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The Urban Heat Island: Implications for Health in a Changing Environment

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Abstract
Purpose of Review The Urban Heat Island (UHI) is a well-studied phenomenon, whereby urban areas are generally warmer than surrounding suburban and rural areas. The most direct effect on health from the UHI is due to heat risk, which is exacerbated in urban areas, particularly during heat waves. However, there may be health benefits from warming during colder months. This review highlights recent attempts to quantitatively estimate the health impacts of the UHI and estimations of the health benefits of UHI mitigation measures.
Recent Findings Climate change, increasing urbanisation and an ageing population in much of the world, is likely to increase the risks to health from the UHI, particularly from heat exposure. Studies have shown increased health risks in urban populations compared with rural or suburban populations in hot weather and a disproportionate impact on more vulnerable social groups. Estimations of the impacts of various mitigation techniques suggest that a range of measures could reduce health impacts from heat and bring other benefits to health and wellbeing.
Summary The impact of the UHI on heat-related health is significant, although often overlooked, particularly when considering future impacts associated with climate change. Multiple factors should be considered when designing mitigation measures in urban environments in order to maximise health benefits and avoid unintended negative effects.

Keywords Temperature · Heat · Built environment · Mitigation · Adaptation · Mortality · Cities

This article is part of the Topical Collection on *Built Environment and Health*

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Introduction

People living in cities worldwide face a variety of risks to health, due to pollution of the air, water and soil from industry and traffic, from noise and from over-crowding and poor housing [1]. This is of particular concern to the public health community, as 2007 marked the tipping point whereby more people lived in urban than rural areas, globally [2]. Increasing urbanisation, climate change and ageing populations mean that health risks for urban populations will continue to increase in the future [3], particularly in the developing world [4, 5]. The Urban Heat Island (UHI) effect, which describes the observation that temperatures in towns and cities are generally higher than in surrounding rural or suburban areas [6], represents one mechanism by which the health of urban populations can be compromised. The UHI effect can exacerbate health impacts by affecting rainfall patterns [7], interacting with and worsening air pollution [8], increasing flood risk and decreasing water quality [9]. However, the most direct impact of the UHI on human health is through exposure to increased temperature, which can be particularly problematic during heat waves.

There is a large body of research which associates exposure to high or low temperatures to increased illness, hospitalisation and mortality, globally [10–13]. Events such as heat waves can lead to peaks in heat-related mortality over the space of a few days, for example the European heat wave of 2003 was associated with thousands of excess deaths [14]. City populations are especially at risk due to the additional higher temperature associated with the UHI effect during heat waves, which can exacerbate health impacts from heat. For example, Paris and other French cities were particularly affected by the 2003 heat wave [15, 16].

We reviewed recent studies which characterised and quantified health impacts relating to the UHI, primarily through exposure to heat, and those which assessed the potential impacts on health of UHI mitigation measures. We did not review studies on measurements or the physics of the UHI, subjects which are well covered elsewhere [17, 18]. Where possible we focused on studies which provided quantitative estimates of the health impacts of the UHI effect. Figure 1 illustrates the main topics covered by this review.

