Street Orientation and Side of the Street Greatly Influence the Microclimatic Benefits Street Trees Can Provide in Summer

Ruzana Sanusi,* Denise Johnstone, Peter May, and Stephen J. Livesley

Abstract

Maintaining human thermal comfort (HTC) is essential for pedestrians because people outside can be more susceptible to heat stress and heat stroke. Modification of street microclimates using tree canopy cover can provide important benefits to pedestrians, but how beneficial and under what circumstances is not clear. On sunny summer days, microclimatic measures were made in residential streets with low and high percentages of tree canopy cover in Melbourne, Australia. Streets with east-west (E-W) and streets with north-south (N-S) orientation were repeatedly measured for air temperature, relative humidity, wind speed, solar radiation, and mean radiant temperature on both sides of the street between early morning and midafternoon. Physiological equivalent temperature was estimated to indicate HTC throughout the day. In streets with high-percentage canopy cover, air temperature, relative humidity, solar radiation, and mean radiant temperature were significantly lower than in streets with low-percentage canopy cover. The reductions in air temperature under high-percentage canopy cover were greater for E-W streets (2.1°C) than for N-S streets (0.9°C). For N-S streets, air temperature, mean radiant temperature, and solar radiation were greater on the east pavement in the early morning and greatest on the west pavement in the midafternoon. The midday thermal benefits are restricted to E-W streets, which are oriented in the same direction as the summer sun’s zenith. High-percentage canopy cover reduced wind speeds but not enough to offset the other microclimate benefits. These findings can assist urban planners in designing street tree landscapes for optimal HTC in summer, especially in areas of high pedestrian density.

The urban forest is an important element of any town or city, representing the whole network of trees in the urban landscape. These urban trees are expected to provide multiple benefits, including improving microclimatic conditions for urban residents (Georgi and Zafiriadis, 2006). Trees do this by intercepting incoming solar radiation and preventing it from penetrating into street canyons (Matzarakis et al., 1999), thus providing shade and cooling benefits. Urban street trees can decrease local air temperatures and create a cooler, more comfortable environment for urban residents, particularly pedestrians, in summer (Lohr et al., 2004). Because the number of people living in towns and cities increases each year such that the number of urban residents is projected to nearly double by 2050 (United Nations Population Division, 2008), these benefits are becoming more important.

Many local government bodies aim to increase tree canopy cover as part of their urban forest strategies. For example, the City of Sydney aims to increase tree canopy cover from 15.5 to 23.25% by 2030 (City of Sydney, 2013). The City of Melbourne has set a target of increasing tree canopy cover from 22 to 40% by 2032 (City of Melbourne, 2012). These strategies aim to mitigate the detrimental impacts of the urban heat island, heat waves, and climate change by using trees to help improve the environment and the health and wellbeing of urban residents. The levels of tree canopy cover in street canyons may be small compared with that in urban parks and reserves, but street trees are important because they border the road network and shade pedestrian rights of way.

The capacity of street trees to provide benefits to pedestrians, especially at the micrometeorological level, is dependent on percentage tree canopy cover, the tree species, and street canyon characteristics. There are several tree characteristics or traits that may influence the microclimatic benefits that tree canopy cover can provide (de Abreu-Harbich et al., 2015; Lin and Lin, 2010). Different tree species have different leaf size, leaf orientation, transpiration rates, and canopy architecture, and these traits can provide different microclimate modification and shading benefits. From the perspective of the street canyon,

Abbreviations: HTC, human thermal comfort; PET, physiological equivalent temperature; SVF, sky view factor; T_mrt, mean radiant temperature.

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doi:10.2134/jeq2015.01.0039
Freely available online through the author-supported open-access option.
Received 26 Jan. 2015.
Accepted 30 Apr. 2015.
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building height, street width, and street orientation can also influence the ability of a tree canopy to provide microclimatic benefits to pedestrians. The height of the buildings can modify wind movement by channeling wind and changing wind speeds (Shashua-Bar et al., 2006). The width of the street can also influence the microclimatic conditions, such as rates of air mixing or self-shading. For example, a wide street with low buildings and no tree canopy cover will have lower thermal comfort for pedestrians (Johansson and Emmanuel, 2006). In addition, street orientation can influence how trees can modify street microclimate because it influences the duration and timing of solar radiation interception according to the sun’s zenith. On hot summer days, the potential cooling benefits from street trees are particularly influenced by tree and street factors, and it is on these days that improving human thermal comfort (HTC) is most important (Ali-Toudert and Mayer, 2007).

