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The effect of tree shade and grass on surface and globe temperatures in an urban area

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ABSTRACT

The process of urbanisation alters the thermal balance of an area resulting in an urban heat island effect where cities can be several degrees centigrade warmer than the surrounding rural landscape. This increased heat can make cities uncomfortable places and, during heat waves, can pose serious health risks. This study looked at the role that trees and grass can play in reducing regional and local temperatures in urban areas during the summer within the urban landscape of Manchester, UK. In June and July 2009 and 2010, we monitored the surface temperatures of small plots composed of concrete and grass in the presence or absence of tree shading, and measured globe temperatures above each of the surfaces. The same measures were also recorded at mid-day on larger expanses of asphalt and grass in an urban park. Both surface and shade greatly affected surface temperatures. Grass reduced maximum surface temperatures by up to 24 °C, similar to model predictions, while tree shade reduced them by up to 19 °C. In contrast, surface composition had little effect upon globe temperatures, whereas shading reduced them by up to 5–7 °C. These results show that both grass and trees can effectively cool surfaces and so can provide regional cooling, helping reduce the urban heat island in hot weather. In contrast grass has little effect upon local air or globe temperatures, so should have little effect on human comfort, whereas tree shade can provide effective local cooling.

Introduction

The processes by which urbanisation causes an urban heat island (UHI) are well known. The built surfaces, such as concrete, asphalt and bricks, found in urban areas, absorb more heat during the day than the former vegetated surface, warm the air more by convection, and re-radiate more heat back into the urban landscape at night (Oke, 1982; Kuttler, 2008). The loss of vegetation reduces the albedo, decreasing reflection of short-wave radiation, and more importantly reduces evapotranspiration, decreasing cooling due to transfer of latent heat. In the UK, urban centres can consequently be up to 7 °C warmer (Wilby, 2003) than the surrounding rural areas (Wilby, 2003). Urban heat islands are a particular problem on hot summer days when they increase the need for air conditioning in buildings, and cause discomfort to people, both indoors and outdoors. The problem of the UHI is likely to get worse with climate change, as mean temperatures are predicted to rise, as are the frequencies of heat waves. For instance, projections for Manchester, UK are that for the medium emissions scenario the mean summer temperature will rise by 3.7 °C by the 2080s, and maximum temperatures by 4.8 °C (UKCP, 2009) with even larger increases in the temperatures on the hottest days. The increase in the magnitude and frequency of urban heat waves will potentially cause severe health problems and an increased number of heat related illnesses and deaths, particularly for the elderly. Such effects were already seen in the European heat wave of 2003, when 35,000 excess deaths were recorded, mainly in urban environments, due to heat-related illnesses (Kosatsky, 2005).

If the loss of vegetation causes the UHI, adding vegetation to urban areas could potentially reduce its magnitude, so research is needed to quantify the cooling effects of urban vegetation. However, there are difficulties in measuring this effect; no two cities, or area within cities, are identical apart from their amount of greenspace, making conventional experimental studies hard to conduct.

One preferred method of getting over this problem is to compare air temperatures in parks (Barradas, 1991; Jauregui, 1990/1991; Spronken-Smith and Oke, 1998; Upmanis et al., 1998; Potchter et al., 2006; Chang et al., 2007; Jansson and Gustafsson, 2007) and small greenspaces (Souch and Souch, 1993; Scott et al., 1999;

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Shashua-Bar et al., 2009), with those in the surrounding streets. Unfortunately these studies ranged widely in location from the tropics to the northernmost parts of Europe, and included only one city, Vancouver (Spronken-Smith and Oke, 1998) which had a climate similar to that of the UK. The results are not surprisingly extremely variable, though the meta analysis of Bowler et al. (2010) concluded that the effects are usually small; parks had on average a daytime temperature only 0.94 °C cooler than the surrounding urban temperature. Similar results were found in a daytime summer transect out through Manchester (Smith et al., 2011); temperatures fell within a large urban park but by less than 1 °C. The smallness of the effect is probably because warm air can be readily advected into parks (Jansson and Gustafsson, 2007), while cool air from parks is advected into the surrounding streets (Upmanis et al., 1998); the extent of such movements will of course depend strongly on the wind speed.

A potentially better method of determining the cooling effect of vegetation is to measure surface temperatures, as these drive regional urban air temperatures, but few measurements of urban surface temperature have been made. Infra red aerial photography of cities (Leuzinger et al., 2010; Pauleit and Duhme, 2000) has measured surface temperatures at single points in time. A study of Basel, Switzerland, for instance, showed that at midday on a hot summer's day, hard surfaces, at 37–60 °C were 12–35 °C warmer than air, whereas the leaves of trees ranged from 1 °C cooler to 4 °C warmer than air temperature (Leuzinger et al., 2010). However, surface temperatures of vegetation and paved areas have rarely been monitored throughout the day. Instead, a modelling approach has sometimes been taken. For instance, Whitford et al. (2001) and Gill et al. (2007) modelled the maximum summer surface temperature of areas in Merseyside and Manchester, UK with different surface cover types, using the energy balance model of Tso et al. (1990, 1991). They came up with differences between maximum surface temperatures of 12.8 °C between the city centre and woodland, with predicted maximum temperatures of 43 °C for non-transpiring surfaces such as concrete, compared to a maximum temperature of 18 °C for wholly transpiring surfaces such as woodlands and grass (Gill, 2006). These results are in reasonable agreement with the results for tree canopies found by Pauleit and Duhme (2000) and Leuzinger et al. (2010), but they urgently need validating.

One aspect of vegetation that has not been investigated is the effect of the three dimensional nature of trees; as well as having a cool canopy, they also shade adjacent areas. This is important for two reasons. First, it will reduce the surface temperature of the shaded area, reducing its storage and convection of heat; to quantify the regional cooling role of trees it is important to measure this effect. Second, shading affects human comfort, since it will alter our perceived temperature, which is dependent more on the radiation flow between ourselves and the local environment than on convection (Matzarakis et al., 2007). How warm we feel therefore depends more on the temperature of our surroundings and the degree of insolation rather than air temperature. A shaded person should feel cooler than one standing in the sun, and a person standing on a hotter surface should feel warmer than one standing on a cooler surface (Monteith and Unsworth, 1990). A better measure of perceived heat is therefore obtained, not from an air thermometer, but from a globe thermometer (Thorsson et al., 2007). This is a thermometer held within a 38 mm grey sphere, which is affected by both convection and radiation, just like a person.

