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The Benefits of Tree Shade and Turf on Globe and Surface Temperatures in an Urban Tropical Environment

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Abstract. The process of urbanisation increases temperature and alters the thermal comfort in cities. Urban heat islands (UHIs) result in the rise of ambient temperatures. For example, in the densely populated island state of Singapore, the UHI intensity was some 4.5 °C. Such elevation in heat can negatively impact outdoor thermal comfort and may give rise to serious health problems. The present study investigated the benefits of trees and turf as mitigation strategies for urban areas. Short- and long-term observations were made for surface and globe temperatures over smaller plots of vegetation and hard surfaces involving tree shade and full sun. Similar observations were investigated over a larger extent of vegetation across concrete, asphalt, and turf within an urban park setting. The presence of turf and shade from trees greatly affected surface temperatures, and the effect was most pronounced when both were present. The presence of turf reduced surface temperatures by up to 10 °C, while tree shade led to a 12 °C reduction. Globe temperatures showed that the presence of turf and shading reduced temperatures between 5 and 10 °C. These results suggest that turf and trees can effectively cool surfaces and improve outdoor thermal comfort. The results of this study can be applied to urban planning of greenery and can be used as a reference for other tropical cities with similar climates that are also working to develop mitigation measures to improve the liveability of their cities.

Keywords. Globe Temperature; Surface Temperature; Tree Shade; Turf; Urban Environments.

INTRODUCTION

The effects of the urban heat island (UHI) had been studied extensively in the last decade. Built surfaces, such as concrete, asphalt, and bricks, found in urban areas, absorb heat during the day, and the absorbed heat is re-radiated back into the environment (Arnfield 2003; Kuttler 2008). The temperature differential is larger at night than during the day, and this becomes more pronounced when winds are weak. For example, Jusuf et al. (2007) showed that in the day and within an urban city, the effect of UHI on surface temperature for various land use types was in the order of industrial, commercial, airport, residential, and park, respectively, while at night, the order changes to commercial, residential, park, industrial, and airport. Similarly, Rinner and Hussain (2011) also confirmed that there was higher average surface temperature for commercial and industrial land use and lower average surface temperature for parks and water bodies. The relationships between land use and the UHI effect were further reinforced in the work conducted by Zhang et al. (2013) in Shanghai, China.

The effect of UHI enhances with land surface modification. For example, the loss of vegetation reduces the reflection of solar radiation. Additionally, this change negatively impacts on evapotranspirational cooling. The effect of UHI in various urban centres can result in temperature increments of between 4.5 and 7 °C (Imhoff et al. 2010). The urban heat island is more pronounced in humid tropical environments where the increase in temperature exacerbates the requirement for air conditioning indoors, but this, in turn, causes thermal discomfort to people outdoors. The effect of the UHI is likely to escalate with climate change, as mean ambient temperatures are set to rise. For instance, if nothing is done to combat global warming, temperature projections for Asia are set to rise by 4.8 °C by the year

2100 (Denia 2015). Such increases in ambient temperatures will increase the frequency of urban heat waves that will potentially induce health problems coupled with heat-related illnesses and deaths. Such effects were already seen in the 2018 Northeast Asian heat wave, during which 65 deaths were recorded in a single week. In addition, there were more than 70,000 hospitalisations, all of which were concentrated in urban areas induced by the extreme heat (NHK World-News Japan 2018).

While the effects of UHI had received much attention, there has also been some early as well as recent work conducted in the tropics to understand the benefits of vegetation (e.g., the cooling effect of parks) in mitigating the effects of UHI (Jauregui 1990, 1991; Chow et al. 2016; Elmes et al. 2017; Hwang et al. 2017). These studies were generally focused on examining if the incorporation of vegetation into urban areas would potentially mitigate the effects of UHI and to quantify the cooling effects of vegetation within the urban environment. It is noteworthy, however, that there are problems with such measurements as no two cities, or sites within cities, will be identical. The one exception, however, will be the amount of green spaces. With these inconsistencies, it rules out the possibility of using conventional experimental approaches. Therefore, the preferred method will be to compare air temperatures across various parks (Potchter et al. 2006; Yu and Hien 2006; Chang et al. 2007; Jansson and Gustafsson 2007; Bowler et al. 2010) and small green spaces (Heidt and Neef 2008; Shashua-Bar et al. 2009; Hamada and Ohta 2010; Oliveira et al. 2011) surrounded by streets or roadways.

The limitation with such studies is that the sites vary in location, so the results are expected to exhibit differences according to the site conditions. For example, a meta-analysis carried out by Bowler et al. (2010) found that parks exhibited an average daytime temperature of 0.9 °C cooler than the surrounding urban temperature. This relatively small effect is probably because warm air is absorbed into the park from the surrounding streets and roadways (Hamada and Ohta 2010).

A more effective method of determining the cooling effect of vegetation is to observe surface temperatures. Also noteworthy is that diurnal surface temperatures of vegetation and paved areas have rarely been monitored over a long period. Except for a study in Basel, Switzerland, which showed that during summer at midday, the hard surface temperature was 12 °C warmer than air. By contrast, the canopy of trees was found to be 4 °C warmer than air (Leuzinger et al. 2010). Other research has employed the use of the energy-balance modelling approach (Tso et al. 1990, 1991). For instance, Gill et al. (2007) modelled the maximum summer surface temperature of areas of different surface types in Manchester, United Kingdom, and predicted maximum temperatures of 43 °C for concrete, compared to a maximum temperature of 18 °C for woodland and grass (Gill 2006). These results are comparable to results for tree canopies conducted by Leuzinger et al. (2010).

Another area of importance associated with the effects of UHI which has received some attention is that of shade from trees (Kotzen 2003; Shahidan et al. 2010; Abreu-Harbich et al. 2015). This is important for two reasons. Firstly, the surface temperature of the shaded area is expected to be reduced as a result of reduced heat storage and convection; secondly, shading positively impacts on human comfort, and this is achieved through an altered perception of temperature (Matzarakis et al. 2007). A shaded person should feel cooler than one exposed to 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 measure of perceived heat is therefore obtained, not from an air thermometer but from a globe thermometer (an instrument reading both convection and radiation)(Thorsson et al. 2007). The element of shade is critical, as Rosenzweig et al. (2009) had shown in their work with urban forests and green roofs that when the effect of shading was eliminated in the climate model, reductions in surface air temperatures were underestimated. Importantly, there is evidence to suggest that the urban forest can be managed to impact positively on the UHI, but an evidence base will need to be developed to elucidate the ecosystem service benefits urban trees can provide (Feyisa et al. 2014; Livesley et al. 2016) to mitigate the UHI.

Therefore, this present study had two aims: firstly, to measure the effect of turf cover and tree shade on surface temperatures; and secondly, to measure the effect of turf cover and tree shade on globe temperatures. Globe temperature was measured to provide insights into human comfort as it changes alongside variation in surface temperatures. Hence, although these variables are discussed in this study as separate variables for the purpose of delineating surface conditions and human comfort, in essence, both can be considered interdependent. The study site in this investigation was the tropical city-state of Singapore with year-round humidity of approximately 80%. The objective of this study was to understand the effects of vegetation on the ambient temperature environment. It is a good site for investigation because the UHI intensity is high (Meteorological Service Singapore), with a peak occurring some six hours after sunset. In fact, with climate change, significant warming is to be expected. These changes come alongside high-density living and limited land area, which, in turn, limits the allocation of green spaces. Therefore, enhanced UHI is likely to pose significant problems in the near future.