Microclimatic modifications by street tree canopies can be beneficial to pedestrians, but how beneficial and under what circumstances they are most beneficial is not clear. This study aims to investigate how street microclimate can be modified by high-percentage tree canopy cover in summer and poses the following research questions: (i) What are the microclimatic and HTC differences between streets with low- and high-percentage tree canopy cover in summer? (ii) Do the differences due to low- and high-percentage tree canopy cover vary significantly according to street orientation? (iii) Under high-percentage tree canopy cover, do microclimate and HTC differ between the left and right sides of a street on a sunny summer day, and does this vary according to street orientation?

To minimize confounding factors common in urban landscape studies, microclimate measurements were only made in residential streets with and without Platanus × acerifolia (London Plane Tree) planted at regular intervals along both sidewalks. All streets had low height/width (H/W) ratios and were either in a north-south (N-S) or east-west (E-W) orientation.

### Materials and Methods

This study was conducted in Richmond, Victoria, Australia (37°49′ S, 144°59′ E), which is an inner suburb of Greater Melbourne situated 3 km southeast of the Melbourne city center. This is a typical urban residential area dominated by single- and double-story buildings. Study streets were selected with low- and high-percentage tree canopy covers, with street orientations of either E-W or N-S. During summer 2012–2013, measurements were conducted over six clear sunny days. The measurement dates were as follows: for two E-W streets: 12 Feb. 2013, 6 Mar. 2013, and 13 Mar. 2013; and for two N-S streets: 13 Feb. 2013, 5 Mar. 2013, and 12 Mar. 2013. The mean daytime maximum temperature in Melbourne in summer 2012–2013 was 27.4°C, and the mean night time minimum temperature was 16.2°C. In Melbourne, a calculated average of the maximum and minimum temperatures measured in a 24-h period exceeding 30°C has been shown to correlate with “excess mortality” among vulnerable people (Nicholls et al., 2008). The 24-h air temperature, relative humidity, and solar radiation data for the measurement dates are presented in Fig. 1 to provide a reference to the climate conditions experienced during the experiment.

A description of the measured streets, their orientation, average street canyon H/W ratio, percentage of tree canopy cover (%), and microclimate measurement points are as presented in Table 1. Percentage of tree canopy cover was estimated using i-Tree Canopy (i-T ree Canopy, 2013) by categorizing tree and non-tree surface cover type from aerial photographs at 200 randomly assigned sample points within each street. Streets with high-percentage canopy cover had 77% cover in the E-W street and 70% cover in the N-S street. Streets with low-percentage canopy cover had 19% cover in the E-W street and 17% cover in the N-S street. The specific dimensions and example images of streets with low- and high-percentage canopy covers are presented in Fig. 2. 

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**Fig. 1.** Air temperature, relative humidity, and solar radiation data measured on 12 Feb. 2013, 6 Mar. 2013, and 13 Mar. 2013 for east-west streets and on 13 Feb. 2013, 5 Mar. 2013, and 12 Mar. 2013 for north-south streets. These data were obtained from a meteorological station in Burnley Campus, The University of Melbourne, Victoria, Australia (2 km from the measurement location).
Estimation of Sky View Factor

Hemispheric (fish-eye) photography was used to determine sky view factor (SVF) of each street (Osmond, 2010). Sky view factor indicates the degree of open sky seen from a point 1.1 m above street ground level and is influenced by tree canopy cover, topography, street furniture, and building heights. Sky view factor was measured at the same points as microclimate measurements early in the morning or at sunset once during the measurement period.

Sky view factor was highest with low canopy cover, with mean values of 0.72 and 0.73 in the N-S and E-W street orientation, respectively (Table 1). Streets with high canopy cover had lower SVFs of 0.26 and 0.27 in both street orientations than low canopy cover streets (Table 1).

Measurement of Street Microclimate

Street microclimate was measured using three portable weather stations (Table 2) recording air temperature, relative humidity, wind speed, solar radiation, and mean radiant temperature ($T_{\text{met}}$), which is the mean temperature from all sources of radiation, including shortwave and longwave radiation, direct from the sun and reflected in all directions from all entities, objects, surfaces, and the atmosphere surrounding the human body (Fanger, 1970). For this study, $T_{\text{met}}$ was measured through globe temperature by using a black hollowed copper sphere with a temperature sensor inside (Fanger, 1970; Humphreys, 1977; Nikolopoulou et al., 1999). For measurement of $T_{\text{met}}$, the black globe was allowed 15 min to reach equilibrium with the measurement location conditions. Wind speed was logged every 10 s but averaged to be recorded every minute (CR1000 data logger, Campbell Scientific), and then wind speed data were averaged to represent each 15-min period. Coutts et al. (2015) established an additional calibration of the black globe $T_{\text{met}}$ measurement through comparison to direct measures of radiation, which corrected the convective coefficient value to $0.65 \times 10^{0.53}$. Our study used the same black globes, loggers, and component parts, so we used the same convective coefficient correction. The measured air temperature, wind speed, and globe temperature and a convective coefficient were used in the calculation of $T_{\text{met}}$. 