The present study therefore had two main aims. First to measure the effect of grass cover and tree shade on surface temperatures. Second, to measure the effect of grass cover and tree shade on globe temperatures, so we could investigate the local effects of vegetation, and particularly the way in which humans perceive the urban climate. Manchester, UK, was chosen as the study site, largely so that we could validate the model predictions of Gill et al. (2007). It is also a good example of a city with a temperate, maritime climate, which at present has few problems with heat, though it does show a pronounced urban heat island of 3–5 °C (Smith et al., 2011). However, it is likely to show significant warming with climate change (Gill et al., 2007), and it has a good deal of high density housing where there is little greenspace and the Victorian housing has poor insulation. Summer heat waves are therefore likely to become a problem in the near future.

Materials and methods

Study area

The study was carried out in Greater Manchester, UK, which is a large conurbation (population 2.5 m) located in the North West of England and covering 1300 km^2. It has a temperate maritime climate with a mean annual temperature of 9 °C and annual precipitation of 806 mm. The study sites were both located within 3 km of the city centre, and therefore well within the urban heat island. Both sites were located at the edge of University campuses adjacent to high density housing areas (Gill et al., 2008), and so close to areas of medium to low vegetation cover.

Two sets of experiments were performed. In the first, the effect of small areas of vegetation was examined; the surface and globe temperatures of small plots covered by grass or concrete both in full sun or in continuous tree shade were continuously monitored. The second experiment examined the effects of larger areas of vegetation; midday air, surface and globe temperatures in an urban park were taken on hot sunny days above different surfaces both in sun or shade, and compared with the air temperature outside the park.

Small plot experiments

Experiments to investigate the effects of surface cover and tree shade on surface and globe temperatures were carried out at the University of Manchester botanical grounds (53°26′38″N, 2°12′50″W) over June–July 2009 and June–July 2010. The grounds include a rectangular area of mown grass along the South side approximately 50 m × 20 m (0.1 ha in area). Site A, which was used in the 2009 study, was sited to the north of a row of lime (*Tilia* × *europaea*) trees that afforded an area of shade throughout the course of the day, apart from a brief 30 min spell between 08:00 and 08:30 BST when the low angle of the sun cast light into this area. Site B, which was used in the 2010 study, was sited to the North of a row of trees composed of a Scots pine (*Pinus sylvestris* L.), lime (*Tilia* × *europaea*) and cotoneaster (*Cotoneaster* × *watereri*) which afforded an area of shade throughout the day until 16:00 when the angle of the sun cast light into the area. In the shade of each row of trees, two test plots, one of grass, the other of concrete, were set up. Seven metres to the north of each test area two further plots were installed in a full sun position which received no shading at any point during the day.

The grass plots were surfaced with the ryegrass mixture that covered the floor of the experimental grounds which were mown every 2–4 weeks in summer. Grass plots never showed any sign of water stress, despite not receiving any irrigation. In the concrete plots, this surface was replaced by a 1.8 m × 1.8 m area of concrete made up of 16 Richmond natural concrete flags (450 mm × 450 mm × 35 mm). The paving flags were laid into the existing grass area at a depth of 35 mm so that the top of the flag was level with the soil surface as it would be in the urban environment. For both the shade and sun plots one paved plot and one grass plot were set up 4 m apart (Fig. 1). By setting up the plots

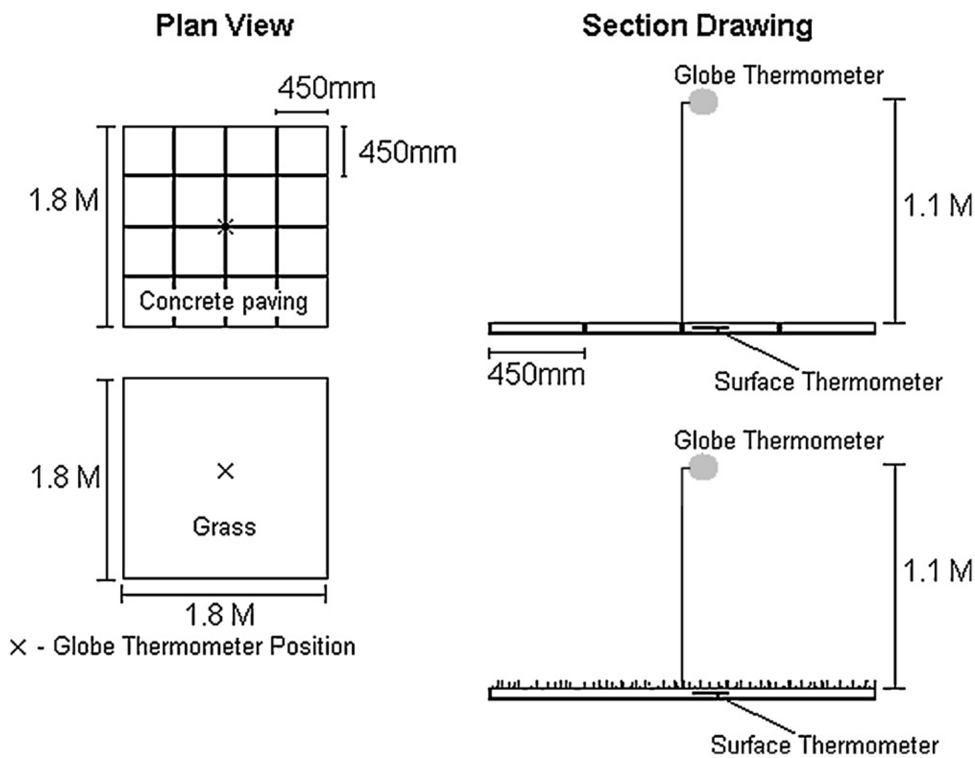

Fig. 1. Diagram of the test plots used to measure surface and globe temperatures above concrete and grass. The position of the globe thermometer in the plan view is marked with an X in both plots and the elevation of the globe thermometer and the position of the HOBO 12 bit temperature smart sensors can be seen in the section view.

in this configuration, it was possible to conduct measurements on each surface type in both shade and full sun conditions, allowing a full examination of each surface's response to the varying solar radiation levels.