MATERIALS AND METHODS

The study was carried out in the city-state of Singapore (1.3521° N, 103.8198° E), which has a population density measured in 2016 to be 7,797 persons per km^2 (Hirschmann 2020). The total population is some 5.6 million with a land area of some 721.5 km^2. The country lies one degree north of the equator. The weather is warm all throughout the year. Rainfall is abundant, coupled with high and uniform year-round temperatures and humidity. There is very little month-to-month variation in temperature and relative humidity. There are, however, diurnal hour-to-hour variations as a result of solar heating. Rainstorms are possible throughout the year but peak during November to December, with an annual precipitation of 2,340 mm. The climate is mostly warm and wet. The average annual solar irradiance was some 1,580 kWh/m^2. This is some 50% higher than those observed in the temperate regions. Cloud cover throughout a single day is considered to be fairly extensive, ranging from 40% to 95%. The study sites were located some 5 to 10 km away from the city centre, which is comprised of extensive tall buildings, roads, and concrete walkways and is an area generally lacking in vegetation and so likely to experience significant urban heating. Additionally, both sites were of close proximity, hence, the climatic conditions were consistent (Table 1). In addition, both study sites were nestled within high-density housing areas, which is likely to amplify the UHI effect given the presence of extensive building materials that will trap heat.

Table 1. 3-monthly mean temperature, rainfall, and humidity data for 2 experimental sites during the experimental period (2015 through 2017).

	Jan–Mar 2015	Apr–Jun 2015	Jul–Sept 2015	Oct–Dec 2015	Jan–Mar 2016	Apr–Jun 2016	Jul–Sept 2016	Oct–Dec 2016	Jan–Mar 2017	Apr–Jun 2017	Jul–Sept 2017	Oct–Dec 2017
Mean temperature for experimental site 1 (°C)	30.4	31.7	30.3	29.1	31.5	31.6	29.4	28.8	30.5	29.3	27.6	27.2
Mean temperature for experimental site 2 (°C)	30.9	31.2	30.8	29.9	31.0	31.3	29.9	28.4	30.8	29.5	27.3	27.8
Mean rainfall for experimental site 1 (mm)	238	157	192	151	166	153	145	165	134	177	289	292
Mean rainfall for experimental site 2 (mm)	233	152	195	158	163	152	142	161	137	174	285	298
Mean humidity for experimental site 1 (%)	72	81	77	78	84	79	75	85	77	85	78	79
Mean humidity for experimental site 2 (%)	75	83	79	75	81	77	77	81	75	82	75	81
Mean wind speed for experimental site 1 (m/s)	3.5	2.5	2.9	5.8	2.8	2.7	3.1	6.1	3.8	3.2	2.4	4.3
Mean wind speed for experimental site 2 (m/s)	3.3	2.2	3.0	5.5	2.7	2.9	3.2	5.9	3.9	3.6	2.2	4.0

In this study, two experiments were carried out involving variable vegetation intensities with the aim to understand the UHI effect in the city-state. The first experiment was in an open field environment with the objective to examine the effect of small patches of vegetation on globe and surface measurements. These plots were comprised either of turf or concrete, and measurements were made in full sun or in full shade provided by the tree canopies. Diurnal measurements from 2015 to 2017 were carried out. The second experiment was to examine the effects of a larger extent of vegetation, such as an urban park, on globe and surface temperatures. Diurnal and midday measurements were made above green and hard surfaces exposed to the sun and also in the shade. This data was later compared against the air temperature in the external park environment. Green areas and parks nestled within high-density housing areas were selected randomly but still close enough to possess consistent climatic conditions.

Effect of Small Patches of Vegetation on the Urban Heat Island Effect

The area used to study the effect of a small patch of vegetation on UHI was comprised of a mixture of turf and hard surfaces measuring approximately 30 × 25 m, which had a row of *Samanea saman* trees spaced some 3 m apart with umbrella-shaped canopies that overlapped each other and provided the site with shade throughout the course of the day until 15:00 hrs, when the position of the sun moved and light from the sun was able to heat up the area. The area was not in direct contact with buildings, roads (e.g., traffic), or any form of infrastructure that might have an influence on the data collected. The trees were medium-sized trees measuring 10 to 12 m in height with a crown volume of between 250 and 300 m^3. The shade provided by these trees was significant and remained consistent across the experimental period. This species was selected for evaluation as it is commonly planted in many tropical urban cities. It is widely sought after for the shade it provides as a result of its umbrella-shaped crown. In addition, it is fast growing, has a high rate of transplant success, and adapts effectively to poor-quality urban soils. Two plots exposed to shade by these trees comprised of turf and concrete were set aside for shade observations. Approximately 10 m adjacent to the shaded plots, a further two plots in full sun with no shade throughout the day were set up. The turf and concrete plots in the sun and shade were spaced approximately 5 m apart.

The plots with turf were made up of *Stenotaphrum secundatum*. Mowing was generally avoided as it would alter the density and impact on the data. However, some pruning (minimal) of the turf was undertaken every once in a while to ensure that the plot was looking tidy. The plots with *Stenotaphrum secundatum* were generally healthy despite not receiving any irrigation. The concrete plots were a footpath used by pedestrians and were comprised of concrete blocks measuring 2 × 2 m (Figure 1).

Diurnal air temperature, wind speed, and rainfall were recorded. The meteorological data was recorded with a weather hawk 916 wireless weather station powered by a solar panel (Scientific Sales, Inc. NJ, USA). Readings were made at 5-min intervals. Air temperature, wind speed, and rainfall data were important for comparative analysis against the ambient meteorological conditions experienced each day.

The surface temperatures in each plot were recorded at 5-min intervals with the 41382LF2 temperature/humidity sensor coupled with a data logger (Scientific Sales, Inc. NJ, USA). Each sensor was set in the middle of every test plot. For the turf plots, the sensors were set into a shallow 8 to 10 mm crevice made to ensure that the sensor was in contact with the soil surface. The sensors for the concrete plots were set into similar 8 to 10 mm crevices (Figure 1). The key objective of setting the sensors within the crevices was to avoid direct solar radiation, which may alter the temperatures recorded by the sensors.