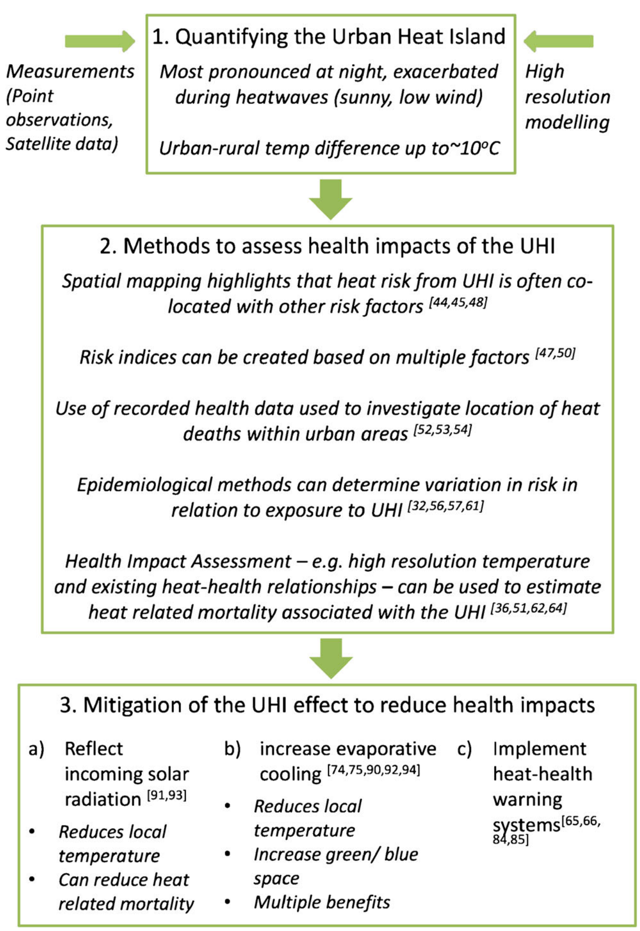

Fig. 1 Summary of topics covered in this review. Examples of relevant publications on methods to assess health impacts of the Urban Heat Island and on mitigation methods to reduce health impacts are indicated by *square brackets*

Characterising and Measuring the Urban Heat Island

The phenomenon of higher ambient temperatures in urban, rather than rural or suburban environments, is largely explained by the differences between land surface materials and building geometry in urban and rural areas, which influence the surface energy balance. In cities, urban materials such as concrete and paving absorb energy from the sun during the day, and slowly release this energy into the air as heat, mostly at nighttime, which is when the temperature difference between urban and rural areas, and hence the UHI intensity, is usually largest. The lack of moisture in urban areas and increased anthropogenic heating also contribute to the UHI effect. The effect was first recorded in 1833 in London, using observations [19]. Since then, the magnitude of the UHI effect has been recognised and estimated in many cities around the world.

The UHI effect can occur in any urbanised area, although it is usually more noticeable in larger cities. UHI 'intensity', usually defined and measured as the difference in temperature between the centre of an urban area and the temperature of a rural reference point outside of the city, scales approximately with population size [20]. In extreme cases, usually at nighttime, temperatures can be up to 5–10 °C higher in the centre of cities like New York, London, Manchester and Birmingham than in the surrounding countryside; although on average, the UHI intensity is usually around 2 to 4 °C [21–24]. Even though there is less incoming solar energy in winter than summer, the UHI effect can be large throughout the year. Most UHI research focuses on summertime, since this is when most of the potential harmful effects occur, and peak temperatures are reached. Less research investigates the wintertime UHI and potential benefits to health which may exist from winter heating in urban areas. The conditions most favourable for a large UHI effect are when skies are clear, due to the increased solar heating in the daytime, and when winds are light so there is a lack of atmospheric mixing and therefore dispersal of the warm air. These conditions often coincide with heat waves, where populations are particularly at risk from the effects of heat.

Challenges When Assessing the Extent of the UHI Effect

Since the existence of the UHI has been acknowledged for so long, methods to quantify its intensity have evolved over time. These can be broadly classified by the use of (a) ground observations (either fixed or mobile), (b) satellite images or (c) modelling using regional climate or meteorological models.

Traditionally, data from pairs of observational sites were used to measure the UHI intensity, although the position and local environment of the observational sites can vary by location, which limits comparability between cities, and point measurements provide little information on spatial variation in temperature across a city. Additionally, temperature monitoring stations have historically been sited outside of city centres to reduce the potential for urban infrastructure influencing ambient temperature measurements. Whilst this siting is useful for analysis of long-term temperature trends without artificial influence, it can limit the availability of urban reference temperature data points. Moving transects taken across a city using vehicles may give more spatial information, and high-density observational networks within cities have occasionally been used [25], but these are difficult and costly to set up and maintain. In recent years, satellite imagery has been used to give an indication of the spatial variation in temperature across a city, although the satellite images represent 'skin' or surface temperature, which is less relevant for human exposure than air temperature at the surface, and images are limited to discrete snapshots in time and only when there is no cloud cover.

These limitations mean that although the intensity of the UHI can be estimated, there is a lack of high-quality information on the variation of risk and population exposure to heat across a city. This fact is highlighted by members of the public health community, who outline the requirements for spatial information on the UHI effect in order to identify areas, where health impacts are likely to be larger, and in order to better protect the public from harmful temperature effects [26].

