

Vegetation Placement for Summer Built Surface Temperature Moderation in an Urban Microclimate

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Abstract Urban vegetation can mitigate increases in summer air temperature by reducing the solar gain received by buildings. To quantify the temperature-moderating influence of city trees and vine-covered buildings, a total of 13 pairs of temperature loggers were installed on the surfaces of eight buildings in downtown Toronto, Canada, for 6 months during the summer of 2008. One logger in each pair was shaded by vegetation while the other measured built surface temperature in full sunlight. We investigated the temperature-moderating benefits of solitary mature trees, clusters of trees, and perennial vines using a linear-mixed model and a multiple regression analysis of degree hour difference. We then assessed the temperature-moderating effect of leaf area, plant size and proximity to building, and plant location relative to solar path. During a period of high solar intensity, we measured an average temperature differential of 11.7 °C, with as many as 10–12 h of sustained cooler built surface temperatures. Vegetation on the west-facing aspect of built structures

provided the greatest temperature moderation, with maximum benefit (peak temperature difference) occurring late in the afternoon. Large mature trees growing within 5 m of buildings showed the greatest ability to moderate built surface temperature, with those growing in clusters delivering limited additional benefit compared with isolated trees. Perennial vines proved as effective as trees at moderating rise in built surface temperature to the south and west sides of buildings, providing an attractive alternative to shade trees where soil volume and space are limited.

Keywords Microclimate · Built surfaces · Urban heat island (UHI) · City trees · Perennial vines · Strategic placement

Introduction

Many urban municipalities are incorporating climate change adaptation strategies and energy conservation initiatives into requirements for new developments (Hamin and Gurran 2009; Grimm et al. 2008). However, strategies for integrating climate resilience into existing urban neighborhoods are also necessary. Most city centers are dominated by built surface, an outcome of development practices that have systematically supplanted vegetation with pavement and buildings. The thermal properties of built materials differ greatly from those of vegetative cover. Built surfaces are typically low-albedo with a high capacity for energy storage (Oke 1978; Streutker 2003), whereas vegetation has a higher albedo, attenuates transmission of solar radiation, and can cool the immediate surroundings through evapotranspiration (Akbari et al. 2001). Within cities, trees and vegetated cover are both publicly and privately owned; however, many of their

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ecological services benefit all city inhabitants and therefore represent an important public asset (Lohr et al. 2004; Sawka et al. 2013). This is especially true of the ability of vegetation to moderate microclimatic air temperature (Akbari and Konopacki 2004; Huang et al. 1987; Simpson and McPherson 1996).

Inhabitants of densely settled urban centres are especially susceptible to the negative impacts of elevated summertime temperatures (Kershaw and Millward 2012). Cities in temperate regions are on average warmer than surrounding rural areas by 0.5–1.5 °C (Chen and Jim 2008). In large metropolitan areas, such as New York City, this difference can exceed 4 °C (Rosenzweig et al. 2006). This discrepancy in air temperature has increased with urbanization (Akbari et al. 2001) and is most significant on hot summer days with cloud-free evenings (Oke 1973). This inclination, termed the Urban Heat Island (UHI) phenomenon, occurs because built surfaces (pavement and buildings) absorb solar radiation during the day and transmit it back into the surrounding environs as thermal energy during the afternoon and early evening (Jim and Chen 2009; Voogt and Oke 2003).

McCarthy et al. (2010) argue that the UHI phenomenon can augment urban temperatures, which are already increasing due to global warming. These authors suggest that extreme heat events may be exacerbated by continued urbanization, the result of which could be temperature increases equivalent to doubling atmospheric CO₂. In the face of such warnings, the temperature-moderating benefits of urban vegetation offer one possibility for minimizing urban microclimatic warming, thus potentially decreasing city dweller's discomfort and reducing reliance on energy-intensive air conditioning.

Urban vegetation has the ability to modify a city's microclimatic temperature by various means, including: (1) reducing the conversion of radiant energy to sensible heat by shading built surfaces (e.g., concrete, asphalt); (2) absorbing and reflecting solar radiation; (3) cooling ambient air through evapotranspiration (exchange of latent heat); and (4) moderating wind speed (Federer 1976; McPherson 1984; Parker 1983). Each of these vegetation-induced adjustments affects microclimate in the immediate area, including that of built structures, which in turn influences human thermal comfort and the subsequent demand for indoor air conditioning (Miller 1997). For example, demand for indoor air conditioning was shown in a study by Akbari et al. (2001) to increase by 3–4 % for every 1 °C increase in ambient air temperature above 18 °C.

Species, size, condition, orientation, and distance from buildings as well as regular maintenance are key determinants of the shading potential of vegetation within the built urban environment (Donovan and Butry 2009; McPherson

and Rowntree 1993; Sawka et al. 2013). In densely developed urban cores, the type of vegetation (trees, shrubs, vines) is often dictated by space requirements for both canopy and roots (Craul 1992, 1999). Therefore, important consideration must be given to choosing a plant with characteristics that will deliver the desired temperature-moderating outcome while minimizing conflict with existing buildings and infrastructure. Tree and shrub species vary significantly in their form and structural characteristics, including leaf area and shading coefficient (Millward and Sabir 2010; Nowak 1996). Leaf area, for example, is of great importance in terms of solar control because of its high, positive correlation with vegetation shading potential and its association with increased evapotranspiration (Kenney 2000). Selecting a planting location that will maximize a tree's thermal-moderating benefits requires assessment of the suitability of the growing medium (e.g., soil volume and quality), identification of potential conflicts (e.g., overhead wires), and consideration of tree orientation with respect to a building. Active management of urban trees is also essential, as the value of many of their environmental services is determined by the health and size of the tree (Millward and Sabir 2011).

The purpose of this study is to increase understanding of the role of vegetation to moderate rise in summertime built surface temperatures. Where vegetation can serve to maintain cooler built surfaces, it can play an important role in mitigating heating of the urban microclimate. While recent research has focussed on the energy-saving benefits of vegetation to offset homeowner demand for energy-intensive indoor cooling (Akbari and Taha 1992; McPherson et al. 1997; Simpson and McPherson 1996; Sawka et al. 2013), few studies have assessed its role as a public asset that can moderate outdoor built surface temperature in densely built urban cityscapes. Therefore, our goal in conducting this research is to evaluate the summer temperature-moderating potential of urban vegetation by investigating built surface temperatures in relation to vegetation species-specific characteristics (i.e., size, leaf area), optimal placement (orientation and proximity to building), and the most effective planting patterns (individual trees vs clusters).

Methods

Study Site

Research was conducted at the University of Toronto, St. George Campus, which is located in the heavily urbanized core of Toronto, Canada (Fig. 1). This location was an ideal study site because it contained multiple large trees