The response of each surface type needed to be compared with the ambient meteorological conditions experienced each day. Therefore, air temperature, wind speed and rainfall were all recorded throughout each day. The air temperature was recorded on a HOBO® weather station with a 12-bit temperature smart sensor attached which was housed in a solar radiation shield. The shield and sensor were mounted to a post located between the shade and full sun plots at a height of 2 m and a reading was taken every 5 min during both test periods. Wind speed measurements were also recorded on the HOBO® weather station with a wind speed smart sensor. This recorded the mean wind speed and the gust speed over each 5 min interval. Rainfall measurements were taken using an Onset data logging rain gauge RG3 which recorded the amount of rainfall and the rate of rainfall throughout each test period.

Surface temperatures of each plot were recorded every 5 min using the HOBO® datalogger. One temperature sensor was positioned in the centre of each individual test plot and fixed within the upper 10 mm of the surface. To achieve this, the sensors for the grass plots were simply inserted into a 10 mm deep cut made in the surface so that the sensor lay parallel to the soil surface. For the concrete plots the sensors were inserted into a pre-drilled 8 mm hole, on the underside of the paving flag, which terminated within the upper 10 mm of the paving flag (Fig. 1). In both cases the sensors were fixed in this way to avoid any direct solar radiation affecting the temperatures recorded by the temperature sensors.

The globe temperatures of each plot were also recorded every 5 min using the HOBO® datalogger. Globe thermometers were positioned 1.1 m above the centre of each test plot (Fig. 1) to represent the average centre of mass of an adult human. In the grass plots virtually all of the surroundings below the thermometer, would be covered by grass, so this would subtend a solid angle of 2π steradians. Ideally, to investigate the effect of a concrete floor on globe temperatures, a similarly large plot of concrete would be needed. However, because of their small 1.8 m × 1.8 m size the concrete would only subtend a solid angle of 26% of that below the thermometer; the rest would be covered by grass. This meant that the effect of concrete would be underestimated. The globe thermometers followed the design of Thorsson et al. (2007) and comprised a hollow 38 mm matt grey acrylic sphere with a 12-bit temperature smart sensor fixed at the centre.

The experiment was run three times in total. Plot A was monitored over a period of 30 days from the 27th June to 27th July 2009. Plot B was monitored from the 12th June to 23rd June 2010. After this, the sizes of the concrete plots were increased to 3.6 m × 3.15 m to investigate the effect of a larger area of engineered surface (now 49% of the solid angle below the thermometer, so the effects of the concrete would be higher) upon the globe temperatures. The plot was then monitored from the 24th June to 13th July 2010.

Park monitoring

To further investigate how the size of the grass and engineered surfaces impact upon air as well as surface and globe temperatures, maximum day temperatures were recorded on cloud free days from the 18th June till the 3rd September 2010 in Whitworth Park (53°27′31″N, 2°13′52″W, total area = 7.8 ha), Manchester, UK. These measurements were recorded from 13:00 to 15:00 BST at three points with contrasting surface cover: a large 136 m × 100 m amenity grassland, which was mown every 2–4 weeks in summer; a large 42 m × 25 m asphalt area; and a 3 m wide path constructed of asphalt and bordered by amenity grassland. At each of these areas, the surface, globe and air temperature were recorded both in full sun and in tree shade (Fig. 2).

The temperatures of hard surfaces were measured using a Fluke 572 infrared thermometer. These measurements were taken with

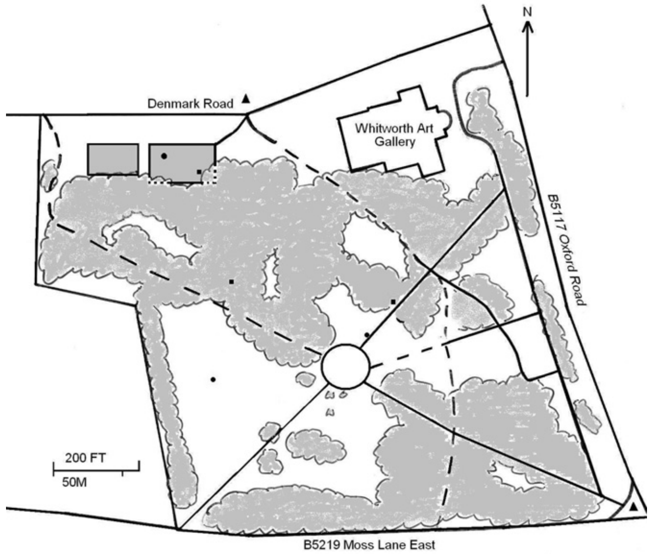

Fig. 2. Map of Whitworth Park, Manchester, UK with sample sites delineated for each surface type. Dots highlight sample areas in sun, squares mark sample sites in shade and the triangles to the north and south east show the positions where external air temperature were recorded.

the thermometer held perpendicular to the surface at a height of 1.1 m; the surface was briefly shaded while the reading was taken to increase the consistency of the results. Surface temperatures of grassland were measured using a Digitron 2084T platinum resistance thermometer with a PT100 blunt tipped temperature probe attached. The probe was inserted into the surface at an angle of 35° to a depth of 10 mm, to avoid the reading being affected by direct solar radiation, and allowed to settle for 2 min before the reading was taken.

Globe temperatures were measured using a Digitron 2084T platinum resistance thermometer with a PT100 blunt tipped temperature probe inserted into a hollow 38 mm matt grey acrylic sphere. The thermometer was fixed to a stand at a height of 1.1 m and this was placed into the centre of each area. The reading was allowed to settle for 5 min before a 5-min average temperature was recorded.

Finally, air temperatures were recorded at each site and also at two urban locations outside the Northern and South Eastern boundary of the park (Fig. 2) using a Digitron 2084T platinum resistance thermometer with a PT100 air probe attached. The air probe was fitted with a radiation shield and elevated to a height of 2 m for 2 min before a reading was taken. All thermometers were calibrated before the monitoring programme began.

Results

Small plot experiments

The methods employed successfully recorded the daily fluctuations of the surface and globe temperatures. Fig. 3 shows the surface temperature results for the 4th July 2009 (a), 17th June 2010 (b) and the 3rd July 2010 (c) which were all typical of hot days, being dry and sunny, except for occasional clouds, and with maximum air temperatures between 23.5 °C and 25 °C.