Modelling studies using high-resolution regional weather and climate models can provide an effective way to quantify the UHI intensity, characterise spatial variations in temperature and, in theory, can be applied to any city in the world. In order to be effective, relevant parameters representing urban characteristics need to be included as inputs to the models, and the unique nature of individual cities and local meteorology should be observed [18]. The effects of urban parameters relevant to the UHI, such as height, shape, three-dimensional area and spatial distribution of buildings and other infrastructure can be determined using field and laboratory studies [27]. This information is then incorporated into building parameter schemes, when running regional models, to improve surface energy exchange in urban areas, e.g. [28]. In addition, by varying model parameters, the range of effects of urban infrastructure and the potential benefits of mitigation measures can be investigated and quantified. Although modelled simulations address some of the shortcomings of traditional measurement techniques, they cannot replace the requirement for reliable observations which are essential for effective model evaluation.

Health Implications of the UHI

Exposure to heat is associated with a range of adverse health effects, ranging from exacerbation of minor existing conditions to increased risk of hospitalisation and death [11]. Heat stroke is not usually the sole cause of death; rather, heat is often a contributory factor to deaths and morbidity from other causes, such as respiratory illness [29]. This risk has been shown to be significant at even moderately high temperatures [12], although health effects are most severe during periods of extremely high temperatures or heat waves. The enhancement of temperatures due to the UHI effect therefore increases heat-related mortality risk in urban areas, and this is likely to further increase in future, due to climate change [30, 31]. Temperatures during heat wave events generally reach a maximum during daytime hours, although high nighttime minimum temperatures, which can keep indoor temperatures high, are also likely to affect health, especially if a heat wave persists over several days. For example, high nighttime temperatures, a key characteristic of the UHI effect, were associated with increased mortality during the 2003 heat wave in Paris [32]. The populations most likely to be adversely affected by heat are generally those in the older age groups and those with existing health conditions.

Several studies have projected the potential impacts of heat on mortality due to climate change [33, 34], and some have shown that although an increase in temperature may lead to decreases in cold-related mortality in future, any benefits are likely to be outweighed by the increase in heat-related deaths due to the combined effects from projected increased mean temperature and heat wave frequency and an ageing, growing population [13, 30]. Since there is less research on the potential health benefits of the UHI in preventing cold-related mortality in winter months, interventions such as modifications to building design to protect against the effects of heat should not exacerbate the risks from cold, and vice versa [35]. Most studies based on climate projections do not explicitly include the UHI effect due to the computational difficulty in resolving features at the urban scale in global climate models, and this may lead to underestimation of health impacts in urban areas [36•]. When urban schemes are included in models, the future impact of the UHI is often discussed, but this is not always related to a health burden [37]. In the following sections, we focus on work which has sought to identify and quantify the heat-related health impacts directly associated with the UHI.

Assessing Heat Risk in Urban Areas

Variations in land surface type mean that temperature varies across a city resulting in similar variations in the potential for population exposure to heat. Higher UHI intensities tend to occur in centrally located parts of the city, where people are often more likely to be socially disadvantaged. In turn, these socio-economic factors may modify how harmful the UHI effect can be and increase vulnerability to the UHI in urban populations [1].There is evidence that vegetated and therefore cooler neighbourhoods are home to more affluent populations and that heat-related health risks are lower in these areas [38].

In addition, poorer neighbourhoods often lack critical physical and social resources to cope with extreme heat [39]. Studies in the USA also suggest strong relationships between land cover, neighbourhood social conditions and surface temperatures [40]. In particular, surface temperature is statistically higher in areas characterised by poverty, ethnic minority groups, lack of education, elderly populations and increased crime due in part to high population density and therefore abundance of manmade surfaces in these areas [41].

Dwelling type and building characteristics play fundamental roles in determining health risks from heat, and are likely to be linked to social factors. For example, air conditioning can protect against heat-related impacts by reducing indoor temperature, but is not always available to more vulnerable population groups, despite becoming more affordable. Air conditioning can lead to increased energy consumption and greenhouse gas emissions (when not powered by renewable energy sources) and can exacerbate the UHI by dissipating heat outdoors. Some evidence suggests that air conditioning needs to be available in the whole house to be effective, and there is also a risk that constant use can increase physiological dependence upon it [42]. Building design to prevent overheating in homes is a key factor determining the vulnerability of the population and a research topic in itself [43].

