our review focuses on studies that measure air temperature in a specific greening type (parks, trees, green roofs, ground vegetation) rather than an undescribed green or vegetation surface cover. We use systematic review methodology to provide a robust and transparent framework to collate relevant studies and synthesise their findings. Meta-analysis is used to statistically synthesise data on the temperature differences between urban parks and non-green urban areas to quantify the average cooling effect of a park across studies. Our review also aims to investigate the strength of evidence on variables that may moderate the air temperature of green space, to investigate the context-dependence of their potential climatic benefits.

2 Search and selection of studies

The methodology of a systematic review includes comprehensive searching of literature and the application of predefined criteria to identify relevant articles. Relevant articles are then subjected to critical appraisal of methodological quality and their findings are summarised. This methodology is designed to ensure that the review conclusions are as unbiased as possible and based on the best available evidence.

Searching for relevant research data was conducted using databases, internet search engines and websites of environmental and health organisations, using combinations of relevant keywords (such as 'temperature', 'vegetation', urban'). To be included in the review, a study was required to measure temperature at ground level in an urban area in any geographic location and to compare temperatures in a green site(s) and a non-green site(s) (the latter acting as a comparator/control). We thus do not include studies that only compare the air temperature of green sites that differ in the amount of vegetation cover, with no "control" site. Included studies must also have investigated a greening type that could be assigned to at least one of the following categories: ground vegetation (e.g. a plot of grass); roof vegetation; trees (single/clusters or woods) and parks or green areas (e.g. gardens), which were usually mixtures of ground vegetation and trees. We structure the review by these different possible greening intervention types. These categories were identified from an initial review of all articles and clearly there is overlap between them, but we use the author's description of the study sites to best categorise the greening type under study.

3 Synthesis

Meta-analysis was conducted for the largest sub-group of articles, which comprised studies on urban parks or green areas such as gardens. Meta-analysis involves the calculation of an 'effect size' from individual studies, which is a statistic that summarises its overall result.

Effect sizes are then combined by calculating their average and its 95% confidence interval; a weighted average [was used],... This weighting means that studies with a more precise estimate of the effect size have greater influence on the estimated average effect size across studies.

Data on air temperatures were extracted from the text, tables or figures ... presented in articles. In this review, a study's effect size is the average of the differences in temperature between the green and non-green area (i.e. $T_{urban} - T_{park}$ in °C), based on measurements taken at the same time. For studies measuring multiple sites within each green and non-green area, the average of sites within each area was calculated and then the differences of the average temperatures. ... These effect sizes were calculated separately, when possible, for each different park or green area for which there were available data. In studies measuring temperature more frequently than every hour, data are derived from hourly replication and in studies presenting data separately for different seasons, we focus on data from the summer. In some cases, data were not presented in a form that could be readily extracted or only a subset of the data collected was presented. When possible the authors of these articles were contacted to request data, however, we were not able to obtain all relevant data. For articles on other greening interventions, quantitative synthesis was not deemed suitable due to the low number of studies and variability in the type of greening, study methodology and reporting of data. We present a narrative synthesis of all articles and focus on patterns observed in air temperature rather than surface temperature unless otherwise stated.

4 Overview of studies

Our search identified 74 articles that had measured temperature at ground level in a green and non-green urban area, but only 47 of these could be categorised into one of our greening interventions of interest, based on the information presented in the article. The effects of parks and trees have received most attention while the effects of green roofs and ground vegetation have been less studied. In most cases, studies investigated a small number of different green sites and few studies were experimental (i.e. the green element under the control of the investigator). In some cases temperatures were only measured over a few days and several measured (or at least presented in the article) the temperature difference over 1 single day. Most studies were conducted in urban areas within the temperate zone. Further details of studies investigating parks, trees and forests, and ground and roof vegetation are presented in tables.

[Four data tables have been removed for clarity].