The pattern of surface temperature change was similar on all three days. The concrete surfaces were always hotter than the surrounding air, rising to peaks of around 40 °C in the sun, and 28 °C in the shade, around 17 °C and 4 °C higher than peak air temperature. Grass surface temperature was much lower, rising to peaks of around 23 °C in the sun and 19 °C in the shade, around 1 °C and 4 °C lower than peak air temperatures.

While the overall patterns of temperature changes were similar on cooler days, the differences in maximum temperatures were lower; this mirrored the smaller differences between maximum and minimum air temperature on these days.

To investigate the patterns quantitatively, we produced graphs of surface temperature against air temperature for each day. The relationships were highly linear; surface temperature rose and fell in line with air temperature, but the slope of the relationships were different depending on the surface conditions. Since neither surface nor air temperature could be treated as an independent variable (they were both affected by time of day and incoming short wave radiation) the slopes of the linear relationships between surface temperature and air temperature were quantified by carrying out reduced major axis regression. This method is preferred to conventional linear regression when (as in this case) there is no clear independent variable (Ennos, 2011). The slopes for each day were subjected to analysis using one-way ANOVA and it was found that they did not differ significantly between hot, average or cool days. Therefore a single mean slope was calculated for each surface in each test period. To give an intercept for the relationship between surface and air temperature, the difference between minimum surface temperature and minimum air temperature was calculated for each day in each test period, and the mean difference over all the days was taken as the intercept.

The result of this analysis is a single plot for each test period (Fig. 4) showing the relationship between the surface temperature and air temperature, relative to the minimum air temperature. The results for all three experiments were similar, one-way ANOVA showing significant differences between the slopes of the regression lines (see Table 1). Concrete increased in temperature at 2.3–2.6 times the rate of air when exposed to the sun but at only 1.3–1.6 times air temperature in the shade. Grass increased by only 0.5–0.7 times air temperature in the sun and 0.3–0.6 times in the shade. The vertical lines in Fig. 4 show the average difference between maximum and minimum air temperatures recorded on cool (maximum temperature less than 20 °C), average (maximum temperature between 20 °C and 25 °C) and hot days (maximum temperature over 25 °C). The mean difference between the maximum surface temperature and maximum air temperature can be determined by looking down the lines. It can be seen that there are much larger differences between maximum surface temperature and maximum air temperature on hot days.

Table 1
The mean and standard errors of the slopes and intercepts of the regression lines (see Fig. 4) between the surface temperature and air temperature of the concrete and grass plots in both sun and shade.

	Mean slope (SE)	Mean intercept (SE)
2009		
Concrete sun	2.257 (±0.097)	2.437 (±0.239)
Concrete shade	1.267 (±0.040)	0.815 (±0.181)
Grass sun	0.678 (±0.021)	3.908 (±0.594)
Grass shade	0.485 (±0.022)	1.815 (±0.509)
June 2010		
Concrete sun	2.622 (±0.144)	1.520 (±0.080)
Concrete shade	1.368 (±0.118)	−0.280 (±0.046)
Grass sun	0.528 (±0.028)	5.350 (±0.090)
Grass shade	0.339 (±0.026)	3.19 (±0.044)
July 2010		
Concrete sun	2.579 (±0.180)	1.376 (±0.202)
Concrete shade	1.586 (±0.089)	−0.147 (±0.224)
Grass sun	0.537 (±0.027)	3.753 (±0.373)
Grass shade	0.571 (±0.045)	1.401 (±0.349)

The temperature patterns displayed by the globe thermometers differed greatly from the surface temperatures. Fig. 5 shows the