Similarly, globe temperatures in each plot were recorded at 5-min intervals. This monitoring was aimed at estimating the effect of temperature, humidity, wind speed, and visible as well as infrared radiation on thermal comfort. The globe thermometers (Testo, SMI Sdn. Bhd. Malaysia) were placed at a height of 1.2 m in the centre of each plot (Figure 1). Care was taken to ensure that the area beneath the thermometer was covered by grass with a subtended $2\,\pi$ solid angle. It is noteworthy that for the concrete test plots, because of the limited 2 × 2 m concrete slabs, a subtended solid angle of 75% beneath the thermometer was comprised of concrete while the rest was made up of turf. This was suggestive of some underestimation in the globe temperatures over concrete, though the effect is expected to be negligible. The globe thermometers used had a hollow 150-mm-diameter

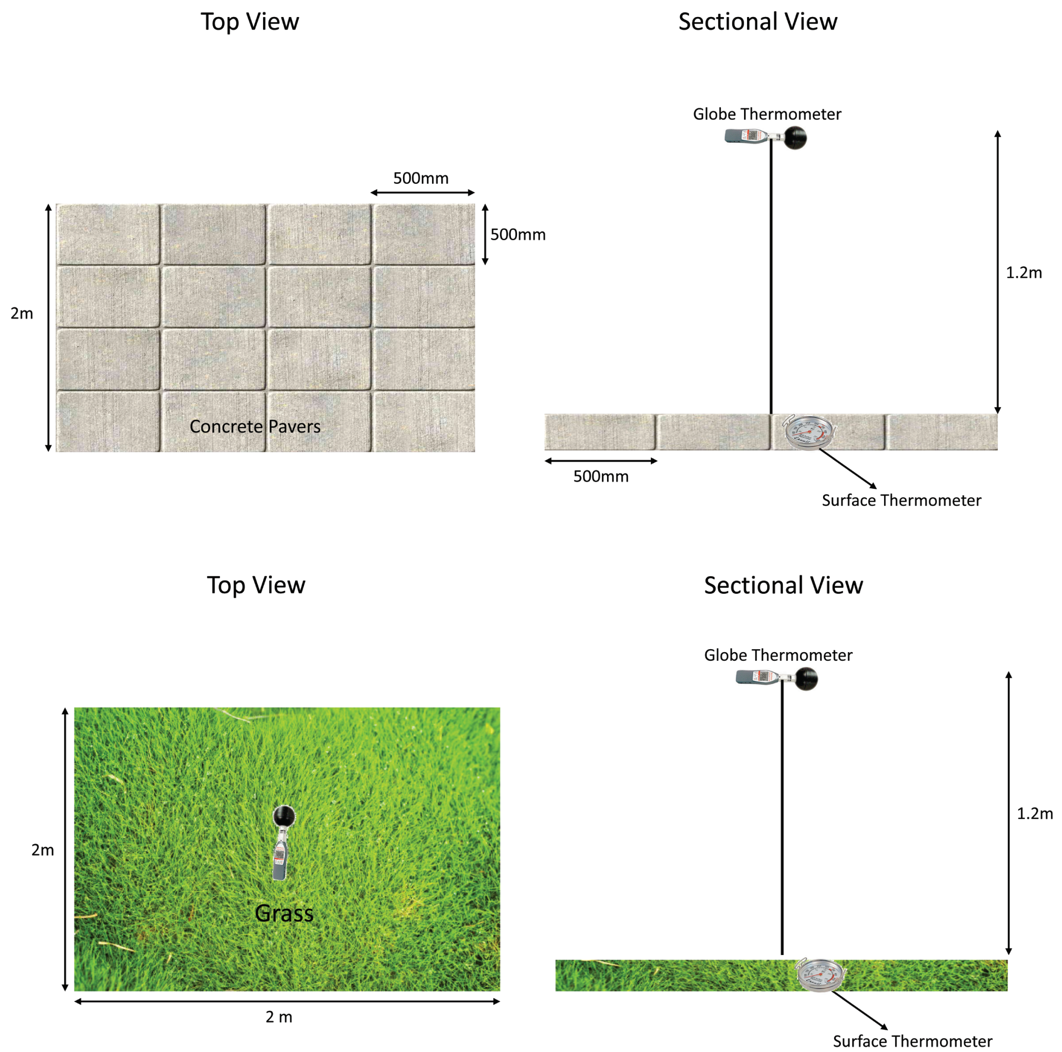

Figure 1. Illustrations (not drawn to scale) showing plots used to measure surface and globe temperatures over concrete and grass.

black sphere together with a type K thermocouple and a 1.5-m cable (Testo, Sdn. Bhd. Malaysia; model 0602 0743) attached to an IAQ data logger (Testo, Sdn. Bhd. Malaysia; model 0577 0400). The experimental design was similar to that of Armson et al. (2012).

Larger Extent of Vegetation (in a Park) and the Urban Heat Island Effect

Maximum daytime temperatures were recorded alongside surface and globe temperatures on hot, sunny days with the intent of understanding if larger green areas will positively impact on the UHI effect. Diurnal measurements were made thrice each month across the experimental period, and the recordings included a 4,050-m^2 field, a basketball court comprised of a concrete surface measuring 30 × 15 m, and a 2-m-wide pedestrian walkway made of asphalt that was flanked by turf. Measurements were recorded both in full sun and in shade provided by trees.

The same 41382LF2 temperature/humidity sensor coupled with a data logger (Scientific Sales, Inc. NJ, USA) was mounted at a height of 1.2 m, placed perpendicular to the surface, and used to determine the temperature of hard surfaces. Surface temperatures of the field were determined with a temperature meter coupled with a probe that was inserted some 8 to 10 mm into the soil. This was done to avoid direct solar radiation that might alter the results. Three measurement points, each across hard and field surfaces, were used.

For globe temperatures, a 5-min average temperature was recorded using a thermometer set on a stand at a height of 1.2 m positioned at three sites within each surface type. For air temperatures, the 41382LF2 temperature/humidity sensor coupled with a data logger was used to determine temperature readings above each surface type and also at 6 urban locations outside the park. These 6 measurement points were selected to ensure that the data collected represented the entire external park setting. The readings were made at a height of 1.2 m, and a 5-min average temperature was recorded.

RESULTS

Small Patches of Vegetation

Mean surface temperature data over a 3-month period in 2017—namely, February, June, and December—is presented in Figure 2. These months were selected as they represented warm temperatures, very hot temperatures, and a period of highest precipitation, respectively. Given the highly uniform climate in the tropics, the fluctuations in the diurnal temperature were not pronounced except for a slight elevation in surface temperatures between 12:00 and 14:00 hrs (Figure 2). Therefore, in general, the data for surface temperatures was observed to be constant across all 3 months.

The data was subjected to analysis using one-way ANOVA. The concrete surface exposed to the sun was always warmer and reaching a peak of 53 °C in June, which is typically the warmest month in the year. Conversely, the same hard surface set in the shade displayed a maximum temperature of 48 °C, which was some 5 °C lower than the results for the same surface type exposed to solar radiation (Figure 2). The surface temperature when turf was present was found to be greatly reduced. This was especially pronounced when shade and turf were present (Figure 2). Surface temperatures for shaded turf surfaces in the warmer months of February and June were found to be close to the prevailing air temperatures (Figure 2a and 2b). The maximum surface temperature for the warmest month of June for surfaces covered in turf and exposed to solar radiation was some 43 °C. When this was compared to a hard surface also exposed to the sun, there was a 10 °C reduction in temperature when vegetation was present. Comparatively, a turf surface in the shade had peak temperatures of around 36 °C. The difference between a shaded hard and a shaded vegetated surface was far greater with a 12 °C reduction (Figure 2) in temperature.

