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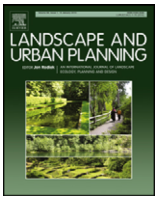

Review

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.

Contents

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 (McMichael et al., 2003; Patz et al., 2005). 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 (Stott et al., 2004; Tan et al., 2007). For instance, an estimated 15,000 excess deaths were attributed to the heat wave event across France in August 2003 (Fouillet et al., 2006).

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

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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 (Taha et al., 1988; Oke, 1989; Sham, 1990; Taha, 1997). Increasing temperatures resulting from global climate change may exacerbate the health impacts of the higher temperatures that are already common in urban areas (Luber and McGeehin, 2008). 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.

An adaptation strategy that has been proposed is to 'green' urban areas, essentially by increasing the abundance and cover of vegetation (Givoni, 1991; Gill et al., 2007). Vegetation and urban materials differ in moisture, aerodynamic and thermal properties, and so urban greening could affect temperatures through different processes (Oke, 1989; Givoni, 1991). 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 (Taha et al., 1988; Grimmond and Oke, 1991). 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 (Oke, 1989). 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 (Bonan, 1997). 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 (normalized difference vegetation index) and temperature (Hung et al., 2006; Tiangco et al., 2008). 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 (Taha et al., 1988; Avissar, 1996). 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 (Givoni, 1991). 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 has been described in detail elsewhere for both healthcare (Khan et al., 2003) and environmental (Pullin and Stewart, 2006) fields. In brief, it includes construction of an *a priori* protocol, 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, which can include a quantitative synthesis when appropriate. This methodology is designed to ensure that the review conclusions are as unbiased as possible and based on the best available evidence. Full details of the conduct of this review are available from Bowler et al. (2010).

Searching for relevant research data was conducted using databases of different disciplines (environmental and public health), internet search engines and websites of environmental and health organisations, using combinations of relevant keywords (such as 'temperature', 'vegetation', 'urban'). Inclusion criteria were explicitly defined to describe the key features of a relevant study for the review. To meet the inclusion criteria, and therefore 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 (e.g. Grimmond et al., 1996; Katayama et al., 1993). Such studies are beyond the scope of this particular review. 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. Kappa analysis was used to verify the level of reviewer agreement on 'article inclusion decisions' between two reviewers on a subset of articles (DB and LBA; Kappa = 0.57, which indicates 'moderate' agreement' sensu Landis and Koch, 1977). This ensures the application of inclusion criteria to identify relevant studies was repeatable. The full text of all articles that were judged as potentially relevant, based on reading their abstract, were searched for using the internet, Bangor University library and the British Library, but some articles could not be successfully retrieved.

3. Synthesis

We aimed to characterise the methodology of these studies and summarise their findings based on the data presented in articles. From each article, we extracted information on research methods, times and location of data collection, type of greening, the number of green and non-green sites, and, importantly, information on their findings with respect to the potential cooling effects of green space. We identified the availability of data from articles that would be amenable for statistical meta-analysis. 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.

Table 1

Details on aspects of the methodology for studies investigating different types of green sites: green roofs, grass (ground vegetation), trees (single or clusters of trees), forests, and parks and other green areas such as gardens. Median number of sites was estimated with respect to the specific type of green site (e.g. number of sites in a park study is the number of parks) while the total number of green sites was the sum of sites across all studies.

Type of green site	No. of studies	Median sites per study	Total no. green sites	No. of experiments	No. on 1 day only
Green roof	6	1	14	4	0
Grass	6	1	10	1	1
Tree(s)	11	3	378	0	4
Forest	4	1	4	0	0
Parks	24	1.5	125	0	6

The number of studies 'on 1 day only' reflects the number of studies in which the study either measured or only presented in the article the temperature difference over one day only.