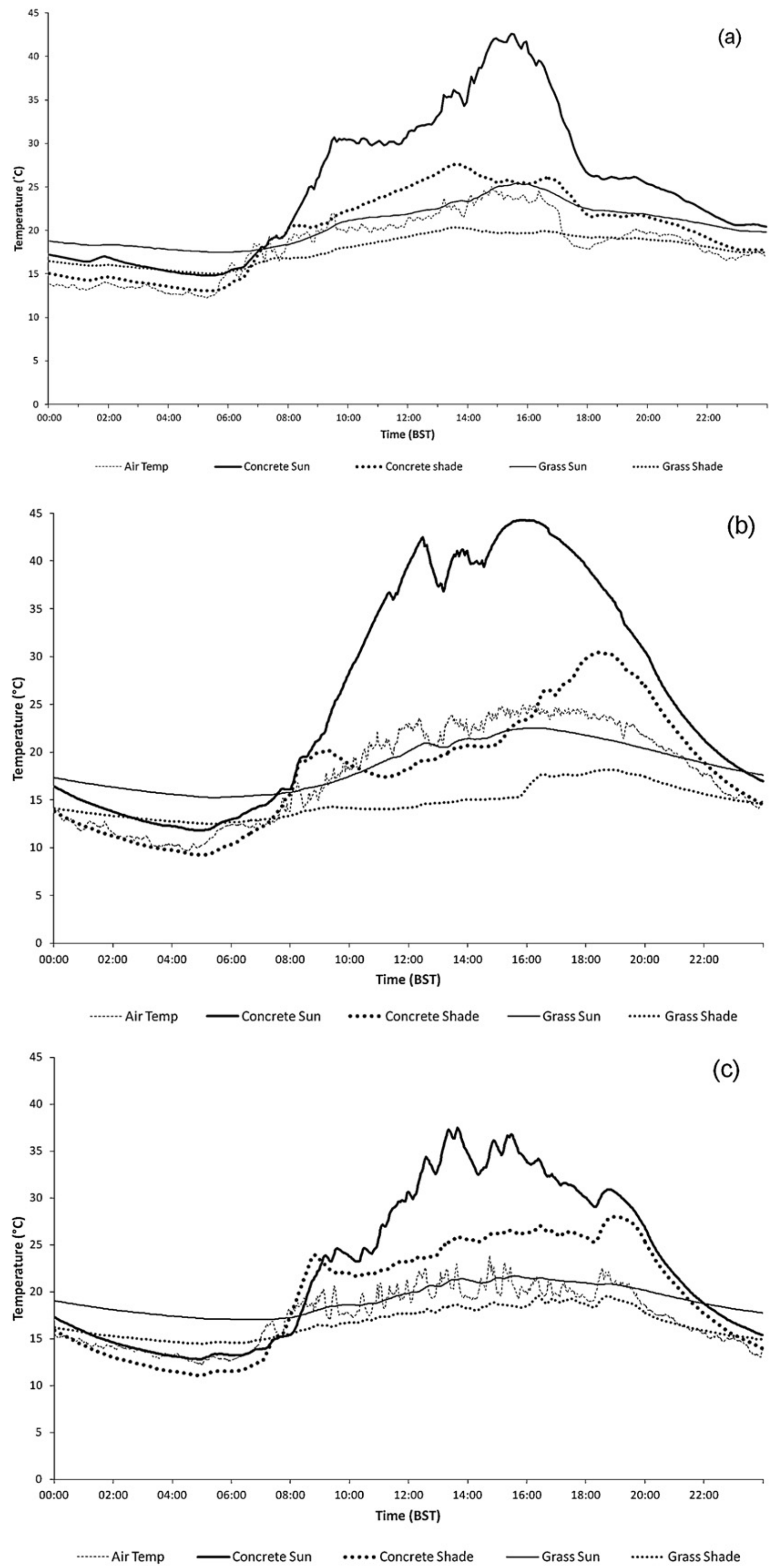

Fig. 3. The diurnal variation of the surface temperature of concrete and grass plots in sun and shade, as well as the local air temperature on the 4th July 2009 (a), 17th June 2010 (b) and 3rd July 2010 (c). It can be seen that the concrete is regularly hotter than the grass even when grass is exposed to full sun conditions.

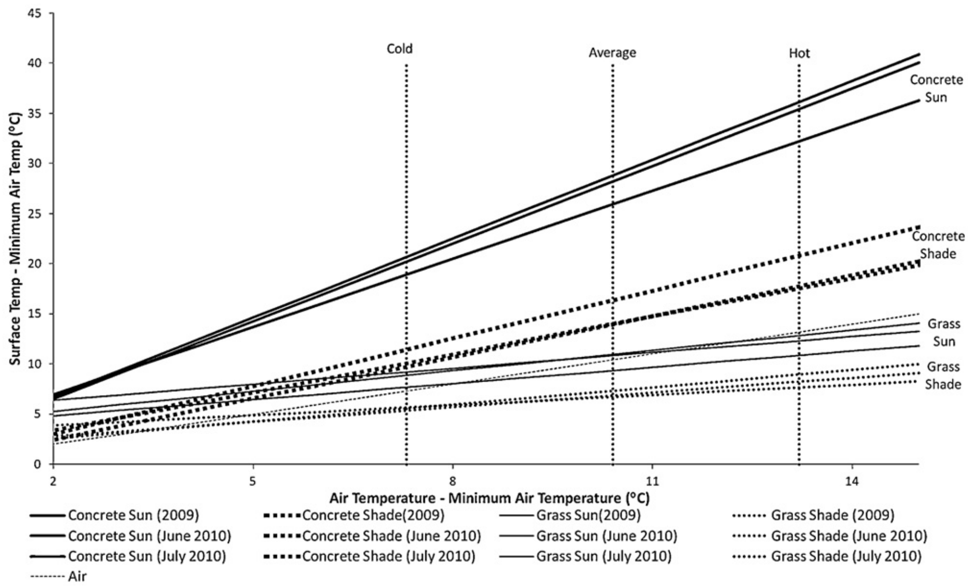

Fig. 4. Graph showing the relationship between the surface temperature of the concrete and grass plots in sun and shade and the local air temperature, relative to the minimum air temperature. The vertical lines show the average differences between maximum and minimum air temperatures on cold, average and hot days.

temperature results of the globe thermometers from the 4th July 2009 (a), 17th June 2010 (b) and the 3rd July 2010 (c).

Like surface temperatures, it can be seen from Fig. 5 that globe temperatures rose from a minimum around dawn to reach a maximum at 13:30 BST, falling rapidly after 16:20 BST. Unlike the surface temperatures, however, the globe temperatures rose and fell less gradually; they reached high temperatures more quickly and showed a higher level of variability than surface temperature, falling rapidly in response to the sun being shielded behind cloud or to gusts of wind. However, the major difference was that though radiant temperatures were affected greatly by whether they were in the shade or not, they were hardly affected by the surface beneath them. The globe thermometers in the sun rose to peaks around 32–34 °C above both concrete and grass, 7–9 °C hotter than the air. In contrast the shade globe temperatures were much closer to air temperature reaching maximums around 27 °C above both concrete and grass, only 2 °C hotter than the air. This pattern was seen on all days, though the difference between the sun plots and the shade plots was lower on cloudy days.

The globe temperature data was analysed in the same way as the surface temperature data to give a graph showing the relationships between globe and air temperatures (Fig. 6). It can be seen that the globe temperatures increased at 1.6–2.1 times the rate of air in the sun, but at only 1.1–1.3 times the rate of air in the shade (Table 2). In all cases the globe temperatures above the concrete in the sun were slightly lower than those above the grass. The size of the concrete surface had no effect on this pattern. The vertical lines in Fig. 6 again show the average difference between maximum and minimum air temperatures recorded on cool, average and hot days. It can be seen that there are much larger differences between maximum globe temperature and maximum air temperature on hot days.

Park temperatures

Both urban and parkland air temperatures varied between days, ranging from 19.2 °C to 24.7 °C. To remove the variability caused by differences between the days, we calculated the difference between the park and the mean air temperature outside the park, to give temperature differences. Mean temperature differences between park and urban temperatures are shown in Fig. 7a. Paired *t* tests showed that in nearly all cases, air temperatures were lower within the park than outside, park air temperatures being on average 0.8 °C cooler than the surrounding urban air temperature.

To investigate the effects of the various surfaces and shade conditions upon the park air temperature, a two-way ANOVA was carried out. This analysis showed that surface conditions had no effect on the air temperature ($F_{2,34} = 0.375$, $p = 0.690$), but tree shade did have an effect ($F_{1,34} = 9.187$, $p = 0.005$). Temperatures in the shade were on average 0.9 °C lower than in the sun and 1.4 °C lower than external air temperatures.