Spatial Mapping to Identify Heat Risk

Mapping techniques to identify population risk from exposure to heat across a city make use of highly spatially resolved information from climate or meteorological modelling, satellite imagery [44] or interpolated observations [45] to characterise variations in urban temperature. Other factors which modify the effects of heat on health, such as age or socio-economic distribution, can also be mapped at the same time. Attempts have been made to combine maps of hazards, including the UHI effect as well as environmental, demographic or physical factors, to give indications of risk variability across a city, in the form of heat risk models [46–49]. In some cases, this has resulted in creating an index of risk.

In the UK, the creation of a heat vulnerability index for the city of London was based on nine proxy measures of heat risk, selected following a literature search, and used principal component analysis, weighted according to health impact [50]. The nine variables included information about housing, socio-economic status, population density, access to heating and air conditioning, occupant age and underlying health condition. Results showed strong statistical evidence of clustering of areas of high vulnerability, e.g. high population density in central London and poor health status and welfare dependency in the east. Although satellite data and monitoring sites were used to estimate the UHI intensity, there was a lack of consistent highly spatially and temporally resolved temperature information, and air pollution (often a significant risk factor in urban areas) was not included as a risk factor [50].

Another London study highlighted the 'triple jeopardy' of age, UHI intensity and dwelling type (although not socio-economic status) on heat risk [51•]. High-resolution modelled temperature for a single hot day was included in the study, and the analysis was carried out using GIS techniques. Exposure to daily mean maximum temperature was derived from outdoor temperature, UHI anomaly per dwelling (outdoor temperature compared with the average outdoor temperature for all dwellings) and indoor temperature. Results showed that UHI intensity and particularly dwelling type were the main factors contributing to heat mortality risk [51•].

Quantification of the Health Burden Associated With the UHI

Mapping studies go some way to identifying areas of heat vulnerability, particularly when combined with demographic and socio-economic data. Some mapping studies are linked with recorded health data such as hospital admissions or mortality figures, for example an analysis based on satellite data of temperature for Philadelphia in the USA detected that the spatial distribution of heat wave deaths in 1993 was co-located with the urban poor as well as with higher UHI intensity [52]. In Brisbane, hospital admissions data were analysed using Bayesian modelling, and it was found there were significant increases in emergency, non-accidental hospitalizations with increasing daily maximum temperature in summer for a number of areas in the city, particularly those with high population density and low income [53]. An investigation of mortality based on apparent temperature derived by spatial interpolation (using kriging) of sparse observation sites for Massachusetts, USA, in urban and rural areas suggested that demographic factors, such as ethnicity and age, may be more important than level of urbanisation, at least for this particular study area [54]. A US impact assessment for mortality and energy use for cold and warm seasons [55] showed that the impact of the UHI on heat-related deaths was estimated at an increase of 1.1 deaths per million population, and the impact of the UHI on cold-related deaths was a decrease of 4.0 deaths per million. The author highlighted the importance of taking the potential health benefits of the UHI into account as well as costs. However, the results were derived simply by relating information from death certificates on the underlying probable cause of death (e.g. heat, cold) to urbanisation level in various cities.

Epidemiological methods (cross sectional or longitudinal) can be employed to investigate the risk of mortality depending on the heat exposure experienced in different parts of a city, often using satellite imagery. The analysis can be carried out by (a) stratifying the data based on local temperature (or UHI intensity), and calculating the temperature-mortality relationship separately for regions of different temperature, e.g. [56–58], or (b) by comparing results for urban and rural/suburban areas [59]. Case-control epidemiological studies may also be employed, based on urban and rural population samples [32]. Analyses may include cold effects, as well as heat, and morbidity as well as mortality, such as a study in the Czech Republic which focused on cardiovascular outcomes and found some evidence to suggest that the UHI was one possible risk factor for heat stress, along with demographic factors and exposure to air pollution [60]. A recent study for London went further by seeking to investigate whether there were differences in the susceptibility to heat and cold experienced by populations in urban and rural regions using case-crossover epidemiological analyses, and whether adaptation to heat and cold could be detected [61•]. The study used modelled temperature for London at a resolution of 1 km^2 to derive an UHI anomaly, defined here as the difference between local temperature and London mean temperature for each day, and investigated different zones around London. There was some evidence for acclimatisation or adaptation to heat in London, although this was not clear for cold effects [61•].