Effect sizes are then combined by calculating their average and its 95% confidence interval; this is a weighted average, with the effect size from each study weighted by the inverse of its variance (i.e. the precision of the effect size; Lipsey and Wilson, 2001). 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 (using TechDig 2.0) 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. $T_{\text{urban}} - T_{\text{park}}$ 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. The variance of the differences in temperature provided the precision of each effect size. 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. In two cases, calculation of variance was based on the variance of temperatures rather than the temperature differences, as only the former could be calculated from the data presented (Chen and Wong, 2006; Chang et al., 2007). In four cases, because all the data were not retrieved, effect sizes could only be calculated from the subset of the data that was presented (Jauregui, 1991; Kjelgren and Clark, 1992; Ca et al., 1998; Lahme and Bruse, 2003). We verified the robustness of our results to the exclusion of these effect sizes.

Following calculation of the average effect size, variation in the effect size among different studies (termed "heterogeneity" in meta-analysis) was investigated. Cochran's homogeneity test was used to test whether the amount of heterogeneity was greater than expected by chance alone. We explored a number of variables that might explain heterogeneity however this was limited by the information presented within articles. Variables that could be tested were: park area; study type (study of park compared with park surroundings, usually within 500 m from the boundary, versus study of park compared with an urban site elsewhere, beyond the park surroundings); data presentation in the article (all relevant data versus only a subset); control for sun/shade in measurement such as through the use of a radiation shield (explicit control versus no reported attempt to control; for the day-time analysis only); method of data collection (fixed versus mobile measurements) and climatic zone (differences between Köppen climate classification groups; de Blij and Muller, 1993).

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. Table 1 presents the number of studies that investigated each greening intervention and aspects of their methodology. 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 2–4 respectively.

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. Fig. 1 displays the estimated 'effect size' for each park in the day ($T_{\text{urban}} - T_{\text{park}}$ 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 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).

Homogeneity analysis indicated that there was significant variation in the effect size among different parks in the day ($Q = 508.99$; df = 25; $p < 0.001$) and at night ($Q = 271.34$; df = 11; $p < 0.001$). Investigation of variation in the day found no evidence ($p > 0.05$) that the factors tested were important (see 'Section 3' for the list of factors tested). 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 (Jauregui, 1991) and the effect was insignificant on removal of this study. Comparison of night-time effect sizes from cities in different climate groups found that the four effect sizes from a semi-arid climate (Köppen climate group B) were greater ($p < 0.001$) than the

Table 2
Characteristics of studies that have investigated the effects of parks and gardens.