Mean differences between the surface temperatures in the park and the air temperature outside it are shown in Fig. 7b. To investigate the effects of the various surface and shade conditions upon the surface temperature, a two-way ANOVA was carried out. This analysis showed that both surface conditions ($F_{2,34} = 30.752$, $p \leq 0.005$) and shade ($F_{1,34} = 196.795$, $p \leq 0.005$) had significant effects and there was also a significant interaction between them ($F_{2,34} = 7.911$, $p \leq 0.005$). The asphalt area and path were both warmer than the grass, and shade reduced surface temperatures on all surfaces, but shading reduced the surface temperatures of the built surfaces

Table 2
The mean and standard errors of the slopes and intercepts of the regression lines (see Fig. 6) between the globe temperature and air temperature above concrete and grass in both sun and shade.

	Mean slope (SE)	Mean intercept (SE)
2009		
Concrete sun	2.000 (±0.05)	−1.388 (±0.074)
Concrete shade	1.290 (±0.02)	−0.623 (±0.038)
Grass sun	2.050 (±0.05)	−1.316 (±0.236)
Grass shade	1.280 (±0.02)	−0.687 (±0.13)
June 2010		
Concrete sun	1.620 (±0.05)	−0.905 (±0.08)
Concrete shade	1.157 (±0.05)	−0.620 (±0.046)
Grass sun	1.668 (±0.06)	−0.993 (±0.09)
Grass shade	1.097 (±0.04)	−0.548 (±0.044)
July 2010		
Concrete sun	1.588 (±0.039)	−0.597 (±0.071)
Concrete shade	1.189 (±0.037)	−0.462 (±0.062)
Grass sun	1.663 (±0.053)	−0.874 (±0.081)
Grass shade	1.128 (±0.027)	−0.499 (±0.063)

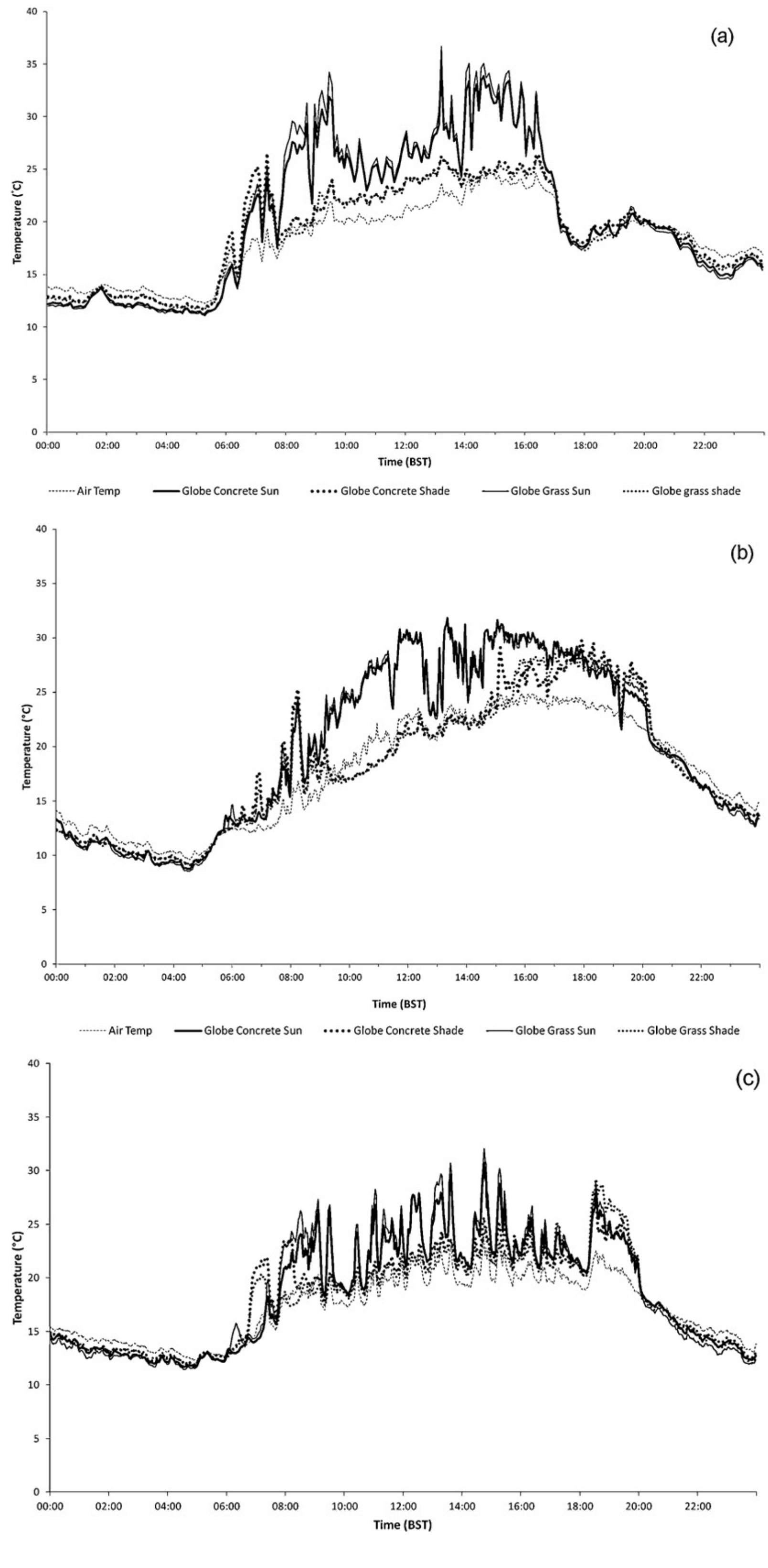

Fig. 5. The diurnal variation of the globe temperature above concrete and grass plots in sun and shade as well as the local air temperature on the 4th July 2009 (a), 17th June 2010 (b) and 3rd July 2010 (c). It can be seen that though being in the sun increases the globe temperature by up to 8 °C, the temperatures are not greatly affected by the surfaces below the thermometer.