Health impact assessment methods can be employed to estimate the health burden of the UHI in terms of the heat-related mortality associated with the excess temperature due to the UHI effect. Such studies use epidemiologically derived relationships between temperature and mortality, along with highly spatially resolved modelled temperature exposure data and baseline health data to estimate the impact of the UHI intensity on heat-related mortality. For example, the spatial study [51•] described above went on to combine modelled urban temperatures at 1 km^2 resolution and an existing temperature-mortality relationship to determine how heat-related mortality was affected by various factors in London. The modelled temperature in this case was used to derive an UHI anomaly based on building location compared with the London average, rather than compared with a rural or suburban reference, and the impact analysis was based on indoor air temperatures, which are heavily modified by dwelling characteristics [51•].

Another London-based analysis included projected temperatures and population to calculate the effects of climate change on heat mortality [62]. They used a Climate Projections Weather Generator (UCKP09) for future decades, which simulates temperature projections for each 5 km^2 grid cell, and included downscaled information on the UHI based on derived relationships between land use and anthropogenic heat flux [62]. A sensitivity analysis for adaptation to the order of 1 or 2 °C is included to demonstrate that heat-related mortality may be reduced by 32 to 69% in the future, although this 1–2 °C degree of adaptation is not based on empirical evidence of the scale of adaptation we might expect in future, and which is uncertain [63].

To directly estimate the impact on health that can be attributed to the UHI, modelling techniques can be employed to estimate the impact of land use on temperature, and hence on heat mortality. In a recent modelling experiment, temperatures were simulated by regional climate models at high resolution, with and without urban surfaces in the West Midlands, a region of the UK, for the 2003 heat wave, and for projected temperatures in future decades [36•]. A health impact assessment was carried out for the two modelled simulations, with and without urban land use, and the mortality results were compared in order to quantify the role of urban surfaces in relation to heat mortality. The experiment showed that around half of the heat-related mortality during the heat wave period in August 2003 in the West Midlands could be attributed to the UHI effect, i.e. the excess heat mortality as a result of the excess temperature due to the UHI [36•]. Projections for the future suggested that a similar heat wave event in 2080, under a medium climate change emission scenario, could lead to a threefold increase in heat-related mortality [36•]. Another study, this time based in the USA analysed the relationship between temperature and mortality and included climate and urbanisation projections for the future to calculate mortality [64•]. They found that increases in minimum and mean temperatures were responsible for projected increases in annual heat-related mortality of around 50% and up to 300% by the 2050s.These types of study make a case for consideration of the enhancement of temperature from urban surfaces when calculating health impacts under climate change conditions using global climate models; otherwise, the potential effects of the UHI on health will not be fully captured.

Mitigation Techniques for Reducing the Harmful Effects of the UHI

There are two broad types of mitigation technique for reducing the UHI effect at the city scale: those which aim to increase solar reflectivity, using 'cool' or reflective materials for buildings and surfaces, and those which aim to increase evapotranspiration through increased greening and water availability. The harmful effects of excess heat associated with the UHI may also be mitigated through behavioural change, improved building design and reduced anthropogenic heat emissions in urban areas. The adoption of heat-health warning systems [65] tailored to urban environments could be considered to be an alternative mitigation measure [66]. Detailed reviews on the various techniques employed to counteract the UHI effect in terms of temperature reduction are covered elsewhere, e.g. [67]. Here we consider mitigation measures in the context of reduction of negative health impacts.

Reflective or cool roofs are characterised by their ability to reflect solar energy, and, as such, can be used as a countermeasure to reduce the impacts of the UHI effect [68, 69]. The heat-related health benefits from the implementation of cool or reflective roofs and pavements can therefore be considered to be a direct effect resulting from a reduction in local temperature. The health benefits relating to increasing urban green space or blue space (water), however, are more complex. It is widely understood that urban greening can have a positive effect on reducing the UHI effect [70–72], but there may be additional benefits of urban greening on health, through reduced temperature exposure, increased access to green space (which may improve mental health and wellbeing), reductions to air pollution and more [73•]. In Lisbon, Portugal, proximity to urban green and blue spaces was associated with decreased mortality for elderly populations, after adjusting for confounding factors, and in the case of water bodies, the health benefit was still seen several kilometres away [74]. The authors acknowledge that it was not possible to determine whether the health benefits resulted from reduced temperature, improved health status of populations near green and blue spaces or from reduced stress. Similarly, a protective effect of green space on mortality was found for areas with low socio-economic status in Spain [75]. Literature reviews of the evidence for the health benefits of urban green spaces conclude that although they are generally found to be good for health, a causal relationship is difficult to determine, given the complexity of the relationships involved [76, 77•].