To confirm that the data observed in Figure 2 is not a result of abnormal temperature conditions in that particular year, the study also took into account the long-term relationship between surface and air temperatures across hard and vegetated surfaces that were exposed to sunny and shaded conditions (Figure 3). In general, the data exhibited similar results to what was observed in Figure 2, where the warmest surface was concrete exposed to solar radiation, with mean temperatures peaking at 44.6 °C in 2017 (Figure 3). Conversely, vegetated surfaces exposed to sun had mean temperatures peaking at 36 °C in the same year (8.6 °C difference)(Figure 3). Data for shaded conditions also indicated peaked readings in 2017. Mean temperatures were 36 and 30.2 °C for hard and vegetated surfaces, respectively. Though smaller, one-way ANOVA still showed a significant 5.8 °C difference ($P \leq 0.02$), indicating the benefit of temperature reduction when vegetation is present (Figure 3).

The temperature trends for globe thermometers were similar to those for surface temperatures. This was to be expected given the fairly uniform ambient temperatures experienced in the tropics. It is, however, important to look at globe temperatures because of the high humidity present in the tropics. This data will serve as a means of assessing the combined effects of radiation, air temperatures, and air velocity on human comfort. Temperature results of the globe thermometers in the months of February, June, and December in 2017 are presented in Figure 4.

Similar to surface temperatures, globe temperatures rose from a minimum around dawn to reach a maximum at noon and gradually decline. Unlike surface temperatures, globe temperatures tended to reach higher temperatures more swiftly and, by 14:00 hrs, had started to decline. This was potentially a result of cloud cover or strong gusts of wind. Conversely, with surface temperatures, there were still increases observed at 14:00 hrs.

Similar to surface temperature, the concrete surface exposed to the sun was always warmer, reaching a peak of 59 °C in June, which was 6 °C warmer than surface temperature (Figure 4). Data for hard surfaces set in the shade displayed a maximum temperature of 54 °C, which was some 6 °C higher than the results for surface temperature (Figure 4). With turf present, the maximum globe temperature for sun-exposed and shade conditions were 49 and 42 °C, respectively.

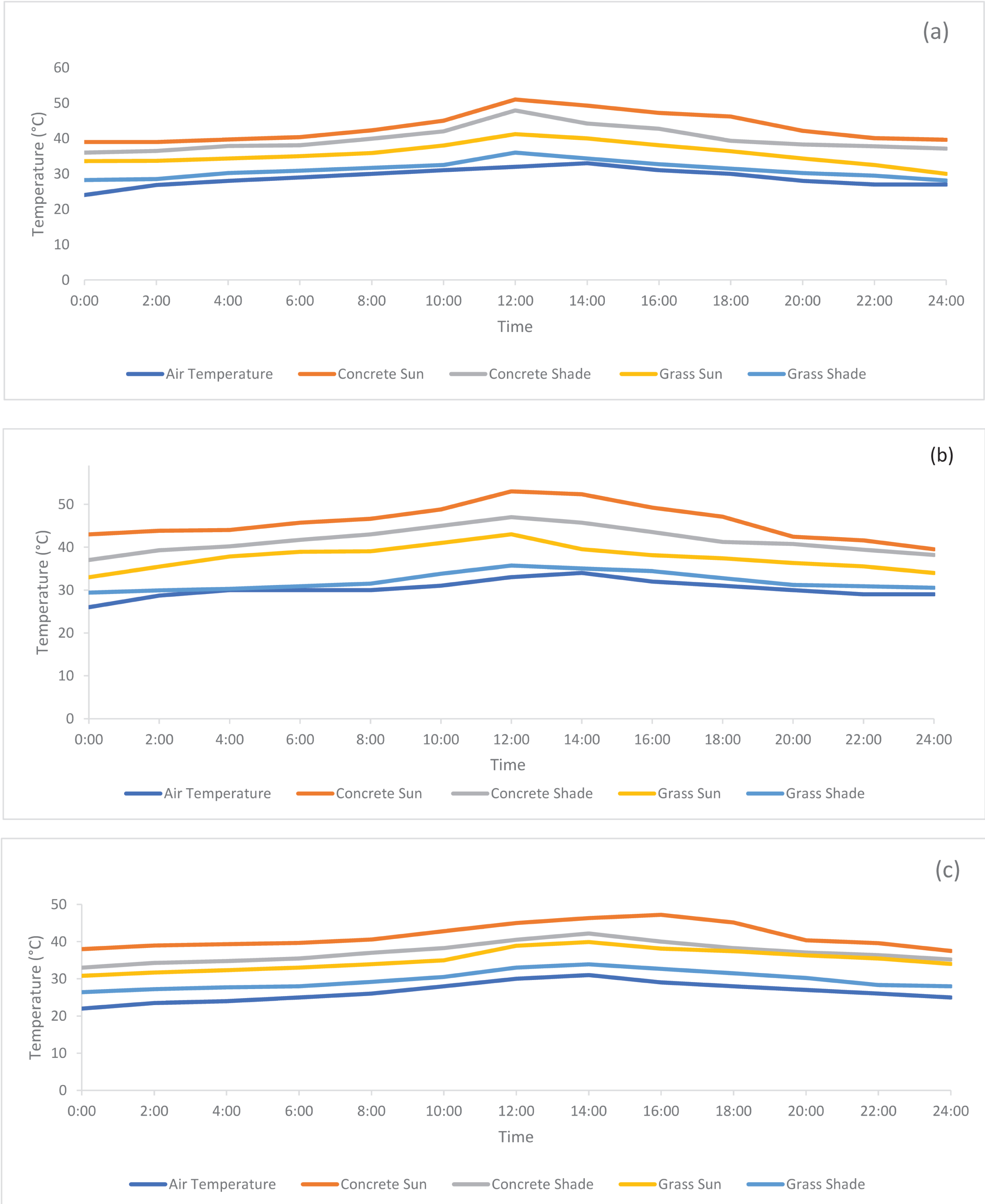

Figure 2. Mean diurnal variation of surface temperature over concrete and grass in sun and shade coupled with the prevailing local temperature in (a) February, (b) June, and (c) December of 2017.