Citation	Urban area	Climate	Month	Green site and comparator	Features of green site	Size (ha)
Almendros Coca (1992)	Madrid, Spain	Dry-summer subtropical	Various dates[3]	1 park compared to an urban area	Trees, gardens, water areas	120
Bacci et al. (2003)	Florence, Italy	Dry-summer subtropical	June–August, December–February[3]	6 green areas compared to city centre	Gardens with trees	0.02–6.9
Barradas (1991)	Mexico City, Mexico	Dry-winter temperate	May–November[1]	5 parks compared to their surroundings	Parks vary in traffic and paved area	1.9–9.9
Ca et al. (1998)	Tama New Town, Japan	Humid subtropical	August–September[3]	1 park compared to nearby urban sites	Grass field	–
Chang et al. (2007)	Taipei City, Taiwan	Humid subtropical	August–September, December–February[3]	61 parks compared to their surroundings	Parks vary in trees and paved area	0.1–>25
Chen and Wong (2006)	Singapore	Tropical rainforest	January–February and June[3]	2 parks compared to their surroundings	Nature Reserve and park with trees	12 and 36
Gomez et al. (1998)	Valencia, Spain	Dry-summer subtropical	January–February[2]	2 green areas compared to urban sites	Park and bed garden	20
Jansson et al. (2007)	Stockholm, Sweden	Warm-summer continental	July[3]	1 park compared to its surroundings	Grass with groves of deciduous trees	15
Jauregui (1991)	Mexico City, Mexico	Dry-winter temperate	All year[3]	1 park compared to an urban site	Multi-use park with trees	c. 525
Jonsson (2004)	Gaborone, Botswana	Semi-arid	September–November[3]	5 green areas compared to the CBD	Irrigated park, gardens, golf course	–
Kjelgren and Clark (1992)	Seattle, USA	Dry-summer subtropical	June–August[1]	1 park compared to a plaza and street	Park border with turf and mature trees	–
Lahme and Bruse (2003)	Essen, Germany	Maritime temperate	September[3]	1 park compared to its surroundings	Park with lake, paved paths and grass	–
Mayer and Höppe (1987)	Munich, Germany	Warm-summer continental	July[1]	1 backyard compared to 2 streets	Grass with trees	0.16
Miyazaki et al. (1996)	Osaka, Japan	Humid subtropical	August[1]	4 green areas compared to urban sites	Parks and a promenade	0.9–108
Potchter et al. (2006)	Tel Aviv, Israel	Dry-summer subtropical	June–August[3]	3 parks compared to their surroundings	Grass and different amounts of trees	2.5–3.5
Saito et al. (1991)	Kumamoto, Japan	Humid subtropical	August–September[1]	2 green areas compared to their surroundings	Park and shrine with trees	0.24–2.25
Shahgedanova et al. (1997)	Moscow, Russia	Warm-summer continental	All year[1]	1 park compared to the city centre	–	–
Spronken-Smith and Oke (1998)	Vancouver, Canada	Maritime temperate	July–August[3]	10 parks compared to their surroundings	Both studies: grass, grass with tree border, Savannah, golf course, garden, multi-use, forest	3–53
Spronken-Smith and Oke (1998)	Sacramento, USA	Dry-summer subtropical	August[3]	10 parks compared to their surroundings		2–15
Thorsson et al. (2007)	Matsudo, Japan	Humid subtropical	March–May[1]	1 park compared to an urban site	Grass lawn, forest, playground	2.1
Upmanis et al. (1998)	Gothenburg, Sweden	Maritime temperate	All year[2]	3 parks compared to their surroundings	Grass, bushes and deciduous trees	2.4–156
Watkins (2002)	London, UK	Maritime temperate	August[1]	1 park compared to surrounding streets	Grass with trees bordering path	50
Watkins (2002)	London, UK	Maritime temperate	September[1]	1 park compared to surrounding streets	–	2.25
Zoulia et al. (2009)	Athens, Greece	Dry-summer subtropical	July[1]	1 park compared to its surroundings, and city centre	–	15.5

The information was extracted from the text of articles when it was reported. Climates were classified by the Köppen climate classification (de Blij and Muller, 1993). Superscripts on month denote whether temperature was collected in the day (1), night (2: after 22:00) or both (3).

Table 3
Characteristics of studies that have investigated the effects of trees and forests.

Citation	Urban area	Climate	Month	Green site and comparator	Features of green site incl. size (ha)/height (ft)
Bueno-Bartholomei and Labaki (2003)	Campinas, Brazil	Humid subtropical	Summer/winter[1]	14 trees—beneath and nearby	12 different species*
de Kauffman et al. (2002)	Maracaibo, Venezuela	Tropical	November–April[3]	1 tree—beneath and nearby	1 species (*Prosopis juliflora*)
Georgi and Zafiriadis (2006)	Thessaloniki, Greece	Dry-summer subtropical	July–August[1]	294 trees—beneath and nearby	21 species*
Gill (2006)	Manchester, UK	Maritime temperate	September[1]	3 tree canopies—beneath and nearby	Urban squares/garden with areas of grass and trees
Golden et al. (2007)	Phoenix, USA	Arid	June[3]	1 tree—beneath and nearby	1 species (*Prosopis alba*; 25 ft)
Gulyás et al. (2006)	Szeged, Hungary	Warm-summer continental	August[1]	3 street trees canopies—beneath and nearby	Deciduous trees
Heisler and Wang (1998)	Atlanta, USA	Humid subtropical	July[3]	A mature forest stand compared to 2 urban sites	–
Huang et al. (2008)	Nanjing, China	Humid subtropical	July–September[3]	Trees/woods compared to non-green sites	–
Johansson and Emmanuel (2006)	Colombo, Sri Lanka	Tropical rainforest	April–May[3]	4 street canyons with trees and 1 non-green canyon.	Canyons vary in green and non-green features
Padmanabhamurty (1991)	Delhi, India	Humid subtropical	–	An urban forest—inside and outside	–
Shashua-Bar and Hoffman (2000)	Tel Aviv, Israel	Dry-summer subtropical	July–August[3]	11 sites with trees and nearby treeless sites	Gardens, courtyards, avenues with trees (c. 0.045–1.1 ha)
Souch and Souch (1993)	Indiana, USA	Hot-summer continental	August[1]	44 trees compared to an open reference site	3 species*(c. 49–75 ft)
Streiling and Matzarakis (2003)	Freiburg, Germany	Warm-summer continental	September[1]	2 trees/clusters—beneath and nearby	*Aesculus hippocastanum*
Taha et al. (1991)	California, USA	Dry-summer subtropical	October[3]	A tree canopy—beneath and nearby	Isolated orchard (c. 4.6 ha)
Yilmaz et al. (2007)	Erzurun, Turkey	Warm-summer continental	August–June[1]	An urban forest compared to city centre	*Pinus sylvestris* (3.2 ha)