4.1 Parks and green areas

Our meta-analysis initially focused on measurements during the day (06:00–20:00) for which there were most data available. Figure 3 displays the estimated 'effect size' for each park in the day ($T_{urban} - T_{park}$ in °C). The average temperature reduction in the day was 0.94 °C (95% CI = 0.71–1.16), based on 26 effect sizes from 16 studies. Analysis on the subset of data measured at night (22:00–06:00) based on

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Figure 3

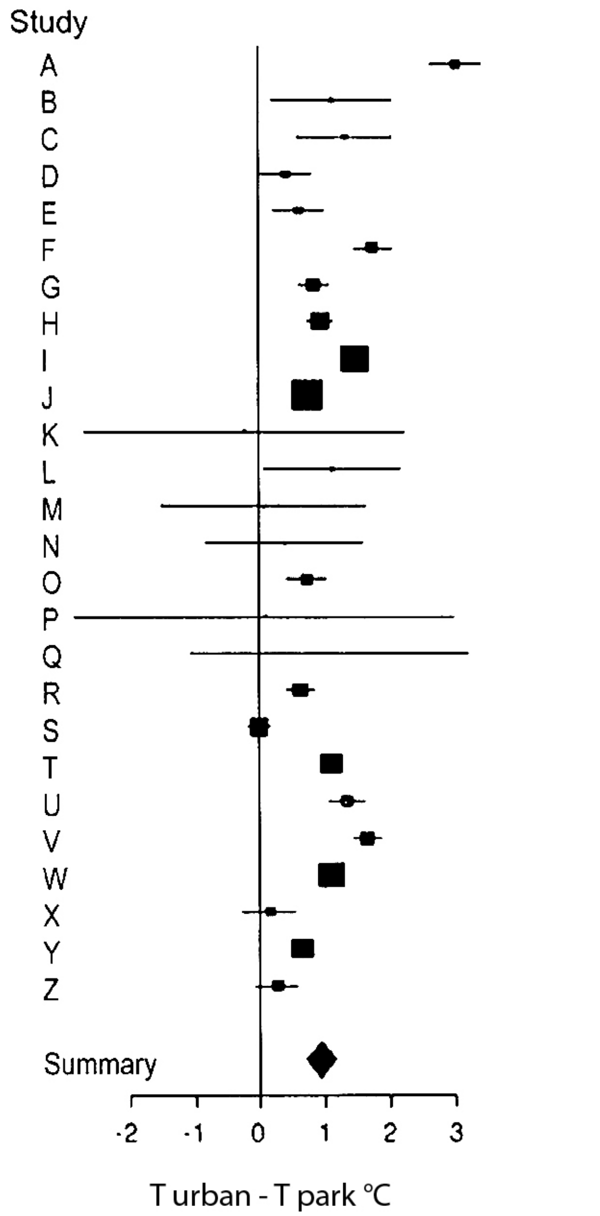

Figure 3. Black squares represent the average temperature difference between a builtup area and a park or green area in the day (the effect size; Turban -Tpark °C). The horizontal bars are the 95% confidence intervals for each effect size. The vertical axis line represents the line of no temperature difference; positive effect sizes indicate that the park was cooler. The average effect size ("Summary"; shown as a diamond symbol) was calculated as a weighted average.

The size of black squares reflects the "weight" given to each study.

12 effect sizes from 7 studies found a similar average temperature reduction of 1.15°C (95% CI = 0.86–1.45).

In these analyses, similar results were obtained using average data per article rather than per park (i.e. accounting for potential non-independence of data from studies measuring more than 1 park)... There was some initial support for a positive effect of park size on the estimated cooling effect at night ($p < 0.001$) however this was driven by a single outlying data point from 1 large park (Study K) and the effect was insignificant on removal of this study.

The cooling estimate of a park at night was smaller in studies comparing the difference between a park and its surroundings (0.65°C; 95% CI = 0.43–0.87) than in studies where the temperature of the park was compared with an urban site elsewhere in the town or city (2.26°; 95% CI = 1.14–3.37). This result could be indicative of an extension of the park's cooling effect into its surroundings, which would reduce the temperature difference.

Given the relatively few separate studies that we could meta-analyse, the analysis has only limited power to detect the significance of factors affecting temperature. However a number of variables were identified from studies that compared the cooling effects of multiple parks. Four studies measured several parks of different sizes. The results of these studies show that larger parks were either more likely to be cooler or that the cooling effect was greater.