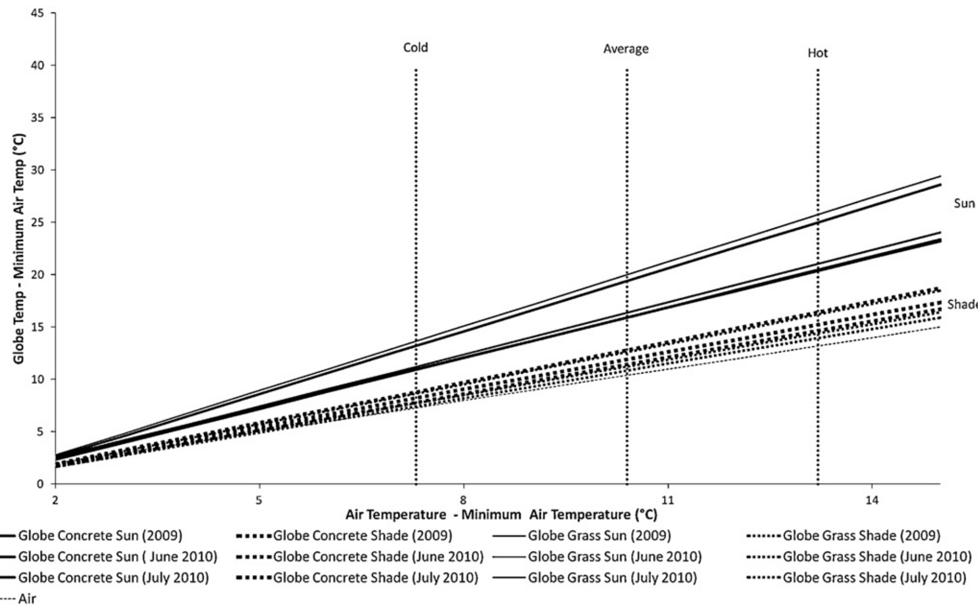

Fig. 6. Graph showing the relationship between the globe temperatures above concrete and grass in sun and shade and the local air temperature, relative to the minimum air temperature. The vertical lines show the average difference between maximum and minimum air temperatures on cold, average and hot days.

more than that of the grass. Therefore, though the built surfaces were around 14 °C warmer than the grass in the sun, and 18 °C warmer than external air temperatures, the concrete was only around 5 °C warmer than grass in the shade, around 2 °C below external air temperatures.

Mean differences between the globe temperatures in the park and the air temperature outside it are shown in Fig. 7c. To investigate the effects of the various surface and shade conditions upon the globe temperature, a two-way ANOVA was carried out. This analysis showed that surface conditions had no effect on the globe temperature ($F_{2,34} = 0.017$, $p = 0.983$), but that tree shade did have an effect ($F_{1,34} = 150.540$, $p \leq 0.005$). Globe temperatures in the sun were on average about 6 °C higher than in the shade, and about 5 °C higher than external air temperatures.

Discussion

Surface temperatures

As expected, concrete and asphalt surfaces in the sun heated up much more than grass surfaces in all four experiments. In the small experimental plots the concrete in full sun rose to peak temperatures on hot days some 19–23 °C higher than air temperature, whereas grass in full sun had peak temperatures 0–3 °C cooler than air temperature (Fig. 3a–c). This meant that grass plots were around 24 °C cooler than concrete. In the park, concrete and asphalt surfaces were some 18 °C warmer than local air temperature, whereas grass was only around 3 °C warmer, a difference of 15 °C. The cooling effects provided by grass in the small (0.1 ha) plots are therefore similar to the 25 °C predicted by Gill et al. (2007). However, much less cooling was seen in the larger park (7.8 ha) and the grass was actually warmer than the surrounding air. This is actually what one would expect in a large area of grassland, even in a well-watered sward, because according to the Penman–Monteith equation, some of the solar energy would be converted into sensible heat (Monteith and Unsworth, 1990; Allen et al., 1998). In the small plots the grass probably provided more cooling because of the oasis effect; warm air from the surrounding area would have been brought in by advection, increasing evapotranspiration (Allen et al., 1998) and providing additional cooling. These results therefore suggest that increasing the area of grassland in urban areas can effectively help reduce the urban heat island. They also suggest that many small patches of grassland are more effective than a single large area, though simultaneous measurements of the surface temperatures of small and large grass plots would be needed to properly test this.

Tree shading is another method of cooling the surface. It can be seen that the peak surface temperature of concrete can be reduced by up to 12 °C in the small plots (Fig. 3a–c) and 19 °C in the park (Fig. 7b). Therefore in circumstances where grass is impractical, tree planting can effectively reduce the temperature of built surfaces. Tree shade also reduced air temperatures significantly in the park, whereas grass alone did not, suggesting that the effects seen by other researchers and summarised by Bowler et al. (2010) are mainly due to the presence of trees. This suggests that instead trees may be even more effective than grass at reducing the urban heat island due to the combined oasis and clothesline effects (Allen et al., 1998), especially as a typical tree casts a greater area of shade than the canopy area. However, though some recent measurements on urban trees suggest that trees do indeed provide higher evapotranspiration than an equivalent area of grass (Shashua-Bar et al., 2009; Rahman et al., 2011) others do not (Peters et al., 2011). Experiments are needed to verify this for Manchester. Our results make it clear, though, that having both trees and grass would be even better than either alone, as surface temperatures of grass in shade can be 4–7 °C cooler than the surrounding air.

Globe temperatures

In contrast to surface temperatures, globe temperatures were hardly affected by the surface cover above which they were measured, but greatly reduced by shade. The globe thermometers above concrete and grass in full sun both rose to a maximum of 9 °C warmer than the surrounding air, whereas in tree shade they rose to only around 2 °C warmer, a reduction of 5–7 °C; similar reductions were provided by the trees in the park. The surface, in contrast, had little effect. This was no doubt because of the greatly reduced short wave radiation levels received in the shade, though these were not directly measured. In fact, contrary to expectations, the maximum globe temperatures recorded above grass were actually