![Fig. 2](image)

**Table 1. Characteristics of the streets used for data collection.**

<table>
<thead>
<tr>
<th>Street</th>
<th>Street orientation</th>
<th>Tree canopy cover</th>
<th>Canopy cover</th>
<th>Average H/W† ratio</th>
<th>Sky view factor</th>
<th>Measurement points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charlotte St.</td>
<td>east-west</td>
<td>low</td>
<td>19</td>
<td>0.25</td>
<td>0.73</td>
<td>measured where there was no shading by trees at any time of the day</td>
</tr>
<tr>
<td>Elm Grove</td>
<td>east-west</td>
<td>high</td>
<td>77</td>
<td>0.29</td>
<td>0.26</td>
<td>measured at random points under the near continuous canopy</td>
</tr>
<tr>
<td>Burnley St.</td>
<td>north-south</td>
<td>low</td>
<td>17</td>
<td>0.21</td>
<td>0.72</td>
<td>measured where there was no shading by trees at any time of the day</td>
</tr>
<tr>
<td>Bendigo St.</td>
<td>north-south</td>
<td>high</td>
<td>70</td>
<td>0.23</td>
<td>0.27</td>
<td>measured at random points under the near continuous canopy</td>
</tr>
</tbody>
</table>

† Height/width.
Physiological Equivalent Temperature Index for Human Thermal Comfort

The thermal index used to estimate HTC in this study was physiologically equivalent temperature (PET). This index standardizes human factors with a metabolic rate at 80 W (equivalent to light activity) and clothing of 0.9 clo (equivalent to a light business suit). The microclimatic parameters of air temperature, relative humidity, wind speed, solar radiation, and $T_{mrt}$ were used as an input for PET estimation. RayMan software was used in this study to estimate PET (Matzarakis et al., 2007). Physiologically equivalent temperature gives a value in °C, which is easy for professionals, such as urban planners, to use and relate to (Deb and Ramachandraiah, 2010).

Data Analysis

Data were analyzed using ANOVA and $t$ test (GENSTAT 16). A LSD test was used to determine significant ($p \leq 0.05$) difference among groups.

Results

Street Microclimate and Human Thermal Comfort between Streets with Low- and High-Percentage Canopy Cover

There were significant ($p \leq 0.05$) microclimate benefits in high-percentage canopy cover streets as compared with the low-percentage canopy cover streets for both street orientations (Fig. 3). However, this is not apparent in the early morning because similar mean air temperatures were measured in both N-S (~20°C) and E-W (~21°C) streets under both high- and low-percentage canopy covers (Fig. 3). For E-W streets, midday and midafternoon measures of air temperature were significantly different ($p \leq 0.001$) between high- and low-percentage canopy covers, whereas in N-S streets only midafternoon measures of air temperature were significantly different ($p \leq 0.001$). On the other hand, solar radiation, $T_{mrt}$, and PET were found to be significantly different between high- and low-percentage canopy streets at most measurement times for both street orientations ($p \leq 0.05$).

The reduction of solar radiation in high-percentage canopy cover streets assists in the reduction of $T_{mrt}$ in both street orientations (Fig. 3). For example, at midday in N-S streets, the mean solar radiation differed significantly ($p \leq 0.001$) from 908 W m$^{-2}$ under the low-canopy cover to 379 W m$^{-2}$ under the high-percentage canopy cover, thus significantly influencing $T_{mrt}$, which was 44.8 and 36.8°C, respectively. These large reductions in solar radiation and $T_{mrt}$ in turn significantly reduce midday PET estimates ($p \leq 0.01$) from “strong heat stress” (37.6°C) to “moderate heat stress” (33.6°C). Although the high-percentage canopy cover significantly reduced the wind speed ($p \leq 0.001$) in N-S streets, wind speeds were small (range, 0–1.0 m s$^{-1}$) (Fig. 3). In contrast, E-W streets did not show a consistent reduction in wind speed with higher-percentage tree canopy cover (Fig. 3).