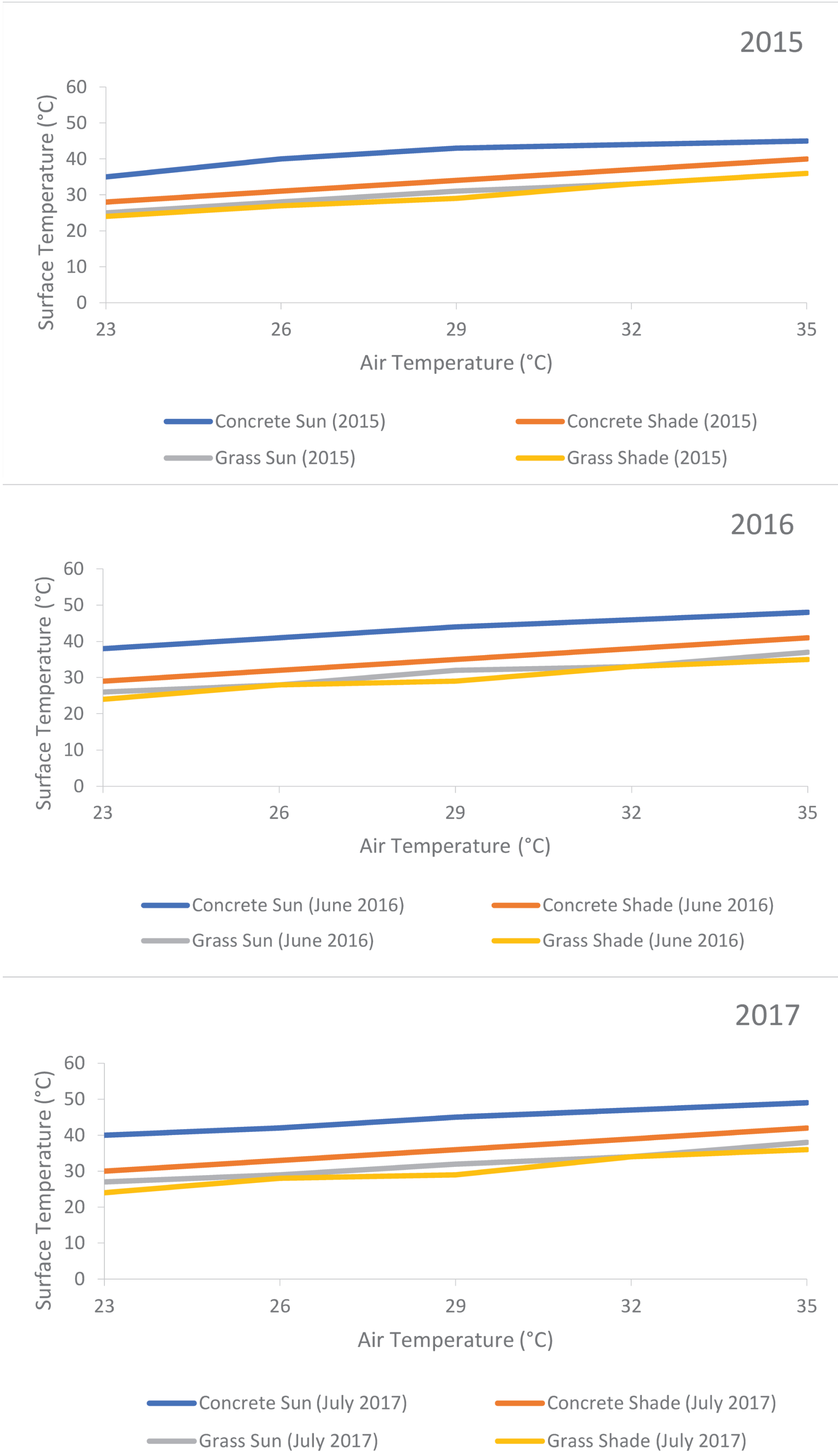

Figure 3. Relationships between air and surface temperatures over concrete and grass under sun and shade across a 3-year period (2015–2017).

Figure 4. Mean diurnal variation of globe temperature over concrete and grass in sun and shade coupled with the prevailing local temperature in (a) February, (b) June, and (c) December of 2017.

Similarly, in both instances, a 6 °C increment was observed when compared against surface temperatures (Figure 4).

Another difference observed between globe and surface temperatures was that the shaded turf surfaces in all 3 months were found to be higher than the prevailing air temperatures (Figure 4). The largest temperature difference (8.3 °C) for globe temperatures was found to be between surfaces covered in turf as opposed to concrete exposed to solar radiation (Figure 4). When this difference was compared to surfaces in the shade, there was a 7.5 °C variation in temperature (Figure 4). This outcome highlights the benefits of vegetation in mitigating the effects of solar radiation. Comparatively, the difference in globe temperatures on concrete for sun and shaded conditions was 4.7 °C while that for vegetated surfaces (sun vs. shade) was 5.6 °C (Figure 4). This indicated the benefit of shade on outdoor human comfort.

The globe temperature data was analysed in the same way as the surface temperature data. The aim was to show the long-term relationships between globe and air temperatures (Figure 5). It was expected that a weak correlation would be seen as, typically, in such environments where the climate is fairly uniform with very little month-to-month variation in temperature, a