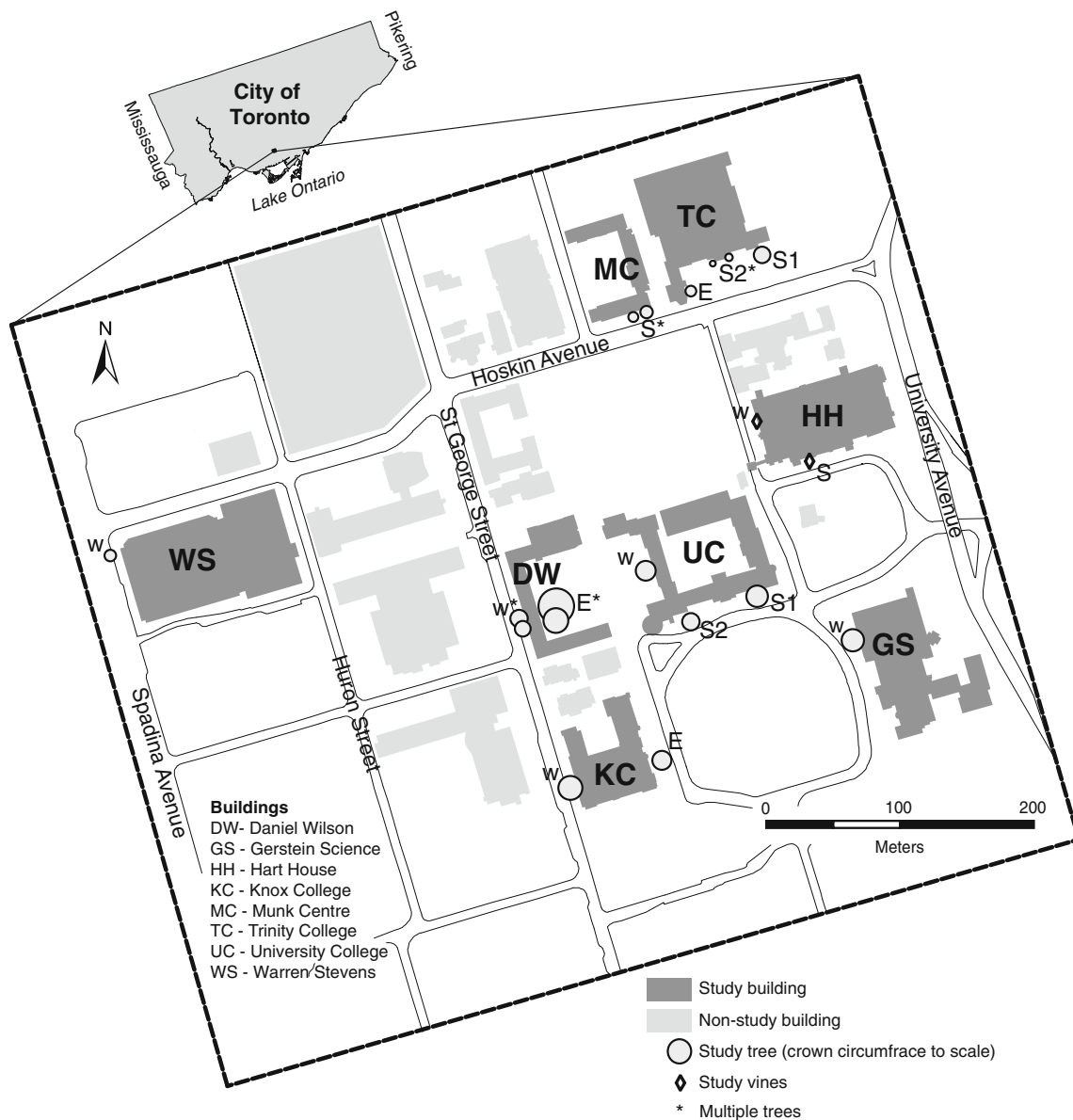


Fig. 1 Location of the study site (St. George Campus, University of Toronto) with investigated buildings and shade vegetation

growing in close proximity to built structures. In addition, several buildings were partially covered with the perennial vine, Boston ivy (*Parthenocissus tricuspidata*). Work in this study location also allowed us to evaluate the temperature-moderating properties of tree species common to Toronto’s downtown core, thus providing insight into the impact that the city’s current mix of trees provide.

Temperature loggers were deployed such that one logger in each pair was mounted to the building surface in the shade of vegetation while the other recorded built surface temperature in non-shaded conditions during peak solar access times (the time of day when insolation is most direct on built structures). Logger positions were concentrated on south- and west-facing aspects of two and three story

buildings, while two east-facing aspects were also examined to identify early-morning heating patterns. A total of 13 pairs were set-up, with paired loggers positioned on the same building to maintain consistency of aspect and building materials. In some cases, more than one pair of loggers was located on a single building, each pair on a different aspect.

Data Collection

The paired sampling approach was conducted using 26 WatchDog 100 Series temperature loggers (Spectrum Technologies Inc.). These loggers were selected for their accuracy ($\pm 0.6\text{ }^\circ\text{C}$), size, and memory capacity

(8,000 entries). Each logger was mounted directly to the building surface and then covered with a white louvered radiation shield (constructed of UV stabilized thermoplastic and measuring 15 cm × 15 cm at the point of wall contact). The radiation shields were designed to maximize surface albedo (reflectivity) so as to minimize the absorption of solar radiation and thus avoid artificially elevated temperature readings.

Although the loggers were factory calibrated (all loggers recording within 0.5 °C of each other), working with 26 individual instruments required optimal pairing prior to deployment. To accomplish this, all loggers were programmed to collect continuous data at 10-min intervals for 13 days, during which time temperatures varied between 4 and 26 °C. A multivariate correlation analysis of recorded data was then used to match two loggers with the greatest similarity; the resulting pairs were subsequently used in the study.

To maintain consistency, the paired loggers were positioned as close to 5 m above the ground surface as feasible. This elevation was selected because it approximated the elevation between floors on the middle of a two-story urban structure, while it also positioned loggers out of reach of potential vandals. All loggers were programmed to take synchronous temperature readings every 10 min from April 25 to November 3, 2008. This sampling period encompassed the peak temperatures of Toronto's summer months (usually June to August) and ensured that vegetation was leafed out (mid-May to mid-October). Individual loggers recorded 144 entries each day for 193 days, for a total of approximately 27,500 recordings each over the course of the study. Logger memory constraints dictated data download to a field laptop at four intervals throughout the study; this required that a logger was taken off-line for no more than 2 h before being placed back in its original building location.

General meteorological characteristics of the study site were measured using a Watchdog 2900ET meteorological station (Spectrum Technologies Inc.). Specifically, this station was designed to capture ambient air temperature (°C), relative humidity (%), incoming solar radiation (W/m²), and wind speed (m/s) at 10-min intervals that were synchronous with building logger measurements. The meteorological station was located within 1 km of the study site.

We collected individual tree characteristics at each logger pair location, including species, diameter at breast height (DBH), height, crown depth, crown width, drip-line area, leaf area index (LAI), distance from center-of-bole to the building wall, and orientation of the tree relative to the building. LAI was calculated using digital hemispherical images taken of each tree in mid-June (fully leafed-out canopies) (Millward and Sabir 2010). Four photographs (at

the four major cardinal directions and at half the bole–drip-line radius) were acquired for each tree in the early hours of the morning to ensure homogenous diffuse lighting conditions. HemiView 2.1 software (Delta-T Devices 1999) was used to process each photo and to estimate an average LAI value for each tree.

Analyses

Data Preparation

Temperature data were collapsed into 1-h intervals by recording the arithmetic average of the 10-min logger entries. We preferred a collection of high-frequency temporal measurements (every 10 min) to longer intervals as we wished to have our data reflect an integrated measure of temperature across a pre-defined time period, rather than simply bounding its ends (i.e., collecting one measurement every hour). For each of the 13 pairs, temperatures recorded by the shaded loggers were subtracted from those recorded by the full-sun loggers. Peak solar access time periods were assigned to each of the building orientations (east, south, and west aspect) based upon temperature difference analysis for the entire 6-month period.

Longitudinal Analysis

When using longitudinal data in a statistical analysis, particular methods are required to compensate for the presence of autocorrelation in the data structure (Chatfield 2003). Studies using repeated measures, such as temperature measurements obtained from the same logger at shorter time intervals, exhibit higher positive temporal autocorrelation than measurements taken further apart in time. In the same way, measurements obtained by the same logger (or pair of loggers) tend to be closer in value than measurements acquired from different loggers that are further apart (higher positive spatial autocorrelation) (Littell et al. 2006). In our study, a stratified time-based random sample was extracted from the population of temperature data for analysis using the statistical software package SAS (SAS/STAT Software 2012). Stratified sampling of the logger and month ensured that each of the loggers was represented and that the full data set was sampled for every analysis. Various SAS PROC MIXED procedures were fit in order to analyze the data set. Month was used as a CLASS variable in the model statement, and time (date/hours) in the REPEATED statement. Once run, estimate statements produced a series of probability values (*P* values) that assisted in interpreting the significance of model results. To avoid the bias that could be produced by standard regression and ANOVA models (Littell et al. 2006), an appropriate covariance structure was built into

the SAS PROC MIXED model used in subsequent analyses.