Green roofs are another method employed to mitigate UHI intensity by introducing vegetation at roof level to increase evapotranspiration. Vertical 'green walls' can also carry out a similar function [78]. Unlike cool roofs, which are fairly simple in their function of reflecting solar radiation, a number of factors determine the effectiveness of green roofs in reducing UHI intensity. The cooling potential depends on local climate, vegetation type, density, soil depth, irrigation and maintenance, and in some cases, the reflectivity (albedo) of green roofs may be lower than the reflectivity of the original roofing material [79]. A further consideration is that since the vegetation is at roof height, there is less benefit from the greening to be felt at ground level. There are, however, likely to be benefits of green roofs in terms of CO_2 uptake, air pollution reduction, run-off reduction, biodiversity and in insulating effects in winter [80, 81].

Cool roofs are considered to be a more practical, cheaper method of UHI mitigation than green roofs [82], although green roofs and walls can make useful contributions to a range of health improvements. The reported health benefits of well-designed and maintained urban green spaces make them desirable to include within urban environments, whilst taking care to minimise any potential risks, for example from urban vectors or pollen emissions [83•]. It is worth noting that although many studies investigate the potential effects of "greening" of cities, in practice, trees and green spaces are more often lost to urban development and infrastructure. Whilst it is useful to quantify the benefits of adding green space, particularly when developing and urbanising existing green areas, we should be realistic as to the practicality of greening large areas of our existing cities.

In this review, we do not cover the topics of building design and modification, for example the use of external shutters or shading to mitigate the UHI and minimise overheating impacts. It is worth noting that one mitigation measure for minimising heat-related health impacts from the UHI which does not require physical changes to infrastructure is the implementation of heat-health warning systems such as heat wave plans [65, 84, 85]. These plans should acknowledge that heat effects are likely to be more pronounced in city centres, where residents may experience adverse health effects due to higher temperatures compared to surrounding rural areas.

Assessing the Health Benefits of UHI Mitigation

Modelling can be used to estimate potential health benefits and costs relating to various mitigation measures through impact assessment methods. For example, benefits from reductions in UHI intensity from reflective roofs may have unintended consequences in terms of increasing concentrations of some air pollutants, depending on the method employed, for example changes in solar reflectivity can affect local chemical production of ozone [69]. This highlights the need for integrated modelling techniques and the use of multi-criteria decision analysis when considering planning and policy implementation [86]. Spatial mapping techniques may provide information on any disparity of the effectiveness of strategies based on various demographic and socio-economic factors [87] and make the case for actions at the local level [88].

Recent work investigating heat-related health risks and the potential for countermeasures to the UHI highlights the importance of considering the indoor environment, when many studies focus only on reduction of outdoor temperatures [89]. Results showed that reductions in outdoor temperature do not always reduce the indoor heat risk and that for the indoor environment, trees, green and cool (reflective) roofs and paving may have some benefits to health, but passive cooling and air conditioning should also be considered for risk reduction [89]. However, the hazard reduction potential is presented qualitatively and data on the effectiveness of air conditioning is sparse. Air conditioning may be beneficial to health in hot weather, but it is problematic in terms of increasing unwanted anthropogenic heating, energy consumption and emissions of greenhouse gases. Reliance on air conditioning may become challenging in the event of power outages, so passive measures to provide cooling in buildings are more desirable [42].

Quantitative methods have been employed to estimate the future health effects of climate change alongside various mitigation measures, e.g. using spatial and risk assessment methods quantitatively, to show that increasing vegetation (tree coverage) could reduce heat stress effects through increased evapotranspiration in a US study [90]. The use of trees has multiple co-benefits, such as social improvements and protection from urban flooding, although a potential downside is increased water demand and energy demand for maintenance. Street trees can be considered to provide 'ecosystem services' in terms of improved human health, and are linked with wider co-benefits, as well as potential unintended negative effects [83•]. To maximise the benefits, care needs to be given to design of the tree canopy, choice of species and the need for maintenance.