See Table 2 legend for further details. An asterisk indicated that the tree species studied are listed in the article.

Table 4
Characteristics of studies that have investigated the effects of ground vegetation and green roofs.

Citation	Urban area	Climate	Month	Green site and comparator	Features of green site incl. area (ha)
Alexandri and Jones (2007)	Cardiff, UK	Maritime temperate	August[3]	Green roof compared to concrete	Grass (0.00036 ha)
Gill (2006)	Manchester, UK	Maritime temperate	September[1]	Green ground cover compared to hard surfaces within 2 urban areas	Grass
Harazono et al. (1991)	Osaka, Japan	Humid subtropical	All year[3]	Green roof compared to concrete	Irrigated bush trees and plants (0.014 ha)
Huang et al. (2008)	Nanjing, China	Humid subtropical	July–September[3]	Green ground cover compared to concrete within 3 urban areas	Grass
Kjelgren and Montague (1998)	Utah, USA	Arid	July–August[1]	Green ground cover compared to asphalt	Irrigated turf plot (0.025 ha)
Köhler et al. (2002)	Neubrandenberg, Germany	Warm-summer continental	May, July, September and December[3]	Green roof compared to gravel	Sedum and moss
Mizuno et al. (1991)	Osaka, Japan	Humid subtropical	Summer, autumn and winter[3]	Various sites including green ground cover	Grass
Mueller and Day (2005)	Phoenix, USA	Arid	All year[3]	Green ground cover compared to asphalt, gravel and concrete	Irrigated Bermuda grass (0.0067 ha)
Takebayashi and Moriyama (2007)	Kobe, Japan	Humid subtropical	August and November[3]	Green roof compared to concrete, bare soil, and reflectance paint.	Grass (0.000152 ha)
Wong et al. (2003)	Singapore	Tropical rainforest	October–November[3]	Green roof compared to a hard surface	Garden roof divided into 6 areas
Wong et al. (2007)	Singapore	Tropical rainforest	September[3]	Before and after green roof	Garden roof divided into 4 green areas
Yilmaz et al. (2008)	Erzurum, Turkey	Warm-summer continental	August[3]	Green ground cover compared to concrete and soil	Grass

See Table 2 legend for further details.