A crucial issue to the value of parks, and in particular their impact on public health, is whether a park has any effect on the temperature of the wider surrounding area. Study H studied two large parks in Singapore and measured temperatures at increasing distance from the park up to approximately 500 m from the boundary. For both parks, temperatures gradually increased with increasing distance from the park boundary. In a long-term study of three parks in Gothenburg, ...the night-time cooling effect of a park could extend beyond the park boundary, particularly for the largest of the three parks studied (156 ha). For this park, the data suggested that the effect could reach up to 1 km from the park's boundary. Observations made by other studies also indicate an extension of the cooling effect.

4.2 Urban trees and forests

Several studies have focused specifically on the effects of trees, comparing temperatures in a site with trees, with those of a nearby treeless site. There is evidence that air temperature beneath both individual trees and clusters of trees are lower than temperatures in an open area, at least during the day.

Tree species have been shown to vary in their ability to reduce air temperature, which may be due to a number of factors, such as tree size and tree canopy characteristics, which affect the penetration of solar radiation. Two studies compared the effects of a single tree versus a cluster of trees on air temperature. In one of these, marginally higher temperatures were found under the single tree than the cluster, but only one site of each was measured.

The value of adding street trees may vary with the specific urban topography, such as street orientation. It is important to note that buildings can also provide shade.

4.3 Ground and roof vegetation

Our review found fewer studies that investigated the effects of short vegetation cover, excluding those described as a tree or park. Three studies suggested that air temperatures were usually cooler above grass than above concrete. Studies were consistent in finding lower surface temperatures for grass than for concrete or asphalt. Effects of short vegetation have also been studied in the context of a green roof. Studies have compared temperature on or above sections of a roof with vegetation, with sections of a roof (usually the same roof) without vegetation and therefore addressed the local effects of green roofs. The findings have been mixed, with some evidence of lower air temperatures above green sections in some studies, but not in others. These studies were more supportive of surface temperature of green roofs being cooler than non-green roofs or at least less variable. However, the temperature difference can depend on the time of day or month of the year.

5 Discussion on the strength of evidence

This systematic review aimed to assess the evidence on the effectiveness of urban greening as a strategy to reduce urban air temperature. We focused on the subset of studies investigating specific greening types, which may be used to guide the design of urban greening programmes. Most of these studies investigated the difference in temperature between parks or trees and non-green sites within the same urban area. Their findings broadly support the hypotheses that greening can cool the environment, at least at a local scale.

However, the majority of these studies used an observational design, which involved comparing existing variation in greenness within an urban area, rather than using more rigorous study designs such as an experiment. This is perhaps not surprising given the types of interventions involved, which limit the feasibility of conducting experimental work. Nevertheless, in the absence of experimental manipulation, it is important to consider the impact of any potential confounding variables which may bias the estimate of the cooling effect of a green area. Confounding variables are additional factors that vary between the sites being compared and may explain the observed difference in temperature.

In many other studies, the extent to which similar and additional variables vary between sites being compared, is not fully described and/or accounted for with statistical analysis. We therefore suggest that careful selection of representative and comparable sites needs to be more explicitly considered and reported in articles. This is likely to be less of a problem in the studies that compared temperatures in the same locality, for instance, within a park compared to the immediate surroundings or beneath a tree and at a nearby treeless site. However, these studies may

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also underestimate the cooling effect if it extends beyond the green area.
A second methodological issue is that most studies only measured a small number of distinct green sites, for instance, most studies on parks only investigated a single park even if they did take several measurements within the park. This lack of true replication limits the generality of the conclusions that can be drawn from an individual study. This also means that quantitative syntheses such as meta-analysis can be a useful approach to integrating the results from different studies and allowing more general inferences on the effects of greening. It also allows investigation of the potential context-dependence of the benefits of greening, which may be more difficult to test within a single study.

A meta-analytical approach was used in this review to predict the average temperature reduction in a park; however, exploration of heterogeneity was limited by the number of independent sites for which data were available. In addition, some studies only presented a subset of the data collected to present the patterns on a typical day. As more studies are conducted on this topic, we would encourage further meta-analyses. This would be aided by standardised data collection and consistent reporting of data in articles. For the purpose of meta-analysis, this would usually mean reporting of parameters such as means, standard deviations and sample size (or raw data) of data collected during a study.