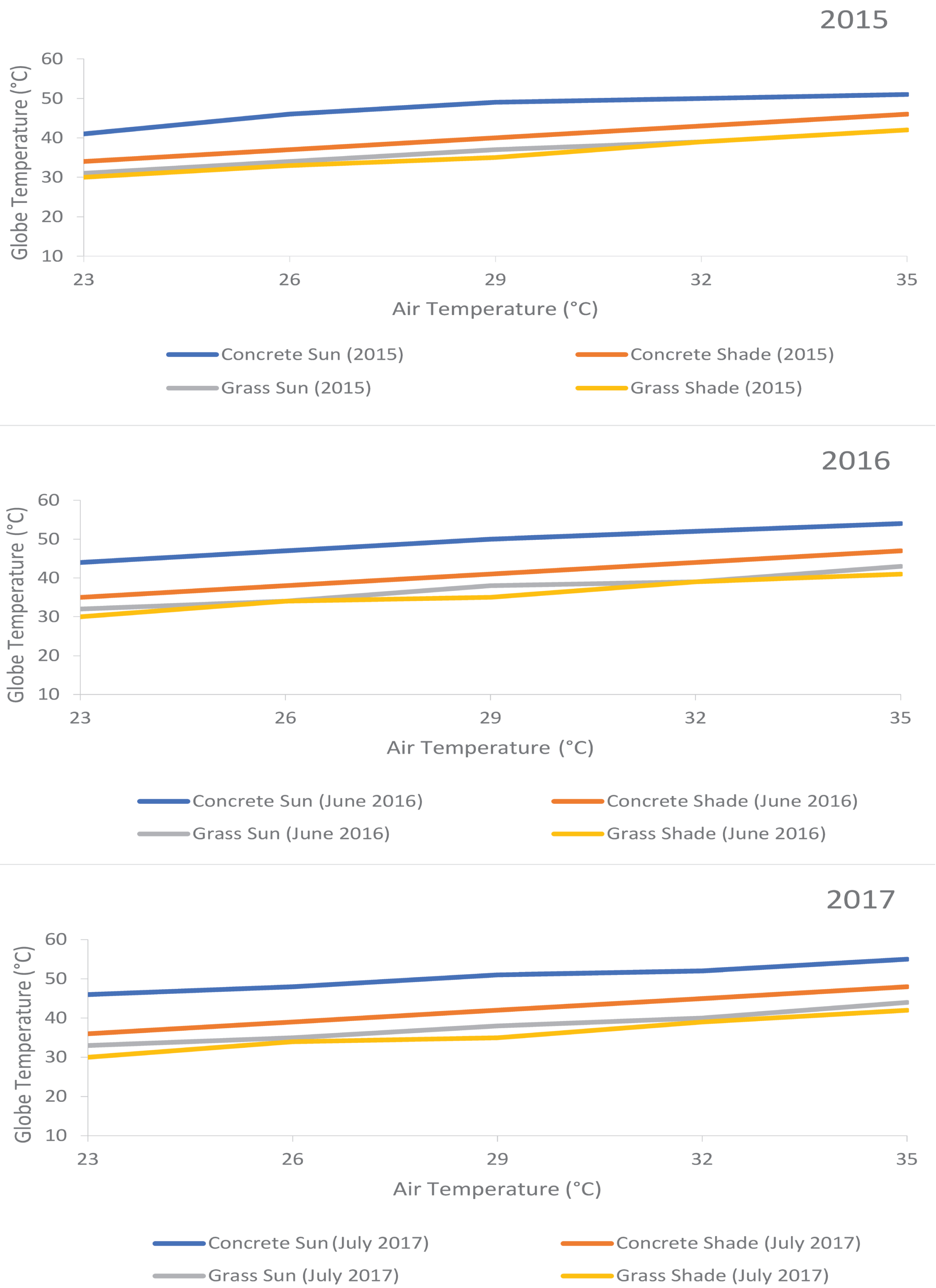

Figure 5. Relationships between air and globe temperatures over concrete and grass under sun and shade across a 3-year period (2015–2017).

strong relationship will be unlikely across the experimental period. However, such data is still of significance as it indicated that the surface and globe data collected was not an outcome of abnormal or extreme ambient conditions (during the experimental period). In general, the data was similar to that in Figure 3. The warmest surface was concrete exposed to solar radiation with mean temperatures peaking at 50.4 °C in 2017 (Figure 5). This was a 5.8 °C increase from surface temperatures. Conversely, vegetated surfaces exposed to sun had mean temperatures peaking at 42 °C in the same year (a 4 °C differential from surface temperatures)(Figure 5). Mean temperatures in the shade were 42 and 36 °C for hard and vegetated surfaces, respectively. The outcome of the ANOVA analysis indicated a smaller but still significant difference ($P \leq 0.01$) of 8.4 and 6 °C for hard and vegetated surfaces, respectively, when compared against similar surface types exposed to full sun (Figure 5).

Larger Extent of Vegetation (Park)

The difference between the temperature in the park and the temperature outside the park was calculated (Figure 6a). Paired *t*-tests showed that in all cases, air temperatures were lower within the park than outside. Air temperatures in the park were significantly cooler than the urban air temperature by 4.5 to 8 °C across the various surface types when exposed to solar radiation. Conversely, under shaded conditions, the temperature differential was between 3 and 7.5 °C. Temperatures in the shade were on average 1.2 °C lower than in the sun and 6.1 °C lower than external air temperatures.

Mean differences between the surface types and sun/shade conditions on park air temperature were determined through a two-way ANOVA (Figure 6a). The analysis indicated significant differences in surface types ($F = 31.015$, $P = 0.004$) and sun/shade ($F = 29.043$, $P = 0.003$) conditions.

Mean differences between the surface temperatures in the park and the air temperatures outside are presented in Figure 6b. To determine the effects of surface types and sun/shade conditions on surface temperatures, a two-way ANOVA was used. The analysis indicated significant differences in surface types ($F = 38.825$, $P \leq 0.005$), and sun/shade ($F = 36.680$, $P \leq 0.005$) conditions had significant interactions ($F = 42.920$, $P \leq 0.005$). Shade decreased temperatures for all surface types with a decrease of between 1.1 and 1.8 °C (Figure 6b). The effect of shading was most pronounced on asphalt as opposed to turf and concrete. The concrete and asphalt were warmer than turf by 8% and 39%, respectively (Figure 6b).

Mean differences between globe temperatures in the park and the air temperatures outside it are presented in Figure 6c. To determine the effects of surface types and sun/shade conditions on globe temperatures, a two-way ANOVA was used. The analysis indicated significant differences in surface types ($F = 27.127$, $P = 0.002$) and sun/shade conditions ($F = 35.40$, $P \leq 0.005$). Shade decreased temperatures for all surface types with a decrease of between 0.5 and 1.8 °C (Figure 6c). The benefit of shading was most pronounced on asphalt and concrete. This was important as asphalt and concrete were warmer than turf by 72% and 68%, respectively (Figure 6c).

DISCUSSION

Surface Temperatures

Hard surfaces exposed to the sun heated up more as opposed to surfaces covered with vegetation. With smaller patches of vegetation, the concrete exposed to solar radiation rose and peaked at 53 °C while the effect of shade on surface temperatures on the same surface type was observed to be 5 °C cooler. Turf in full sun had peak temperatures of 43 °C; comparing this to concrete also exposed to full sun, the temperature was 10 °C cooler with the presence of vegetation (Figure 2). A combination of shade and turf exhibited surface temperatures that were consistent with prevailing temperatures. This was suggestive that the combination of shade and turf was able to significantly control surface temperatures. With a larger extent of vegetation (e.g., park), the air temperature differential across all surface types was found to be cooler in the park as opposed to the external urban environment. In full sun, the air in the park was some 4.5 to 8 °C cooler than the surrounding urban air (outside the park)(Figure 6a). Essentially, areas of the park with shade would contribute to temperatures that were approximately 6 °C cooler than the surrounding urban air. Our findings are similar to those of Armson et al. (2012), where less cooling was observed over a larger extent of vegetation (park) as compared to smaller patches. This was to be expected in parks as part of the solar energy would be converted into sensible heat (Bastiaanssen 2000; Jung et