In addition, we used the spatial power structure of PROC MIXED, SP(POW), to accommodate unequal spacing in the data set present in some analyses. For example, analyses that focused only on daily solar access periods omitted temperature readings from the remainder of the day, creating unequal data sets. SP(POW) creates a simple generalization of the autoregressive structure in which the exponent of the correlation coefficient is calculated directly from distances between unequally spaced time points. For the spatial structure, the distance between observations is calculated from the data (data/time variable) rather than assuming it is at a constant distance. To account for variation between logger pairs and between buildings, we identified these terms as random effects and used the RANDOM statement in PROC MIXED (SAS/STAT Software 2012), which assumes that the logger temperature readings from all locations to which loggers and pairs were assigned in the study represent random samples from a normally distributed population.

Degree Hour Difference (DHD) Analysis

For each pair of temperature loggers, the difference between the sun-exposed and shaded loggers were integrated over the course of each day to determine temperature differential \times duration of the differential, expressed as DHD. DHD provides information on total thermal energy differences between sun and shaded microenvironments daily. Further, it permits an assessment of environmental variables that could explain the energy differential between sun and shaded logger pairs such as climatic conditions (i.e., solar radiation, ambient temperature, wind, relative humidity), aspect, and foliage characteristics. DHD was only calculated at time points where sun-exposed temperature exceeded shaded loggers, so these calculations did not include nighttime temperature data. DHD-22 was similarly calculated with a threshold of 22 °C (i.e., energy differential between sun and shaded loggers only where ambient air temperatures exceeded 22 °C). The rationale for this was that temperature differentials at high ambient temperatures have greater implications for energy use patterns (e.g., energy for air conditioning) than temperature differentials at low ambient temperatures (Akbari et al. 1997; Fountain et al. 1996).

An analysis of variance (ANOVA) was used to determine if there was any effect of aspect (i.e., if the tree is planted to the west vs south or east of a building) on this integrated daily shading benefit. The ANOVA was a mixed model with DHD as the dependent variable, aspect as an independent variable, and date as a blocking factor. Analysis was restricted to dates common to all temperature

logger pairs (i.e., excluding dates when data from one or more logger pairs were unavailable due to maintenance or logger failure). The full data set included May 6 to October 31, 2008.

Multiple regression analysis was used to determine the importance of climatic variables and tree characteristics as drivers of DHD. DHD values were log-transformed to improve fit to linear regression models. Correlation analysis between climatic variables was used to avoid inclusion of highly correlated, redundant variables in the final regression model. The multiple regression was a general linear model, derived using data from all logger pairs and all dates. DHD analyses were performed using SAS (SAS/STAT Software 2012).

Results

Tree Characteristics

A total of 17 trees representing 10 species were growing within our University of Toronto study site (Table 1). The most common was London plane (*Platanus \times acerifolia*; 4 trees), followed by honey locust (*Gleditsia triacanthos* var. *inermis*; 2 trees), silver maple (*Acer saccharinum*; 2 trees), and littleleaf linden (*Tilia cordata*; 2 trees). All other species were represented by a single tree. Eight of the seventeen trees were within 5 m of a building wall, whereas the remaining nine were found at distances greater than 5 m. Of those nine, three were growing at distances slightly greater than 10 m from the building, a proximity that, according to Carver et al. (2004), will provide only minimal direct shading benefits to the building structure.

LAI values ranged from 1.66 to 3.66 for all trees examined in the study. The green ash (*Fraxinus pennsylvanica* var. *lanceolata*) located at UC_W exhibited the highest LAI value (3.66), followed by the silver maple at KC_E (3.44), and the European white birch (*Betula pendula*) located at UC_{S2} (3.42). Tree shading coefficients ranged from 0.62 to 0.89, consistent with the range of 0.67–0.88 reported by Nowak (1996) for the same species. The littleleaf linden located at MC_S had the smallest shading coefficient (0.62). Species with high shading coefficients included white mulberry (*Morus alba*) (0.89; located at TC_{S1}), followed by London plane (0.84; located at DW_W) and green ash (0.80; located at UC_W).

Solar Path and Building Aspect

Daily peak solar access periods vary based on the aspect of the built structure, since the sun's path traces an east-to-west trajectory over the course of a day. Solar path also changes throughout the year, a variation that is latitudinally

Table 1 Characteristics of study trees

Location	Common name	Scientific name	Tree center to building (m)	DBH (cm)	Crown diameter (m)	Height (m)	Crown volume (m ³)	LAI	Drip-line area (m ²)	Outer surface area of Crown (m ²)	Shading coefficient
TC _E	Sugar maple	<i>Acer saccharum</i>	3.5	20	8.4	12.0	273	2.9	55	241	0.67
KC _E	Silver maple	<i>Acer saccharinum</i>	9.9	60	15.4	24.9	2203	3.4	186	945	0.79
DW _{Ea}	Siberian elm	<i>Ulmus pumila</i>	14.6	102	29.0	25.7	5200	2.4	658	2394	0.73
DW _{Eb}	London plane	<i>Platanus × acerifolia</i>	11.9	67	20.2	16.8	1615	1.7	320	1121	0.67
TC _{S1}	White mulberry	<i>Morus alba</i>	11.3	65	13.7	21.3	1405	2.9	146	704	0.89
TC _{S2a}	English oak	<i>Quercus robur</i> "Fastigiata"	4.9	57	4.7	16.6	121	3.1	17	138	0.81
TC _{S2b}	English oak	<i>Quercus robur</i> "Fastigiata"	3.3	59	5.7	21.7	243	3.0	25	223	0.81
UC _{S1}	Honey locust	<i>Gleditsia triacanthos</i>	7.6	48	17.7	17.7	1321	2.2	245	938	0.71
UC _{S2}	European white birch	<i>Betula pendula</i>	10.4	14	8.0	10.9	223	3.4	50	212	0.70
MC _{Sa}	Littleleaf linden	<i>Tilia cordata</i>	3.4	45	9.7	15.5	524	2.6	74	364	0.62
MC _{Sb}	Littleleaf linden	<i>Tilia cordata</i>	3.5	41	8.0	16.3	358	2.8	50	279	0.56
WS _W	Honey locust	<i>Gleditsia triacanthos</i>	4.1	37	13.1	11.8	673	2.2	135	475	0.77
KC _W	Silver maple	<i>Acer saccharinum</i>	8.5	105	19.4	32.3	3525	2.2	296	1318	0.72
UC _W	Green ash	<i>Fraxinus pennsylvanica</i>	8.5	70	15.8	19.6	1686	3.7	196	819	0.80
GS _W	London plane	<i>Platanus × acerifolia</i>	5.4	69	17.7	18.5	1339	2.3	246	946	0.72
DW _{Wa}	London plane	<i>Platanus × acerifolia</i>	3.4	58	14.3	18.4	1289	1.9	159	681	0.69
DW _{Wb}	London plane	<i>Platanus × acerifolia</i>	3.6	46	12.9	17.2	913	2.5	131	544	0.71