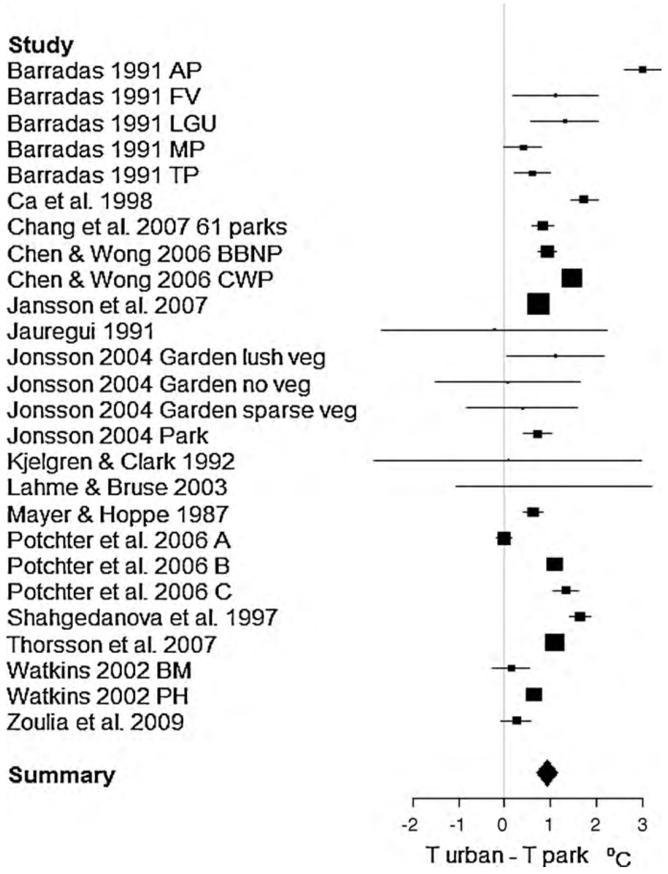

Fig. 1. Black squares represent the average temperature difference between a built-up area and a park or green area in the day (the effect size; $T_{\text{urban}} - T_{\text{park}}$ °C). The horizontal bars are the 95% confidence intervals for each effect size. Study labels give the study citation (and a park identifier when data were obtained from more than 1 park in the study). 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 (see Section 3) and was based on the inverse of the variance.

other effect sizes (seven from Köppen climate group C and one from Köppen climate group A). However, these effect sizes were all from the same study (Jonsson, 2004) and same city (Gabarone, Botswana) and so this result cannot be generalised. 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 °C; 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 (Barradas, 1991; Upmanis et al., 1998; Bacci et al., 2003; Chang et al., 2007). The results of these studies show that larger parks were either more likely to be cooler or that the cooling effect was greater. Comparing the temperatures of 61 parks during the summer at noon in Taipei City, Chang et al. (2007) found that parks over 3 ha were usually cooler than the surrounding urban area while the temperature difference was much more variable for parks less than 3 ha (Chang et al., 2007). In another study, by Barradas (1991), the temperatures of 5 parks in Mexico City, ranging in size from 1.9 to 9.9 ha, were measured every week during the rainy season. The results suggested that larger parks tended to be cooler than their surroundings.

Variation in the composition of vegetation within a park, such as the amount of tree and grass cover can be expected to affect temperature. Potchter et al. (2006) compared 3 parks in Tel Aviv and found that the grass park with few trees tended to be warmer during the day, compared to its surroundings, than 2 other parks with greater tree cover. This effect was suggested to be due to a combination of the shade from buildings in the grass park's surrounding area and heat release from decomposition in the grass. Observations by Spronken-Smith and Oke (1998) across a number of different park types (grass, savannah and multi-use amongst others; see Table 2) were also consistent with a role for trees during the day. The study by Chang et al. (2007) reported that the percentage of tree and shrub cover explained differences in temperature between parks and their surroundings and this was not simply due to a tree shading effect, as measurements were taken in unshaded regions of the parks. Parks may also vary in the proportion of area without vegetation cover, particularly multi-use parks. Increased paved area within a park has been shown to positively correlate with the air temperature difference in studies in Mexico City and Taipei (Barradas, 1991; Chang et al., 2007).

Climate, and specifically temperature and precipitation, can be expected to influence the magnitude of cooling within a park, however, few studies have compared parks in different cities. An exception is a study by Spronken-Smith and Oke (1998) who studied the temperature differences between 10 parks and their surroundings in both Sacramento (dry-summer subtropical) and Vancouver (Maritime temperate). Similar temperature differences were found in the parks of both cities but there was some suggestion that lower air temperatures were possible within irrigated parks in Sacramento. Another study investigated the effect of background temperature on the temperatures of sites with trees in Tel Aviv and found the cooling effect of trees to be greater on days with warmer temperatures (Shashua-Bar and Hoffman, 2000). Our meta-analysis comparing different parks in different countries did not find strong support for a role of climate, however, such an effect may have been obscured by other differences between the studies.