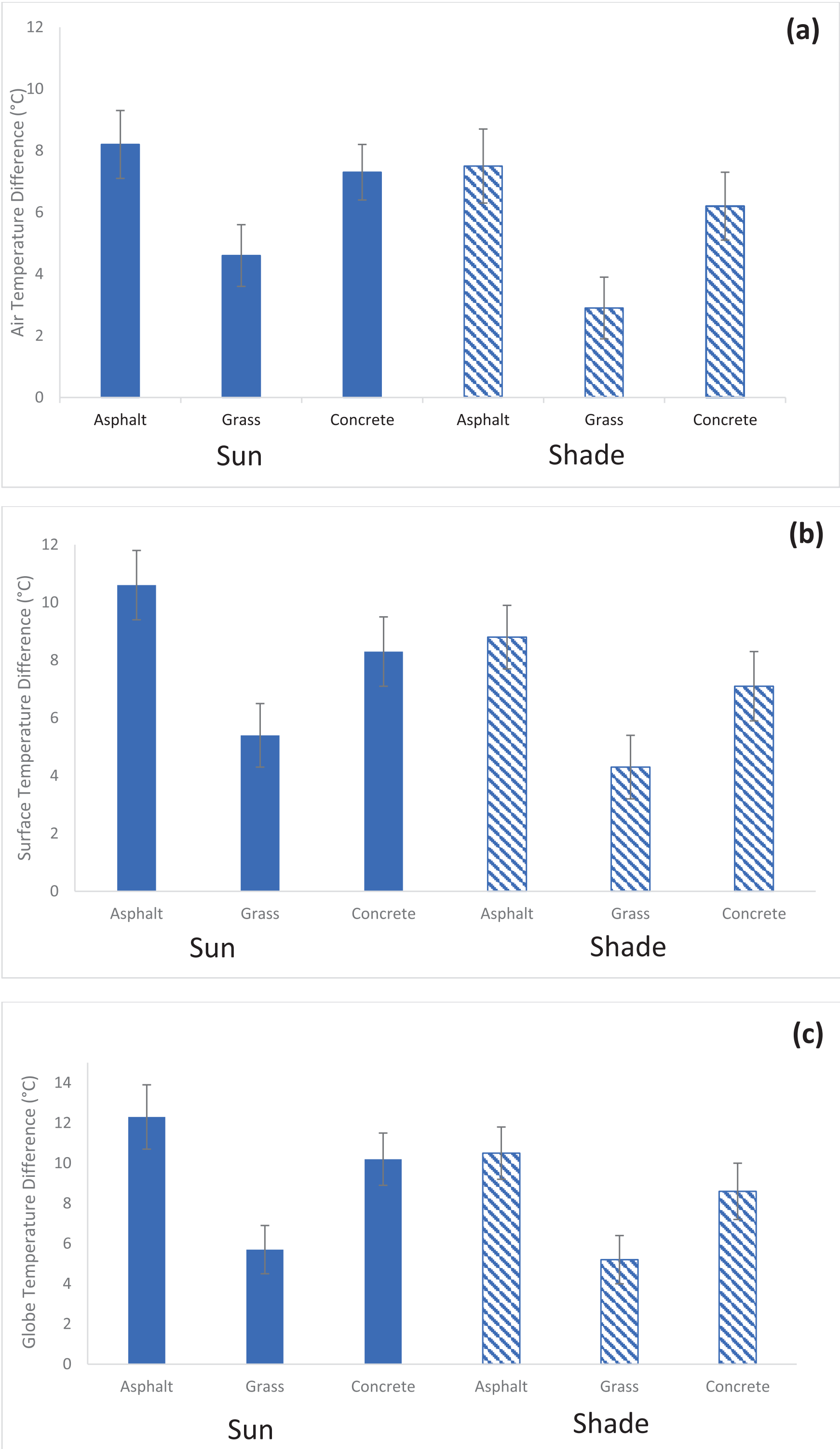

Figure 6. Mean differences between (a) air, (b) surface, and (c) globe temperatures for a large green space (park) and external park (urban) environment.

al. 2011). By contrast, in smaller plots, enhanced cooling was possible due to the buildup of a microclimate, which was cooler than the surrounding air. This is usually achieved through the flow of warm air from the surrounding areas into the plot by means of advection. This, in turn, increases evapotranspiration and cools the plots (oasis effect)(Georgescu et al. 2011). These results have, therefore, confirmed that increasing the presence of small green spaces in urban areas can mitigate the UHI effects. In fact, the data is suggestive that many small patches of turf will be more effective than one large area of vegetation (e.g., park). Still, more intense and concurrent observations of surface temperatures across small and larger turf plots would be necessary to validate this finding.

Shading through tree canopies is another approach to cool surface temperatures. Although the impact of shading on surface temperatures was 50% less as compared to the presence of vegetation, the combination of shade and vegetation within small plots was found to be most effective. This finding was consistent with that of Bowler et al. (2010). It was observed that shade in a park was able to reduce surface temperatures across all surface types by 1.1 to 1.8 °C (Figure 6b), and the reduction was most pronounced over asphalt. This outcome supports the planting of trees coupled with careful selection of canopies that can maximise the potential for shade as a practical solution to mitigate the UHI in cities. Some recent research has, in fact, confirmed that urban trees are more useful than turf in UHI mitigation because trees have higher evapotranspiration rates than an equivalent area of turf (Onishi et al. 2010; Ng et al. 2012). However, other research had reported otherwise (Peters et al. 2011). Nevertheless, because the cooling effect of trees comes primarily from transpiration, a reliable estimate of the cooling effect will be to measure leaf temperatures across the entire canopy or, better still, obtain transpiration rates, which we will consider in future work. In a recent review by Nuruzzaman (2015), it was concluded that across green roofs, shade trees, green vegetation, and water bodies, the most effective and least costly strategy to mitigate UHI was that of green vegetation. Therefore, it is apparent that the implementation of trees and turf would be beneficial to mitigate the UHI over having just one or the other.

Globe Temperatures

It was important to study globe temperatures because of the high temperature and humidity in the tropics, which will impact on outdoor thermal comfort. Generally, the outcomes were similar to surface temperatures. Globe temperatures rose from dawn, peaked at noon, and gradually declined. The difference between globe and surface temperatures was that surface temperatures continued to increase until 14:00 hrs while globe temperatures started to decline at 12:00 hrs (Figure 4). Interestingly, a consistent 6 °C increase in globe temperatures was found across all surface types as well as sun and shade conditions when compared against surface temperatures (Figure 4). Additionally, the data for globe temperatures indicated that the effect of shade and turf was less pronounced as the temperature readings were consistently higher than the prevailing air temperatures (Figure 4). This was different from surface temperatures where the presence of shade and turf resulted in temperature readings that were fairly similar to prevailing air temperatures.

The effect of shade in mitigating the effects of UHI should not be neglected, where the temperature reduction was between 4.7 and 5.6 °C when shade was available (Figure 4). A temperature reduction of between 8 and 10 °C was observed for turf, indicating that vegetation had a key role in heat mitigation strategies (Figure 4).

The temperature differential between globe and surrounding urban air temperature for a park indicated that shade was able to reduce temperatures within the park by 0.5 to 1.8 °C across all surface types (Figure 6c). These reductions were provided by the canopy cover of trees in the park, which would have facilitated the reduction in short wave penetration (Rizwan et al. 2008). This was most pronounced with asphalt and concrete. Apart from the beneficial effects of shade, the data also ascertained the benefits of turf because asphalt and concrete were found to be on average 70% warmer than turf (Figure 6c). Lastly, we are not aware of much research, especially within a tropical urban context, that has studied the effects of shade and vegetation on temperature. We are not suggesting that the results can be applied across all urban sites given the variable conditions such as urban typologies and the wind environment, but the results provide valuable insights into the diurnal temperature environment for plots of smaller and larger extents of greenery. Direct and relative measures of various tree and grass species will most accurately elucidate the effectiveness of cooling through shade and vegetation.

CONCLUSIONS

These results support the importance of turf in cooling urban areas and mitigating the UHI. Furthermore, they confirmed that many small green plots will be more effective than the implementation of larger green spaces. However, it is noteworthy that grasses tend to be highly susceptible to drought and unhealthy turfgrasses will not be able to contribute to the cooling effect (Bohnenstengel et al. 2011). Conversely, trees have deeper root systems and are expected to be more resistant to drought (Engelbrecht and Kursar 2003). Therefore, trees will be an ideal replacement for turf in urban conditions where foot traffic is high or when vehicular loading requirements must be met.