Subscripts a and b (TC and DW) denote two trees shading one temperature logger

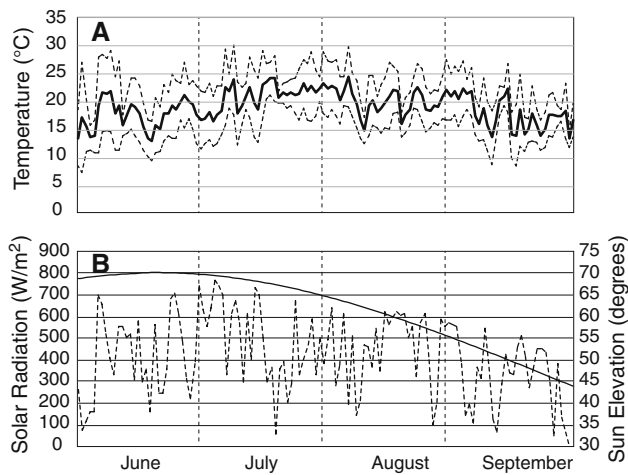


Fig. 2 **a** Solid line represents daily median temperature (°C); dashed line represents daily minimum/maximum temperature (°C). **b** Solid line represents daily maximum sun elevation (°); dashed lines represent daily median solar radiation (W/m²) (sunrise to sunset)

dependent (Fig. 2). Daily peak solar access periods were assigned based on the patterns observed daily throughout the 6-month period for each site, such that Period I consisted of the hours between 5:30 a.m. and 11:30 a.m. for east-facing sites; Period II, 11 a.m. to 4 p.m. for south-facing sites; and Period III, 3 p.m. to 8 p.m. for west-facing

sites. Temperatures recorded at east, south, and west aspects varied significantly in magnitude and according to time-of-day. During these peak periods, the temperature difference between paired sun and shade loggers was found to be statistically significant in more than half the cases (east-facing sites, 58 %; south-facing sites, 58 %; and west-facing sites, 63 %) (Table 2).

Daily Peak Solar Access Period I

Integrated average temperatures (shade and sun locations) measured on east-facing buildings were significantly warmer (1.5–2.3 °C) than those recorded on west-facing buildings from May to August. From May to September, south-facing buildings were significantly warmer (1.1–2.5 °C) than west-facing buildings. There was no difference in integrated average temperatures between east and south-facing walls.

Daily Peak Solar Access Period II

The exterior of east-facing buildings had significantly cooler integrated temperatures (1.8–3.3 °C) than those buildings facing south during May and from August to October. East-facing building exteriors were warmer in July (1.4 °C) than those of west-facing buildings. Similarly, south-facing

Table 2 Results of pre-specified hypothesis tests from the longitudinal mixed model

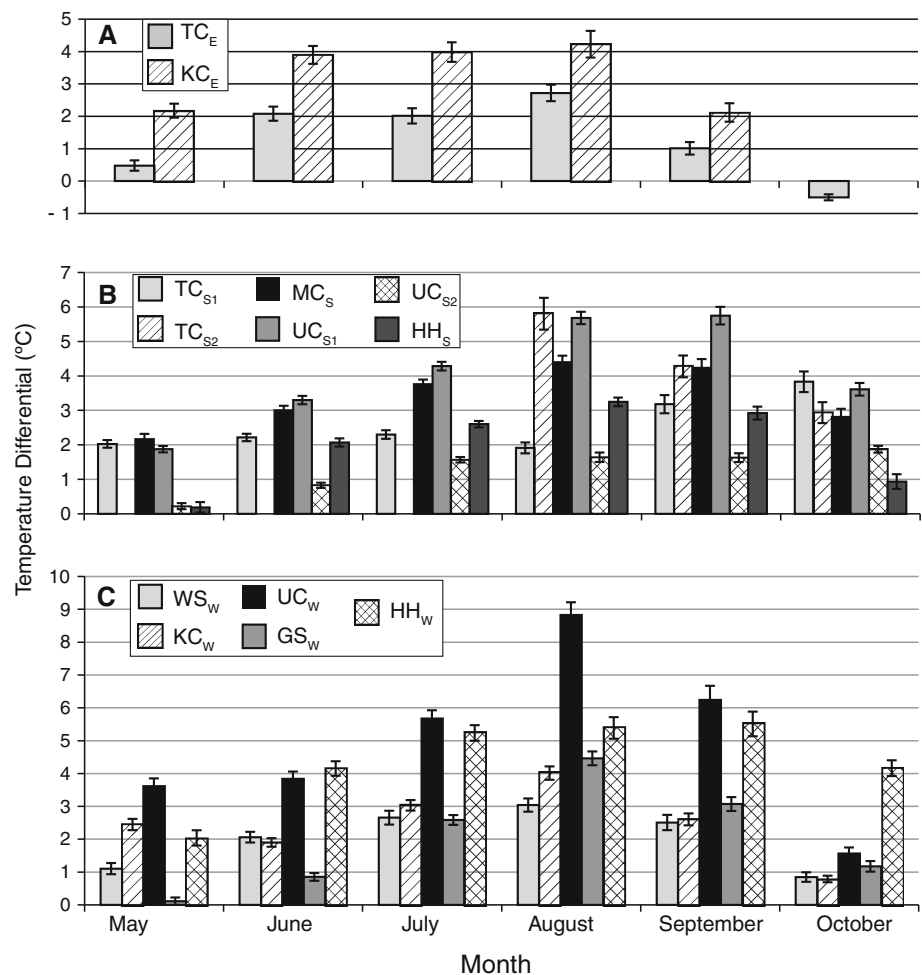
	May	June	July	August	September	October
5:30 a.m.–11:30 a.m.						
East to south	ns	ns	ns	ns	ns	ns
East to west	(+) 1.5*	(+) 2.3***	(+) 2.0***	2.3**	ns	ns
South to west	(+) 1.4*	(+) 1.1*	(+) 1.1*	(+) 2.5**	(+) 2.2**	ns
Shade to sun	ns	(-) 0.9*	(-) 0.7*	(-) 1.4*	(-) 1.1**	ns
11:00 a.m.–4:00 p.m.						
East to south	(-) 1.8*	ns	ns	(-) 2.1*	(-) 3.7**	(-) 3.3*
East to west	ns	ns	(+) 1.4*	ns	ns	ns
South to west	(+) 1.9*	ns	(+) 1.7**	(+) 2.9**	(+) 2.4*	ns
Shade to sun	ns	(-) 2.0***	(-) 2.3***	(-) 3.2***	(-) 2.6***	(-) 2.2***
3:00 p.m.–8:00 p.m.						
East to south	ns	ns	ns	ns	(-) 2.6**	ns
East to west	(-) 2.9**	ns	(-) 2.2**	(-) 1.6**	(-) 3.5***	ns
South to west	(-) 2.1*	(-) 1.4*	(-) 2.1***	(-) 3.1*	ns	ns
Shade to sun	(-) 1.0*	(-) 1.8***	(-) 2.5***	(-) 2.6***	(-) 2.7***	(-) 1.31***

Building orientation and the effect of shade vegetation on mean monthly temperature difference (°C) (shaded vs sun-exposed) for daily peak solar access periods

ns Non-significant

* $P < 0.5$, ** $P < 0.01$, *** $P < 0.001$

Fig. 3 Monthly mean temperature differential ($^{\circ}\text{C}$) (sun-shade) for logger pairs **a** on east-facing walls, **b** on south-facing walls, and **c** on west-facing walls. Error bars depict one standard error



building exteriors were warmer ($1.7\text{--}2.9\text{ }^{\circ}\text{C}$) than those facing west in May and from July to September.

Daily Peak Solar Access Period III

Cooler average integrated temperatures ($2.6\text{ }^{\circ}\text{C}$) were recorded on east-facing buildings compared with south facing in September. East-facing building surfaces were cooler than west-facing ($1.6\text{--}3.5\text{ }^{\circ}\text{C}$) in May and from July to September. From May to August, south-facing exterior buildings were cooler ($1.4\text{--}3.1\text{ }^{\circ}\text{C}$) than west-facing building surfaces.