Street Microclimate and Human Thermal Comfort Differences between Two Street Orientations

Air temperature, $T_{mrt}$, and PET were significantly greater ($p \leq 0.05$) in E-W streets than in N-S streets. For example, at midday, the mean air temperature difference between low- and high-percentage canopy covers in E-W streets could reach 2.1°C, whereas in the N-S street it was restricted to 0.9°C (Table 3). Similarly, mean $T_{mrt}$ exhibited a greater difference between low- and high-percentage canopy cover at midday (10.7°C) in E-W streets compared with N-S streets (8.0°C); PET showed a similar trend, with differences of 4.6 and 4.0°C, respectively (Table 3).

Street Microclimate and Human Thermal Comfort Differences on Different Sides of the Street

The microclimate of N-S streets with high-percentage canopy cover was significantly influenced by the time of day and on which side of the street measurements were made (i.e., east or west). Solar radiation was significantly higher ($p < 0.05$) on the west side than on the east side of the street at midday (Fig. 4). For example, midday solar radiation on the west pavement (681 W m$^{-2}$) was almost double the value for the east pavement (390 W m$^{-2}$) (Fig. 4). A similar pattern was observed for $T_{mrt}$ and therefore for PET. In midafternoon, $T_{mrt}$ and PET were significantly greater on the east side than the west side ($p \leq 0.05$). By midafternoon, the reverse was true such that PET was equivalent to “strong heat stress” on the west side (37.3°C) and equivalent to “moderate heat stress” on the east side (32.0°C) (Fig. 4).

In contrast, there was little difference between opposing sides of the street (north or south) in high-percentage canopy cover in E-W streets. Most microclimatic parameters, for a given time of the day, showed no significant difference between north and south sidewalks of these E-W streets (Fig. 4).

Discussion

This study measured significant microclimate benefits under high-percentage tree canopy cover for both N-S and E-W street orientations. Solar radiation, $T_{mrt}$, and PET were significantly
reduced for streets in both orientations, but air temperature was only significantly reduced in N-S streets in the midafternoon. Microclimate benefits were greater for the high-percentage canopy cover in E-W streets because the differences in air temperature and $T_{mrt}$ between low- and high-percentage tree cover were several degrees Celsius greater than that measured for N-S streets. This may partly be explained by the significant differences between microclimate measures made on opposing sidewalks in N-S streets; in other words, the microclimatic benefits were “time of day” and “side of street” dependent for N-S streets.

Fig. 3. Average air temperature, relative humidity, wind speed, solar radiation, mean radiant temperature ($T_{mrt}$), and physiologically equivalent temperature (PET) in streets with high Platanus × acerifolia canopy cover and low canopy cover. Data collected for three summer days using spot measurements in north-south (left column, A) and east-west (right column, B) orientations in Richmond, Victoria, Australia. Levels of heat stress were presented at the right bottom corner of the graph.

Microclimate and Human Thermal Comfort Effects of Street Tree Canopy in Summer

The microclimate benefits from higher-percentage tree canopy cover are due greatly to the lower SVF, which reduced solar radiation access, ground surface heat accumulation, and thus localized air temperature. The tree canopies reduce SVF and increase the reflection and absorption of solar radiation, thus allowing only a small amount of solar radiation below the canopy (Brown and Gillespie, 1995). The contrast in local microclimate between streets with high- and low-percentage tree canopy cover was greatest in the midafternoon, after solar radiation input in streets with few trees had accumulated throughout the middle of the day. We observed that solar radiation, $T_{mrt}$ and PET were significantly reduced for streets with high-percentage tree canopy in both orientations, but air temperature was only significantly reduced at midday and midafternoon for E-W streets and only at midafternoon for N-S streets. In agreement with our findings, Souch and Souch (1993) noted that the effect of trees on air temperature was small in early morning (07:00–09:00), but the cooling effect became apparent by midday (12:00–14:00), reducing air temperatures by 0.7 to 1.3°C. Less incoming solar radiation in the midmorning observed in our study meant there was less solar radiation within the street canyon due to the shading effect of the trees and possibly the shading effect from buildings along the street canyon as well. Less solar radiation penetrated into the street canyon, resulting in the insignificant cooling effect by the high-percentage canopy covered street in midmorning.