More detailed information on the specific features of the urban sites being compared would also be useful for investigation of the factors affecting the cooling effect of green space. To standardise data collection, debate is needed on the most useful summary temperature parameters, such as daily average, average during daylight hours and/or difference at the warmest time of the day, as well as the number of sites and method of site selection, in order to best describe temperature difference between green and representative non-green areas.

Though the research points towards the potential of using greening, particularly trees, to reduce urban air temperature, it is less able to demonstrate exactly how green infrastructure should be designed in terms of the abundance, type and distribution of greening. Our review attempted to categorise and compare different types of greening but this could only be based on the information provided in articles. To evaluate different types of greening, it would be helpful if studies provided quantitative descriptions of the greening elements under study, for instance, a defined area of grass and/or tree cover, along with information on height or age of vegetation, and plant species. Despite these limitations there was some evidence that the cooling effect of a green area increases with its size, though it is not clear if there is a minimum size threshold or if there is a simple linear relationship. A small number of studies reported that the cooling effect of a park could extend into the surrounding area. ...
However, we found too few studies that explicitly tested this, for instance by analysing and presenting data at increasing distance from the park boundary, to be able to speculate on the strength and shape of this relationship.
Nonetheless, this effect has important implications for the distribution of greening necessary in an urban area for there to be a general cooling effect rather than only localised cooling.

6 Conclusions

Increasing temperatures and the risk of heat wave events in urban areas represents a serious public health concern. We reviewed studies that have investigated the effects of green space on temperatures and these studies present evidence that urban greening, such as parks and trees may act to cool the environment, at least at a local scale. Meta-analysis of data from different studies suggested that, on average, an urban park would be around 1°C cooler than a non-green site. However, this evidence is mostly based on observational data of existing green spaces. Therefore, this hypothesis should continue to be tested through the appropriate monitoring of any urban greening programmes. Monitoring should include collection of temperature data before and after implementation along with comparable ‘control’ non-green sites.

Studies that measured temperature from multiple parks in the same urban area presented data showing that larger parks were cooler. Local climate may also affect the temperature of green space but most studies only collected data from one urban area. The studies also show the effects of different types of vegetation, particularly the difference between short vegetation, such as grass, and tree canopy cover. Shade from trees has been shown to be important for lowering temperatures; however, temperatures have also been shown to be lower in unshaded green sites or above short vegetation, which suggests evaporative cooling may also play a role. Further research is needed on how the benefits of green space change with the particular context, such as local urban environment, climate and type of greening.

The extension of the cooling effect of a green area beyond its boundary is supported by data from a few studies. The scale of any cooling effect beyond the boundary of the green area is particularly important for the likely public health consequences of greening, as green space may not be directly accessible to all who might benefit during very high temperatures. We would therefore suggest that a key line of future research is to explicitly investigate the distance and size-dependence of the effects of green areas, allowing explicit bottom-up predictions of the effect of particular amounts and spatial arrangements of greening. Give the difficulties in conducting well-replicated and experimental research on these topics, drawing results across different studies becomes even more important to enable more general conclusions to be drawn, rather than relying on simple case studies of individual green areas. Improvements in reporting temperature data and information on the type of greening and urban site under study would allow more powerful meta-analyses.

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References
The paper contained 75 references which have been removed for clarity.

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There are no sources printed on this page

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Source A 'Roasting temperatures blamed for spike in death rates', The Daily Mail, 14 July 2010.
Source B Andy Extrace 'Green roofs offer antidote to urban heat island effect, say researchers', guardian.co.uk, 2 September 2010.
Source C Adam Marcus, 'Air conditioning drives down hospitalizations'. www.reuters.com, 23 September 2010.
Source D Roland Ennos, 'Urban Cool', Physicsworld.com, 2 August 2011.
Source E Bowler et al.; 'Urban greening to cool towns and cities: A systematic review of the empirical evidence'; Landscape and Urban Planning, Vol 97, Issue 3; © Elvesier B.V.