Temperature Differential: Shade and Sun Loggers

East-Facing Sites

Two buildings had east-facing aspects: KC_E and TC_E . Monthly average temperature differentials were greatest for KC_E and consistent for June to August (Fig. 3a). The largest hourly average building surface temperature differential between shade and sun loggers was recorded on

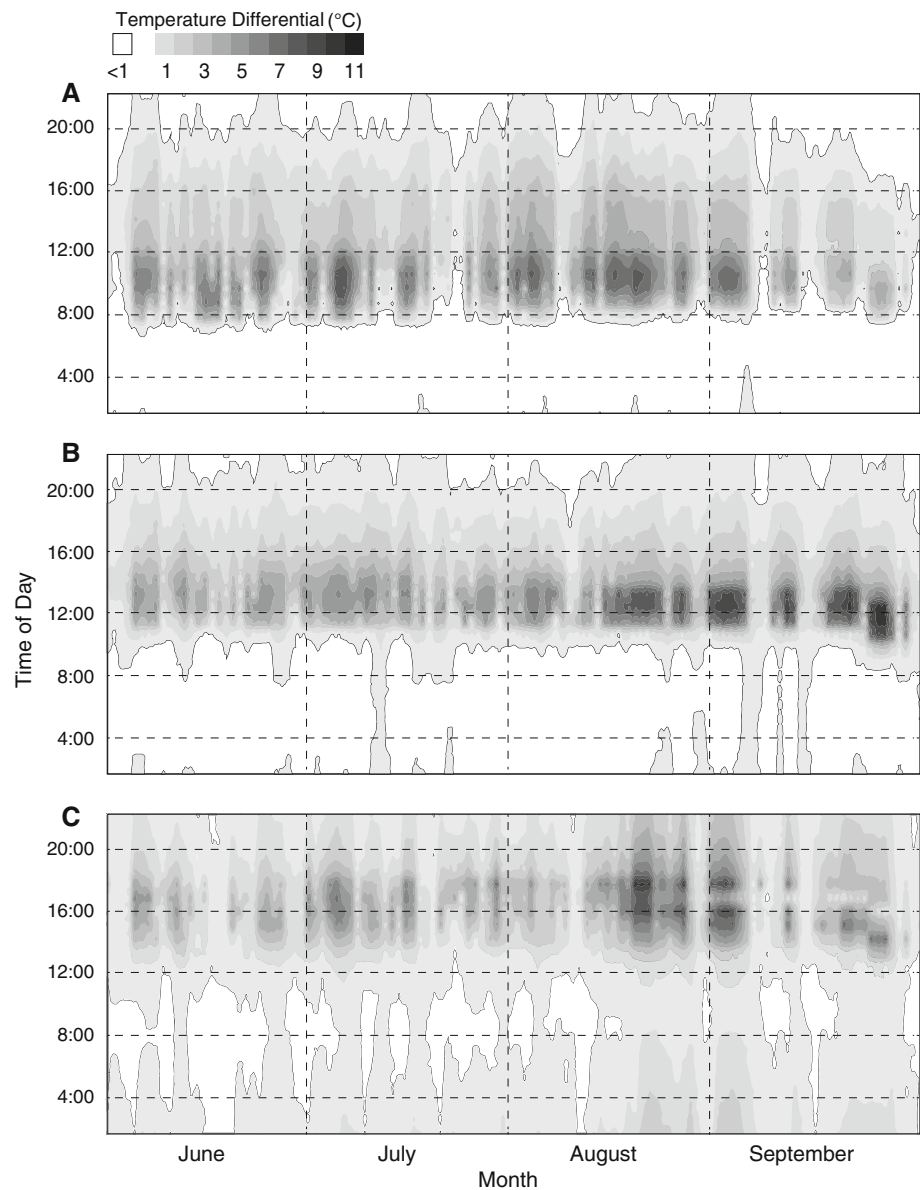
KC_E during August ($7.1\text{ }^{\circ}\text{C}$, standard error [SE] = 0.8), followed by July ($6.8\text{ }^{\circ}\text{C}$, SE = 1.0) and June ($6.4\text{ }^{\circ}\text{C}$, SE = 0.9), all at 9 a.m. (Fig. 4a). Average hourly temperature differentials also peaked at TC_E in August ($6.3\text{ }^{\circ}\text{C}$, SE = 0.5) followed by July ($4.3\text{ }^{\circ}\text{C}$, SE = 0.7) and June ($4.0\text{ }^{\circ}\text{C}$, SE = 0.6); however, in contrast with KC_E , these maximum differences in temperature were recorded at 10 a.m. Overall, the temperature-moderating benefits of the larger silver maple (although farther from the building) produced higher magnitude and longer duration temperature differentials at KC_E (Fig. 4a) when compared with the smaller sugar maple (*Acer saccharum*) growing closer to TC_E . At both sites, temperature differences between shaded and non-shaded loggers were only significant during pre-noon hours (Fig. 5).

South-Facing Sites

A total of six sites had south-facing aspects. Monthly average temperature differentials were greatest at the TC_{S1} site and least at UC_{S2} (Fig. 3b). TC_{S1} exhibited the greatest hourly average temperature difference between sun and

Fig. 4 Temperature differential surface ($^{\circ}\text{C}$) showing the diurnal influence of tree shade on mitigating rise in built surface temperature. Values indicate degrees cooler at shaded sites compared with their sun-exposed complement.

a KC_E —east-facing building,
b TC_{S1} —south-facing building,
c UC_W —west-facing building



shade loggers in October (8.3°C , $\text{SE} = 1.0$) at 11 a.m., followed by September (5.0°C , $\text{SE} = 0.7$), and July (3.2°C , $\text{SE} = 0.3$), both at 12 p.m. (Fig. 4b). The greatest average temperature differences at TC_{S1} occurred at 12 p.m., except for during May and October, when they occurred at 11 a.m. Unlike other logger sites, TC_{S2} was first established on August 18, 2008. This late inclusion in the study occurred because an extra logger became available, creating an opportunity to determine the shading potential of two English oak (*Quercus robur* “Fastigiata”) trees growing at very close proximity to the south of the TC building. The addition permitted comparison of the shading benefits of English oak with the white mulberry, located at TC_{S1} . The greatest average hourly temperature differences between sun and shade loggers at TC_{S2} were recorded in

August at 1 p.m. (8.9°C , $\text{SE} = 0.7$), followed by October (7.2°C , $\text{SE} = 0.9$) and September (7.1°C , $\text{SE} = 0.9$) both at 12 p.m.

The UC building was outfitted with two pairs of loggers (UC_{S1} and UC_{S2}). These sites differed from each other in terms of tree species and the distance of vegetation from the building. UC_{S1} was shaded by a honey locust (7.6 m from the building), while UC_{S2} was shaded by a European white birch located 10.4 m away. UC_1 was observed to have the greatest hourly average temperature difference in September (7.0°C , $\text{SE} = 0.7$), and followed by August (6.8°C , $\text{SE} = 0.5$), both occurring at 1 p.m. Peak hourly average temperature differences recorded in July (5.2°C , $\text{SE} = 0.4$) and October (4.8°C , $\text{SE} = 0.6$) both occurred at 12 p.m. The greatest hourly average temperature