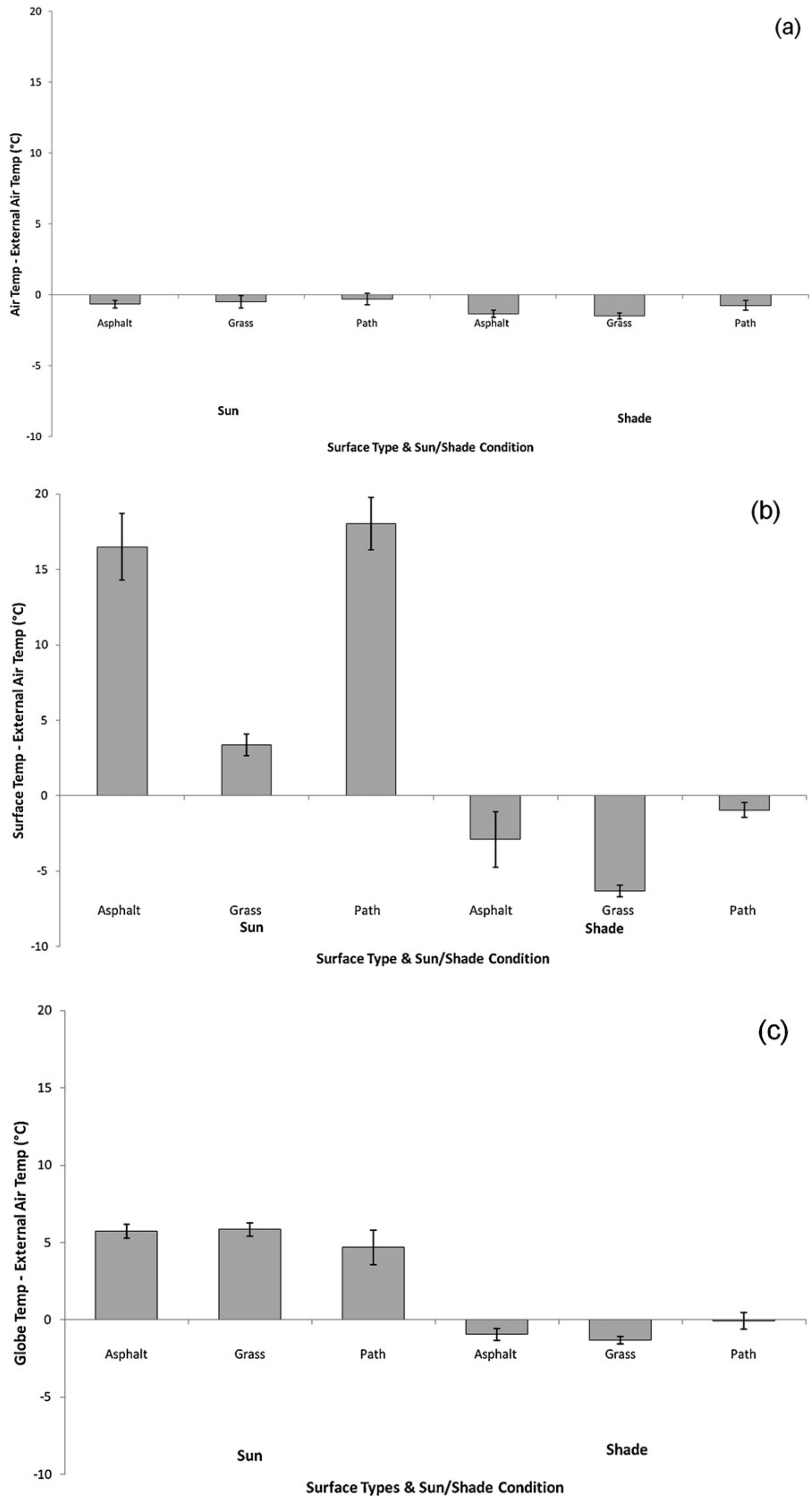

Fig. 7. Graphs showing the differences between mean air (a), surface (b), and globe (c) temperatures within a large urban greenspace and mean external park air temperatures.

slightly higher than above even large areas of concrete, despite their much lower surface temperatures. This was probably because above the grass there are higher levels of short wave radiation, because with its higher albedo the grass reflects more light back upwards!

Regional vs. local effects

These results clearly show the importance of grass in cooling urban areas, mitigating the urban heat island and the probable effects of climate change, and suggest that many small green plots will be more effective than fewer larger ones. This assumes, however, that the grass is not under water stress. Recent research suggests that as climate change progresses, grasses may increasingly suffer from drought in the summer months, reducing its cooling effect (Gill, 2006), whereas deeper rooted trees should be more resistant to drought.

Because of this and because grass is not always a suitable surface in the urban environment, for instance in areas with high footfall or which require vehicular access, trees may also play a role in reducing surface temperatures and thus contribute to UHI reduction. Though tree shading clearly reduced the surface temperatures of both concrete and grass by reducing short wave radiation, this is not actually a useful measure of the regional cooling effect of trees, since they will also provide cooling directly, like the grass, by their transpiration. Hence a better estimate of their effect would be to measure their leaf temperatures as Leuzinger and Körner (2007) did, but at all levels of their canopy, not just the upper surface. An even better way would be to measure their transpiration using a sap flow meter like Shashua-Bar et al. (2009). In fact it seem likely that trees would be rather *more* effective at providing regional cooling than grass as the area of shading they provide is far greater than the footprint area of the tree, especially in mature specimens, creating cooler areas beyond the canopy of the tree.

The biggest difference between trees and grasses, though, is the far greater local effect of tree shade, specifically its ability to lower local air and globe temperatures. This is important as these both greatly affect human comfort (Matzarakis et al., 2007). Outside in the UK, Wilson et al. (2008) found that human comfort is maximized at air temperatures around 20 °C and that when temperatures reached 24.5 °C and above, people actively sought shade which would reduce the globe temperature and the feeling of discomfort due to warmth. Our findings, that tree shading can reduce globe temperatures by 5–7 °C and air temperatures by 1–2 °C, shows that trees have a great and probably increasing role to play in keeping people comfortable in cities. Of course, the effect depends on the depth of the shade. In our small plot experiments, the denser canopy of the limes (a common urban tree in the UK) seemed to reduce globe temperatures by slightly more than the more permeable shade of the pine (rare in urban areas). One would expect faster-growing pioneer trees such as birch and willow to cast less dense shade than climax species such as lime and beech (Horn, 1971) but as far as we are aware little research has been carried out on the shade cast by different trees in urban areas. Further research is needed to compare the shading effectiveness of different tree species and trees of different ages and sizes. These should be compared with shade from buildings, which would probably be even denser and provide even more local cooling.

In conclusion our results clearly show that grass can help reduce the urban heat island in ways that can be predicted using simple meteorological models, while tree shading offers large local cooling benefits. Both are likely to become increasingly important under current climate change predictions. These results are likely to be transferable to other temperate cities where drought is not a problem. Future research should aim to investigate more directly the relative effectiveness of grass and trees in providing regional cooling.

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