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. Chen and Wong (2006) studied 2 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 3 parks in Gothenburg, Upmanis et al. (1998) also demonstrated that the night-time cooling effect of a park could extend beyond the park boundary, particularly for the largest of the 3 parks studied (156 ha). For this park, the data suggested that the effect could reach up to 1 km from the park boundary. Observations made by other studies also indicate an extension of the cooling effect (Jauregui, 1991; Spronken-Smith and Oke, 1998; Shashua-Bar and Hoffman, 2000).

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 (Table 3). There is evidence that air temperature beneath both individual trees (de Kauffman et al., 2002; Bueno-Bartholomei and Labaki, 2003; Georgi and Zafiriadis, 2006; Golden et al., 2007; but not Gulyás et al., 2006) and clusters of trees (Taha et al., 1991; Souch and Souch, 1993; Shashua-Bar and Hoffman, 2000; Streiling and Matzarakis, 2003) are lower than temperatures in an open area, at least during the day. Shashua-Bar and Hoffman

(2000) demonstrated that the specific amount of shading coverage was an important factor affecting temperature. Comparisons of temperature within more dense urban forests and non-green urban sites have also shown lower temperatures in the forested sites (Padmanabhamurty, 1991; Heisler and Wang, 1998; Yilmaz et al., 2007; Huang et al., 2008). However, these studies also demonstrate that a tree canopy can retain heat at night (Taha et al., 1991; Souch and Souch, 1993; Huang et al., 2008).

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 (Bueno-Bartholomei and Labaki, 2003; Georgi and Zafiriadis, 2006 but not Souch and Souch, 1993). 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 (Streiling and Matzarakis, 2003). In a replicated study, Souch and Souch (1993) found no difference between single or clumps (3 or 4 trees) of Sugar maple trees, Acer saccharum in Indiana, USA. This study also compared air temperatures beneath the Sugar maple when growing on either a concrete or grass surface. Warmer temperatures were found beneath those in the street (Souch and Souch, 1993; see also Kjelgren and Montague, 1998), which suggests that there may be important synergies between different greening interventions. The value of adding street trees may vary with the specific urban topography, such as street orientation (but see Gulyás et al., 2006). It is important to note that buildings can also provide shade (Gill, 2006).

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 (Table 4). Three studies suggested that air temperatures were usually cooler above grass than above concrete (Mueller and Day, 2005; Huang et al., 2008; Yilmaz et al., 2008 but not Kjelgren and Montague, 1998). Studies were consistent in finding lower surface temperatures for grass than for concrete or asphalt (Kjelgren and Montague, 1998; Mueller and Day, 2005; Gill, 2006; Yilmaz et al., 2008). 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 (Harazono et al., 1991; Wong et al., 2003), but not in others (Alexandri and Jones, 2007; Wong et al., 2007). These studies were more supportive of surface temperature of green roofs being cooler than non-green roofs (Wong et al., 2003; Alexandri and Jones, 2007; Wong et al., 2007) or at least less variable (Köhler et al., 2002). However, the temperature difference can depend on the time of day or month of the year (Harazono et al., 1991; Takebayashi and Moriyama, 2007).

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 temperatures. 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 hypothesis 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 differences in temperature. For instance, Johansson and Emmanuel (2006) studied 5 different urban canyons which varied in ground cover but also differed with respect to distance from the sea (and sea breeze), height-to-width ratio and canyon orientation, which all affected air temperature and were more important than ground cover. 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 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 (other effect size metrics are possible, such as correlation coefficients, depending on the question; see Lipsey and Wilson, 2001). 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 standardize 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 day, as well as the number of sites and method of site selection, in order to best describe temperature differences 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 (e.g. Upmanis et al., 1998; Chen and Wong, 2006). However we found too few studies that explicitly tested this, for instance by analyzing 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. Models have highlighted the potential importance of additional factors which may modify the effects of urban greening, such as the height-to-width ratio of street canyons (Shashua-Bar et al., 2006; Ali-Toudert and Mayer, 2007; Alexandri and Jones, 2008). Empirical studies could aim to test some of the predictions of this body of theory to provide a tighter coupling between the theory and empirical research.

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 1 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.

Given 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. The approach of systematic review and meta-analysis that combines data from different studies could be used to address further questions on this topic and broaden our understanding of the potential benefits of green space in urban environments.

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