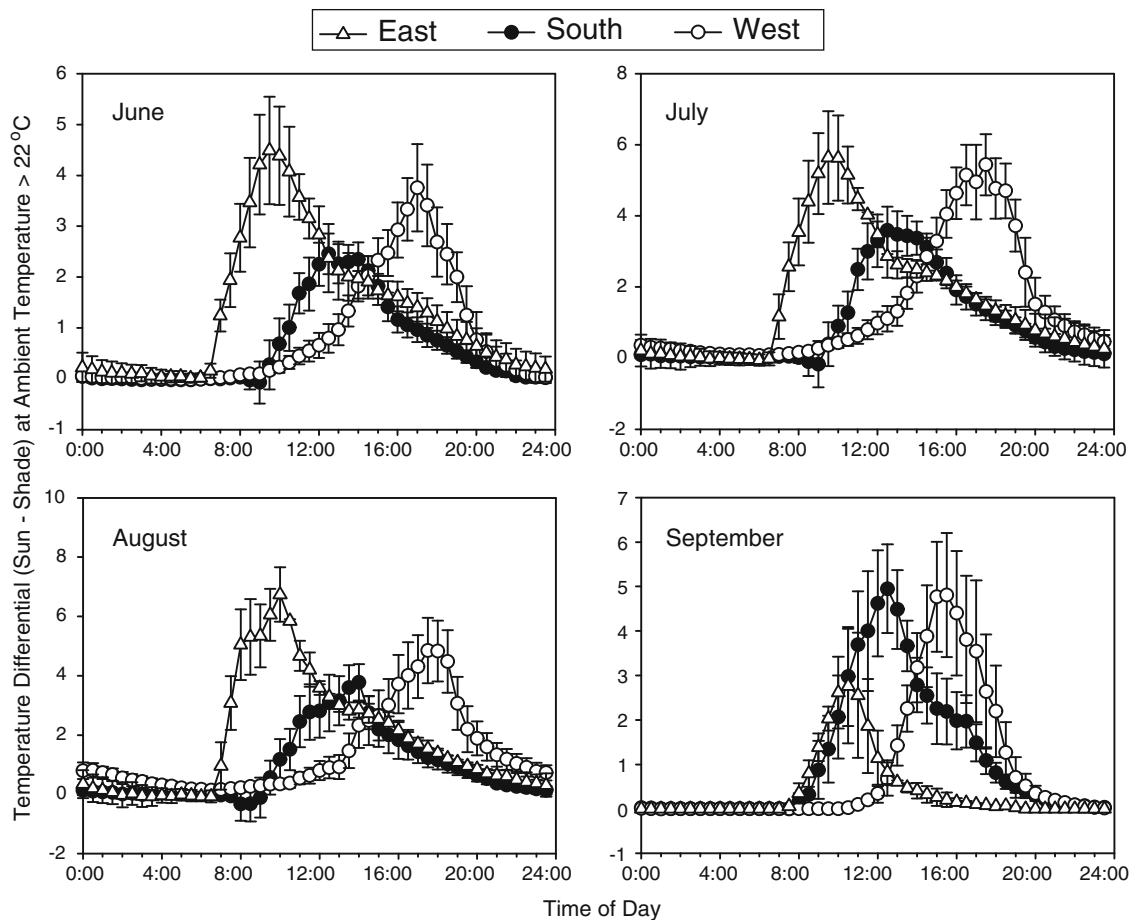


Fig. 5 Temperature differentials calculated at each time point for each logger pair at south, west, and east-facing locations. Monthly average calculated for each logger pair at each time point. Mean and standard error for each of these monthly averages are plotted by

aspect ($n = 5$ for south and west aspects, $n = 2$ for east aspect). June and July are full months. August and September are partial months (August 1–9, September 16–30), based on data availability

difference between sun and shade at UC_{S2} was markedly lower ($3.1\text{ }^{\circ}\text{C}$, $SE = 0.3$), occurring in August at 3 p.m. This was followed by October ($3.0\text{ }^{\circ}\text{C}$, $SE = 0.3$) and September ($2.7\text{ }^{\circ}\text{C}$, $SE = 0.3$), also both at 3 p.m. Overall, the tree shade at UC_{S2} was only valuable for moderating building surface temperatures later in the day when sun elevation was lower and corresponding tree shadows were longer. In addition to producing only approximately half of the magnitude temperature differential values when compared with UC_{S1} , UC_{S2} only sustained differentials above $1\text{ }^{\circ}\text{C}$ for 3–4 h, whereas differentials associated with US_{C1} regularly persisted for 8–10 h.

MC_S is a unique site, with two adjacent trees that provided shade to the central portion of the building throughout the entire day. The greatest average hourly differences in temperature between sun and shade sites occurred in September ($6.5\text{ }^{\circ}\text{C}$, $SE = 0.6$) at 12 p.m., followed by consistently high values in August ($6.3\text{ }^{\circ}\text{C}$, $SE = 0.6$) and October ($6.2\text{ }^{\circ}\text{C}$, $SE = 0.9$), also at 12 p.m. Temperature difference was statistically significant from

approximately 10 a.m. to 4 p.m. over most of the 6-month period.

Unlike the other locations, HH_S was shaded not by trees but by vines (Boston ivy). At HH_S , maximum hourly average temperature differences were observed at 2 p.m. in August ($3.7\text{ }^{\circ}\text{C}$, $SE = 0.4$), followed by September ($3.4\text{ }^{\circ}\text{C}$, $SE = 0.5$) and July ($2.9\text{ }^{\circ}\text{C}$, $SE = 0.2$), also occurring at 2 p.m. No significant temperature differences were observed in May owing to the fact that the vines had not fully leafed out.

West-Facing Sites

A total of five west-facing sites were investigated. Monthly average temperature differentials were greatest at the UC_W site, where they were almost double that of other locations in August (Fig. 3c). Shaded by a very large green ash with a high shading coefficient, UC_W exhibited the largest hourly average temperature difference between sun and shade loggers of all locations evaluated in the study. This

difference peaked at 6 p.m. in August (11.7 °C, SE = 1.2), and was followed by September (8.7 °C, SE = 1.2) at 4 p.m. and July (7.7 °C, SE = 0.7) at 5 p.m. (Fig. 4c). A moderately sized honey locust growing proximate to WS_W was found to have the greatest hourly average temperature-moderating influence in August (5.0 °C, SE = 0.5), followed by July (4.6 °C, SE = 0.6) and September (3.9 °C, SE = 0.7); each occurred at 5 p.m. At KC_W, the timing of the peak daily temperature difference varied over the course of the 6-month study, but with the greatest monthly average difference occurring at 6 p.m. in August (5.6 °C, SE = 0.7), followed by July (3.9 °C, SE = 0.5) and May (3.1 °C, SE = 0.6). GS_W exhibited the greatest average hourly temperature difference between sun and shaded locations in August (6.0 °C, SE = 0.7), followed by September (4.4 °C, SE = 0.7), both at 5 p.m., and July (3.5 °C, SE = 0.4) at 4 p.m. Temperature differences between the two loggers were consistently greater than 1 °C from 2 p.m. to 8 p.m. from July to September.

HH_W, the second vine-covered site, had relatively high temperature differences between sun and shade (compared with tree-shaded sites) over the course of the 6-month study, except for May (vines not fully leafed out) when it only reached 2.8 °C (SE = 0.7) at 5 p.m. The greatest temperature difference occurred in October (7.4 °C, SE = 0.8) at 3 p.m., followed at this same time by September (7.3 °C, SE = 0.8) and July (7.1 °C, SE = 0.7). In August, September, and October, the temperature difference between the two loggers rose above 1 °C starting as early as 11 a.m. and lasted until approximately 2 a.m. the following day.

Comparison of One Versus Two Shade Trees

Comparing temperatures at loggers shaded by a single tree with those shaded by two trees yielded mixed results. No statistically significant difference in temperature ($P > 0.05$) was recorded between DW_E (an east-facing site with several trees) and TC_E and KC_E (each east-facing sites with one tree). Similarly, the west-facing site with multiple trees at DW_W produced shade temperatures that were significantly lower than only one of the west-facing sites with single trees (GS_W).