From a city perspective, trees would be considered more effective than turf at providing cooling simply on the basis that the area of shading especially for large, mature specimens will be far larger than the actual footprint of the tree (Bohnenstengel et al. 2011). The presence of tree canopies and green roofs in urban cities is important as it impacts on human thermal comfort and can help mitigate the effects of UHI (Middel et al. 2015). For example, studies in Singapore have shown that in highly built-up areas, the temperature was on average 7 °C warmer than rural areas. This warmer temperature is generally brought about by the heat emitted from vehicles and air conditioning units. Apart from trees and grasses, research has shown that plants cladded to the façade of buildings and reflective roofs can improve outdoor thermal comfort (within a 4-m radius)(Cheng et al. 2010). By contrast, other reports have shown that trees may not be the most ideal option in improving outdoor thermal comfort. This is because they tended to reduce wind speeds and increase humidity (Mochida and Lun 2008). The reality, however, is that as ambient temperatures rise beyond 28 °C (in the tropics), people will seek shade to reduce the discomfort brought about by heat (Wong and Yu 2005). Our findings here have showed that shading can reduce globe temperatures by 5 °C and surface temperatures by 5 to 12 °C. This is good evidence to support the role shade from trees will have in improving outdoor thermal comfort. Additionally, the combined effects of turf and shade will yield the most ideal outcome for mitigating the UHI effect.

Lastly, similar studies should be conducted in temperate regions for comparative analysis. It is also important to consider the tree species used to maximise the potential for shade (e.g., wide-spreading and dense canopies over those that produce small and sparse foliage). In addition, future work may wish to consider the requirement for fast-growing species (Wang et al. 2016). We noted that there had been little research focused on the shadow cast by various trees as well as those from buildings in urban areas. These are important, as they can have an impact on localised cooling, and work in these areas should be considered in future studies.

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Résumé. Le processus d'urbanisation augmente la température et modifie le confort thermique des villes. Les îlots de chaleur urbains (ICUs) sont la conséquence de la hausse des températures ambiantes. Par exemple, dans l'île densément peuplée de Singapour, l'intensité des ICU était de l'ordre de 4.5 °C. Une telle élévation de la température peut affecter négativement le confort thermique à l'extérieur et résulter en de sérieux problèmes de santé. La présente recherche examine les bienfaits des arbres et du gazon en tant que stratégies d'atténuation pour les zones urbaines. Des observations à court et à long terme furent effectuées au thermomètre-globe et de surface sur de plus petites parcelles de végétation et de surfaces dures tant sous l'ombrage d'arbres qu'en plein soleil. Des observations similaires furent analysées pour une vaste étendue de végétation parsemée de béton, d'asphalte et de gazon à l'intérieur d'un parc urbain. La présence de gazon et d'ombre projetée par les arbres influence la température des surfaces et cet impact est encore plus prononcé lorsque les deux éléments sont combinés. La présence du gazon a réduit les températures de surface jusqu'à 10 °C, tandis que l'ombre des arbres générait une réduction de 12 °C. Avec le thermomètre-globe, la présence de gazon et d'ombre des arbres diminuait les températures de 5 à 10 °C. Ces résultats suggèrent que le gazon et les arbres peuvent efficacement rafraîchir les surfaces et améliorer le confort thermique à l'extérieur. Les résultats de cette étude peuvent être mis en application pour la planification urbaine de la verdure et peuvent être utilisés comme référence pour d'autres villes tropicales possédant des climats similaires et cherchant à développer des mesures d'atténuation en vue d'améliorer le cadre de vie urbain au sein de leurs villes.

Zusammenfassung. Der Prozeß der Urbanisierung fördert den Temperaturanstieg und verändert den thermalen Komfort in den Städten. Urbane Hitzeinseln (UHIs) resultieren aus dem Anstieg der angenehmen Temperaturen. Zum Beispiel betrug die UHI in dem dicht besiedelten Inselstaat von Singapore so etwas um 4.5 °C. Solch ein Anstieg der Hitze kann draussen empfundenen thermalen Komfort negativ beeinflussen und könnte zum Anstieg von ernsten Gesundheitsproblemen führen. Diese Studie untersucht die Vorteile von Bäumen und Grasnarbe als Verminderungsstrategien für urbane Gebiete. Es wurden Kurz- und Langzeitbeobachtungen der Oberflächen- und globalen Temperatur über kleinen Flächen von Vegetation und versiegelten Flächen unter Einbeziehung von Beschattung durch Bäume und voller Sonneneinstrahlung gemacht. Vergleichbare Beobachtungen wurden über Flächen mit größerer Ausdehnung von Vegetation über Beton, Asphalt und Grasnarbe innerhalb einer urbanen Parkanlage untersucht. Die Präsenz von Grasnarbe und Schatten von Bäumen hatte großen Einfluss auf die Oberflächentemperaturen und der Effekt war am größten, wenn beides vorhanden war. Das Vorkommen von Grasnabe reduzierte die Oberflächentemperatur bis hin zu 10 °C, während Baumschatten zu einer Reduktion von 12 °C führte. Die globale Temperatur zeigte, daß die Präsenz von Grasnarbe und Schatten die Temperatur um 5-10 °C reduzieren kann. Diese Ergebnisse zeigen, daß Grasnarbe und Bäume effektiv die Oberflächen kühlen und den thermalen Komfort draussen verbessern. Die Ergebnisse dieser Studie können für urbane Planung von Grünanlagen angewendet warden und als Referenz für andere tropische Städte mit vergleichbarem Klima dienen, die auch bei der Entwicklung von Herabsetzungsmaßnahmen zur Verbesserung der Lebensqualität in den Städten funktionieren.

Resumen. El proceso de urbanización aumenta la temperatura y altera el confort térmico en las ciudades. Las Islas de Calor Urbano (UHIs, por sus siglas en inglés) dan lugar al aumento de las temperaturas ambientales. Por ejemplo, en el estado insular densamente poblado de Singapur, la intensidad de la UHI fue de unos 4.5 °C. Tal elevación en el calor puede afectar negativamente el confort térmico al aire libre y puede dar lugar a graves problemas de salud. El presente estudio investigó los beneficios de los árboles y el césped como estrategias de mitigación para las zonas urbanas. Se hicieron observaciones a corto y largo plazo para temperaturas superficiales y globales sobre parcelas más pequeñas de vegetación y superficies duras que involucran sombra de árboles y sol pleno. Observaciones similares se hicieron sobre una extensión de vegetación mayor a través de hormigón, asfalto y césped dentro de un entorno de parque urbano. La presencia de césped y sombra de los árboles afectó en gran medida las temperaturas superficiales y el efecto fue más pronunciado cuando ambos estaban presentes. La presencia de césped redujo las temperaturas de la superficie hasta en 10 °C, mientras que la sombra de los árboles condujo a una reducción de 12 °C. Las temperaturas globales mostraron que la presencia de césped y sombreado redujo las temperaturas entre 5 y 10 °C. Estos resultados sugieren que el césped y los árboles pueden enfriar eficazmente las superficies y mejorar el confort térmico al aire libre. Los resultados de este estudio se pueden aplicar a la planificación urbana de la vegetación y se pueden utilizar como referencia para otras ciudades tropicales con climas similares que también están trabajando para desarrollar medidas de mitigación para mejorar la habitabilidad de sus ciudades.