Parameters in urban climate models can be adapted to simulate the effects on changes in local temperature from, for example a change in reflectivity (albedo) of roofs [48], and to calculate the potential number of 'deaths avoided' by various UHI mitigation methods. This technique was carried out for New York to investigate the impacts of mitigation on the UHI, energy use and atmospheric chemistry, and applied to a hybrid model to investigate the potential benefits to health [91]. The author suggests that in mid-latitudes, cool roofs do not modify the winter UHI, and will therefore not lead to an increase in cold-related mortality. An increased rooftop albedo from 0.32 to 0.90 related to around 45 avoided heat-related deaths per year in New York City.

A study based on US metropolitan areas estimated changes in heat-related deaths up to 2050 resulting from changes in vegetative cover and surface albedo, and found that combinations of these measures could offset 40–99% of the projected increases due to climate change [92•]. In a related study, four different mitigation strategies were assessed as to their impact on emergency service calls, with increased albedo being highlighted as the most effective strategy in a model for Arizona, USA [93]. In Melbourne, Australia, urban climate modelling of ten urban vegetation schemes for current and future climates was carried out to investigate the effect on heat-related mortality. The study found decreased temperature and related mortality with greening simulations; however, the scale of greening in the central business district would have to be reasonably substantial to achieve the desired health benefits (reductions in mortality from 5 to 28% with an increase in vegetation cover from 15 to 33%) [94].

Impact modelling, incorporating environmental, social and demographic information, is essential as a tool for assessing potential benefits of UHI interventions, but it is difficult to validate the estimated impacts against observed impacts. A system-based approach may be necessary to examine the full range of impacts, benefits and costs [73•]. A US case study highlights the complexity of designing effective UHI mitigation policies, and provides recommendations on how policy makers can optimise performance by clearly identifying an endpoint and integrating scientific and location specific information to overcome existing limitations [95•]. Specific endpoints should be determined from the start (e.g. reduce heat-related mortality) rather than be related to the intervention (e.g. plant a certain number of trees) so that success can be driven by a better understanding of the desired goal.

Conclusions

There is a wealth of existing research on the UHI phenomenon, the impact of heat and climate change on health and the use of building and urban planning to make our cities more healthy and sustainable. This review has only focused on recent literature which aims to quantitatively assess the heat-related health impacts of the UHI effect, and how these impacts may be avoided through various mitigation techniques.

We identified numerous spatial mapping studies which are intended to help local authorities and public health practitioners to identify vulnerable populations. However, in order for this type of work to prove useful, close collaboration between researchers and policy-makers is essential [96]. Quantification of the UHI impact on health is necessary to increase the understanding of policy makers of the present and future risks to health of urban populations, particularly in the context of climate change. Care should be taken to consider multiple exposures in urban environments, which may compound or modify the direct impacts of heat on health; air pollution is a problem in many cities, and should be considered alongside the UHI effect as a hazard to urban health. The work presented here shows that when projecting future heat impacts, omitting the additional temperature increase associated with the UHI—not often characterised in global models—may lead to underestimations of health effects. We have mainly focused on heat-related health impacts, but more research on the winter-time UHI is required to ensure that implementation of planning policy minimises risks in both cold and warm seasons.

We reviewed the most commonly implemented mitigation measures and studies which aimed to quantify the potential health benefits of a range of interventions. This has highlighted again the multiple factors at play, and the need to consider unintended consequences and benefits to health of policies designed to protect against the UHI. The assessment of impacts of mitigation measures should also highlight risks, so as to prevent unintended negative effects, particularly in rapidly urbanising countries.

The current quantity of research on the link between environment and health and wellbeing can provide fundamental evidence of the health benefits we may experience through careful planning and design of our urban spaces. The public health and environmental community should continue to work together to promote measures which provide co-benefits in terms of health, the environment and the economy, for example through cleaner energy, active travel or centralised transport initiatives, all of which are particularly relevant to urban environments. With a growing, ageing and more urbanised population expected in most parts of the world, the development of healthy, sustainable cities, based on sound scientific evidence, should be considered a priority for improved public health and wellbeing.

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Compliance with Ethical Standards

Conflict of Interest Clare Heaviside, Helen Macintyre and Sotiris Vardoulakis declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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