In contrast, temperatures recorded by the shade logger at the south-facing MC_S site, where two trees were present, were much cooler than those at single-tree south-facing sites, particularly UC_{S2} and HH_S. As early as June, the MC_S shaded logger was cooler by a difference of 1 °C or greater compared with shaded loggers at all sample locations with single trees to their south; this difference was most pronounced from 9 a.m. to 6 p.m. The greatest difference in temperature-moderating effects between single and multiple trees occurred between UC_{S2} and MC_S; this

disparity was statistically significant ($P < 0.05$) in July, August, and September. During August, this difference reached 8.9 °C just before 12 p.m.; consistent differences above 8 °C were recorded from 10 a.m. to 12 p.m.

Comparison of Temperature-Moderating Effects of Trees and Vines

A mixed model revealed little difference between the temperatures recorded at sites shaded by vines (HH_S and HH_W) and those at sites with the same aspect shaded by trees. In fact, the logger shaded by vines at HH_S was significantly cooler than the tree-shaded logger a UC_{S2} only in July between 11 a.m. and 4 p.m. ($P < 0.05$); for all other months, there was no significant difference in temperature between HH_S and UC_{S2}. Meanwhile, the temperatures recorded by the vine-shaded logger at HH_W were never statistically significantly warmer or cooler ($P < 0.05$) than west-facing sites receiving shade from a tree.

Among Aspects Comparison of Daily Integrated Shading Benefit (DHD)

DHDs were assessed to determine if there was any effect of aspect (i.e., if the tree is planted to the west vs south or east of a building) on daily shading benefit. Over the duration of the experiment, there was no difference in shading benefits related to aspect. However, when the analysis was restricted to the hottest months (June, July, August, September), there was a significantly higher shading benefit (DHD) from planting trees to the west versus the south. This was true for both total DHD ($P = 0.0043$), and for DHD-22 ($P = 0.0004$). Moreover, the peak temperature difference between sun-exposed and shaded loggers had greater magnitude for west-facing versus south-facing locations in June, July, and August, and the peak occurred later in the day, when ambient temperature was greatest (typically between 1 p.m. and 3 p.m. at our study site). This suggests that trees planted to the west of a building will confer a greater overall shading benefit and one that is better timed to moderate urban microclimatic temperature when peak demand for air conditioning usually occurs within cities. Interestingly, shade from trees growing to the east of a building delivered the greatest overall temperature differential for June, July, and early August, but this benefit occurred during the morning when the need for temperature moderation is less (i.e., ambient urban temperatures are typically moderate).

Climatic Variables Influencing DHD

Daily DHD and Daily DHD-22 (DHD above 22 °C threshold) were highly correlated ($r = 0.84$, $P < 0.001$).

For this reason, a multiple regression analysis of DHD against climatic variables was restricted to daily DHD, as regression of DHD-22 would yield no useful additional information. Ambient temperature was the most useful climatic variable for explaining DHD, accounting for 85 % of the total variation in log DHD. Ambient temperature was correlated with all other climatic variables (relative humidity, wind velocity, radiation) and all of these variables were intercorrelated ($r > 0.25$, Bonferroni $P < 0.001$ for each pair of variables). Each of these variables was included in the final multiple regression model, as each had significant effect on log DHD ($P < 0.001$ for ambient temperature, relative humidity and solar radiation, $P = 0.0126$ for wind velocity). However, the addition of these other variables did not greatly increase predictive power of the final multiple regression model:

$$\begin{aligned} \log \text{ Daily DHD} &= 0.017 \times \text{AT} + 0.012 \times \text{RH} + 0.001 \\ &\times I - 0.031 \times W r^2 = 0.90, P < 0.001, \end{aligned} \quad (1)$$

where AT is ambient air temperature ($^{\circ}\text{C}$), RH is relative humidity (%), I is insolation (incoming solar radiation, W/m^2), and W is wind speed (m/s), each calculated as a daily average for hours where DHD was above zero.

An analysis of the residuals from this regression model found that the model under-predicted or over-predicted DHD for various logger pairs. For example, in west-facing logger pairs, the regression model under-predicted shading benefit for one location shaded by Boston ivy rather than trees (mean residuals 0.313, $\text{SE} = 0.028$), and another shaded by green ash (mean residuals 0.232, $\text{SE} = 0.036$). This tree was not particularly large but had a high leaf-area index and shading coefficient relative to other trees in the study. In south-facing logger pairs, the regression model under-estimated DHD for two locations (mean residuals 0.269, $\text{SE} = 0.041$ and 0.251, $\text{SE} = 0.025$, respectively). Two English oak trees, planted relatively near the building, shaded the first location. The other location was shaded by a honey locust with a large drip-line area relative to its crown size, perhaps shading the logger for a larger portion of the day than some other trees in the study. DHD was over-predicted (mean residuals -0.329 , $\text{SE} = 0.048$) for a west-facing location shaded by a London plane with a relatively low leaf-area index. The logger pair at this location was also on a concrete surface, rather than on a dark surface as was the case for some of the other west-facing logger pairs. This more reflective surface may have reduced the shading impact of the London plane. Finally, the regression model over-estimated shading benefit for a south-facing logger pair shaded by a European white birch, by most measures one of the smallest trees in the study, and one of the most distant from the building surface (mean residuals -0.052 , $\text{SE} = 0.031$).

Vegetation Characteristics Influencing DHD

Residuals analysis suggested total shading benefit may relate to vegetation characteristics. To address this, an analysis of total DHD and tree characteristics was performed. Total DHD is an integrated measure of the shading benefit over the entire 6-month period of study. Daily DHDs were summed from 6 May to 31 October, excluding days for which one or more logger pairs were off-line for data transfer or maintenance. Total DHD over the 6-month interval varied between 2704 and 6092 for twelve logger pairs. Regression analysis was used to explore the relationship between total DHD and vegetation characteristics for locations shaded by trees. A variety of tree attributes were recorded that was highly correlated ($r > 0.74$, $P < 0.05$) for all pairs of the following: crown diameter, tree height, crown height, crown volume, drip-line area, and outer surface area of crown. Crown height (CH) was most strongly related to total DHD and included in the regression analysis as a proxy for these correlated variables, along with shading coefficient, leaf-area index, diameter at breast height, and distance from center of crown to the building. The final multiple regression model found a significant relationship between total DHD and crown height + LAI:

$$\begin{aligned} \text{Total DHD} &= 102 \times \text{CH} + 758 \times \text{LAI} \\ r^2 &= 0.937, P = 0.0001. \end{aligned} \quad (2)$$

Tree size appeared more important than distance from the building (where distance never exceeded 14.6 m), and tree species may also be important in shading benefit as LAI can be species dependent (Sumida and Komiyama 1997). The Hart House locations shaded by vines (Boston ivy) were not included in the regression.

Discussion

Managing urban vegetation as a public asset in order to maximize its ecological benefit is essential in the face of global climate change and the increasing magnitude of the UHI phenomenon (Kershaw and Millward 2012). By mitigating the temperature rise of built surfaces, urban vegetation can minimize urban microclimatic warming, decrease city dwellers' discomfort and therefore lessen demand for costly and energy-intensive indoor air conditioning (Akbari et al. 2001; McPherson 1984). Shade trees are an essential urban landscape design feature that can serve to regulate outdoor summer temperatures within a tolerable range of human thermal comfort. High temperature built surfaces (i.e., those that are not shaded from direct solar radiation) emit large quantities of terrestrial

radiation. Variation in the amount of terrestrial radiation, and its effect on human comfort, can be estimated using a thermal comfort model such as COMFA (Brown and Gillespie 1995). Among other parameters, thermal comfort models rely on meteorological data and location-specific terrestrial radiation inputs to develop heat budget equations that describe the movement of energy to and from a person, within an outdoor landscape. Built surface temperatures collected in the present study can provide terrestrial radiation input to a thermal comfort model, where such a model can be an effective environmental management tool for landscape design of urban spaces.

Our study revealed that vegetation shading the built environment of Toronto's downtown core provided measurable temperature-moderating benefits during peak solar access periods, with built surfaces shaded by vegetation remaining as much as 11.7 °C cooler, and with as many as 10–12 h of sustained cooler (>1 °C) built surface temperatures when compared to equivalent sites receiving direct sunlight. To evaluate the shading potential of urban vegetation, we examined plant orientation with respect to built structures, plant distance from built structures, the impact of clustering, the difference between trees and vines, as well as the influence of allometric and canopy-specific characteristics.

We found that vegetation growing to the west of a built surface provided the greatest overall temperature differentials between shaded and sun-exposed loggers. Furthermore, this temperature-moderating benefit occurred at the time of day (mid- to late-afternoon) when ambient air temperature in Toronto was usually close to a maximum. Kershaw and Millward (2012) indicate that, during extreme heat events, human thermal discomfort usually peaks in the late afternoon and early evening (the effect of prolonged exposure to high temperatures). This discomfort drives greater demand for indoor air conditioning, which peaks as people return home from work (a time of day when institutional and industrial demand for power is still high) (Donovan and Butry 2009). Energy demand to run residential air conditioners increased by greater than 100 % in Toronto between 1990 and 2003, and 81 % of households now have air conditioners (Ontario Power Authority 2005; Statistics Canada 2009). In transmission capacity-constrained areas, spikes in electricity demand for air conditioning in mid- to late-afternoon are critical issues challenging the reliable delivery of electricity in cities (Sawka et al. 2013).

While our results indicate that planting vegetation near west-facing building walls will have the greatest overall impact on surface warming mitigation, shading south- and east-facing surfaces can also moderate temperature rise in the general building vicinity. Dampening urban temperature rise in the morning can have important benefits in

minimizing heating of built surfaces throughout the entire day (McPherson et al. 2006). We found that loggers that did not receive shade and were located on east-facing sites recorded significantly higher temperatures than their west-facing counterparts until approximately 4 p.m., a result that reinforces the value of shading built surfaces (east to south orientation) that have a tendency to absorb insolation and reradiate heat to their immediate surroundings earlier in the day.

In our study, distance from a built surface played an important role in determining a tree's influence over rise in microclimatic temperatures. The closer the tree to the building, the less solar radiation reached the shade logger. Given our study tree locations, we found that a distance of 5–10 m from the building wall was the most effective at preventing the warming of the built surface; this is best exemplified by the difference in temperature-moderating performance of trees at UC_{S1} and UC_{S2}. When trees were more than 10 m away, as was the case in TC_{S1} and UC_{S2}, their ability to mitigate warming of a building surface was minimal, a finding echoed by Hildebrandt and Sarkovich (1998).

The clustering of trees at a particular site did not necessarily translate into greater recorded temperature differences between sun and shade loggers. While our results from south-facing sites reveal greater temperature differences when more trees are present, we observed no significant differences between single trees and multiple trees at east- and west-facing sites. This may reflect study design limitations, since we were not able to control for shade tree distance from the building, tree size, leaf area, or canopy form. Other studies, such as McPherson and Dougherty (1989), do report increasing temperature moderation with multiple trees; however, size of tree canopy must be considered (i.e., in our study many trees were full stature). The greatest difference in temperature between loggers within the same pair was measured at MC_S. This site had two trees growing beside one another parallel to the building wall, minimizing the propensity for redundant shading. By contrast, the trees at TC_{S2}, the other multiple tree location with trees to the south of a building, were growing in an orientation that is more perpendicular to the wall in which they shade, thus contributing to more redundancy of shade.

Vines proved as effective as trees at moderating built surface temperatures, with our mixed model output revealing no significant difference in temperature values between vine-shaded and tree-shaded sites. The “typical day” temperature difference curves for the two vine-shaded sites exhibit the same general pattern and shape as those for tree-shaded sites. While these are limited data to draw on, it seems clear that vines consistently moderate built surface temperatures and, by extension, the proximate microclimate throughout the summer months. In contrast

with trees, shade provided by vines is extremely site specific (i.e., shade is only provided to the built surface on which vines are growing). Shade trees, however, have the potential to shade multiple surfaces throughout the course of the day. Nevertheless, our findings pertaining to vines have important implications for strategic placement of vegetation within an urban landscape, where growing space for large shade trees is often severely limited. Where lack of growing space or soil volume makes it impossible to grow a sizable shade tree, our results indicate that perennial vines offer a viable means of moderating temperature rise in an urban microclimate. Furthermore, vines grow quickly in comparison to trees and can, therefore, provide direct building shade more quickly than a newly planted tree.

For maximum possible shading potential, it is important to ensure a tree reaches its growth potential, since a tree of full stature can provide an order of magnitude more shade than one which is newly planted (Millward and Sabir 2010; Nowak 1996). While the small number of trees investigated in our study does not permit us to recommend species that are best at shading, our results do provide strong evidence that large stature trees with dense leaf structures perform best at mitigating microclimatic temperature rise. Canopy height and LAI explained approximately 94 % of the variation in total DHD (Eq. 2). This finding also hints at the importance of tree maintenance so as to ensure optimal canopy condition. Furthermore, it is essential to point out that large urban trees require adequate soil quality and volume (Jim 2001). If trees are to be part of a strategy to moderate rise in summer urban temperatures, city planners must ensure that suitable attention is given to the growing medium.

Not surprisingly, we determined that meteorological conditions within a city are important drivers of temperature differentials between built surfaces that are shaded and those that are sun-exposed. Our predictive model (Eq. 1), while limited by inputs from a single meteorological station, accounted for a very high degree of variation in DHD. Ambient air temperature accounted for the majority of the model's predictive power, which indicates that as urban microclimatic temperatures increase the temperature difference between shaded and sun-exposed surfaces grows, and in many cases takes longer to reach parity. In this way, shade cast by vegetation is better at moderating temperature rise the hotter ambient air temperatures become.

We note that in some instances the temperatures recorded by our sun loggers were cooler (by as much as 1.2 °C) than those from the corresponding shaded logger; where this occurred, it was most pronounced in the late evening or early morning with the greatest difference where sun loggers were farthest removed from vegetation (e.g., TC_E in October). Without additional instrumentation at each

logger pair site, this observation may be explained by (a) a wind-dampening effect known to occur around trees and vines, providing micro-site insulation that slows heat loss from the built surface (Oke 1978); and, (b) sun loggers losing greater amounts of terrestrial radiation to the cool sky than the shaded loggers that are exchanging terrestrial radiation with the warmer leaves.

Conclusion

This study investigated factors that affect the potential of urban vegetation to mitigate microclimatic warming in cities. By moderating temperature rise in the built environment around them, trees and vines can effectively influence thermal comfort for city inhabitants. When considered as a collective—an urban forest—vegetation that shades built surfaces provides an important service toward diminishing the UHI phenomenon. Our findings highlight a number of factors that should be considered in order to maximize the temperature-moderating benefits that urban vegetation provides. Key among them is the valuable role of large stature trees in moderating temperatures; in our study, bigger trees with full canopies consistently created greater cooling effects than smaller, younger trees. Cities can thus help to moderate summer temperatures by developing and enforcing tree protection bylaws to ensure that large stature trees are not removed unless necessary for safety reasons.

We recommend that policies surrounding new urban tree selection focus on trees that are well adapted to urban conditions, while at the same time have the potential to provide the greatest shading benefit. Where possible, and especially in sparsely treed urban locations, planting strategies should focus on providing shade during peak solar access periods. Under such conditions, preference for shading of west-facing structures will have the greatest magnitude benefit on mitigating rise in microclimatic temperature. For greatest impact, trees should be located 5–10 m from the building wall. In instances where there may not be suitable soil conditions or space to sustain a shade tree, or where nearby obstructions create potential conflicts, perennial vines can provide a viable alternative, proving equally effective at mitigating building surface temperature rise as shade trees.

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