Reduced solar radiation transmittance in streets with high-percentage tree canopy cover decreases the radiant heat intercepted by pedestrians (Shashua-Bar et al., 2011). In our study, $T_{mrt}$ and PET was greater in streets with low-percentage tree canopy cover than in streets with high-percentage canopy cover, suggesting that the re-radiated heat from the surfaces increased heat load to the surroundings, thus reducing HTC (increasing the PET). Mean radiant temperature is the most important meteorological parameter that affects HTC and the human energy balance of pedestrians during summer (Matzarakis et al., 2007). As such, $T_{mrt}$ has been shown to have a stronger correlation to PET than air temperature (Gulyás et al., 2006). Therefore, the presence of trees in urban residential areas is important not only because it reduces air temperatures but also because it significantly reduces $T_{mrt}$ and as such pedestrian thermal stress for most of the day. The high-percentage tree canopy covers in this study (70–77%) were able to improve HTC by reducing thermal stress. For example, from midday onward, in N-S streets high-percentage tree canopy
Microclimate benefits from trees are also provided through evapotranspiration. In the microclimate assessment, significantly higher relative humidity was found in the high-percentage canopy covered streets, suggesting that the water vapor released to the atmosphere from transpiration increases the humidity of the air in that street canyon. As such, it is also assumed that the reduction in air temperature under high-percentage tree canopy cover in our study was partly due to evapotranspiration by those trees (Shashua-Bar and Hoffman, 2000). The potential for evapotranspirative cooling by a tree is, however, reliant on the water balance of that tree (Oke et al., 1989). Therefore, we investigated tree water status during our study. Predawn leaf water potential was measured and was −0.4 Mpa on average (data not shown), indicating good availability of water to the trees. However, water stress level will be different depending on the species (Ranney et al., 1990). In hot, sunny summer conditions, the transpirative cooling may be important to pedestrians. However, from the pedestrians’ perspective, higher humidity from transpiration will not be perceived as a benefit because this will lead to less efficient sweat evaporation from the human body, especially at high levels of physical activity (i.e., brisk walking) (McNall et al., 1967).

Wind speed, on the other hand, was also expected to be greater in streets with low-percentage tree canopy cover because trees are able to alter wind movement within a street canyon by blocking the wind from channeling into the street canyon. In a study by Heisler (1990), the wind speed measured at 2 m height in a residential area also showed that areas with trees reduced the wind speed to 70% in summer due to the obstruction by the trees and buildings. Wania et al. (2012) also suggested that dense tree cover reduced the wind speed and air flow in the street canyons especially in the street with a greater H/W ratio (H/W > 0.5). There was only an apparent reduction in wind speed in N-S streets with high-percentage tree canopy cover, and these wind speeds were all small such that they could not outweigh the beneficial influence of the tree canopy on other street microclimate parameters (i.e., solar radiation, Tmrt). Similarly, in a street PET study by Cohen et al. (2012), wind contributed little to pedestrian PET because wind speed values remained small. Wind can be beneficial for pedestrian thermal comfort because the efficiency of sweat evaporation is greater with wind speed; however, with the presence of trees, lower wind speed will restrict the cooling breeze, thereby lowering the pedestrian thermal comfort (Akbari et al., 1992).

**Effect of Street Orientation: Microclimate and Human Thermal Comfort Benefits**

In our study, microclimate benefits from high-percentage tree canopy cover were greater for streets in an E-W orientation. This demonstrates the dominant effect of the sun’s zenith in summer. Because the E-W streets are oriented in the same direction as the sun’s zenith, the high-percentage tree canopy cover reduced the exposure of the street canyon to solar radiation regardless of time of day, whereas in a N-S street solar radiation was able to transmit under the high-percentage canopy cover in the early morning and midafternoon. Interestingly, the opposite is true for the streets with low-percentage canopy cover, as simulated by Ali-Toudert and Mayer (2006) in terms of human thermal stress duration and intensity. In another study, Oliveira et al. (2011) found greater differences in air temperature, Tmrt, and PET between open and tree canopy–shaded areas in an E-W street as compared with a N-S street, surmising that this was due to the higher duration of solar radiation exposure in E-W streets in summer.

Pearlmutter et al. (2007) suggested that the improvement of thermal comfort through H/W is small for E-W–oriented streets. A street in an E-W orientation has a greater potential for high human thermal stress, but likewise the presence of high-percentage tree canopy cover will give a greater cooling benefit because of the higher risk potential from solar radiation exposure. Hence, planting trees in E-W streets is strategically very important because PET can be greatly reduced, thus improving pedestrian thermal comfort. Therefore, even though increasing tree canopy cover in N-S streets will provide microclimate and PET benefits, these benefits are not as great because some solar radiation will still penetrate the street canyon. This finding highlights the dominant role of solar radiation in different street orientations. Therefore, the prioritized planting of street trees also needs to consider street orientation because this influences the level of solar radiation risk exposure and therefore street microclimate and HTC benefit. For example, Norton et al.
Journal of Environmental Quality 173 (2015) suggest that planting of street trees in E-W streets should be prioritized, especially for wide streets with a small H/W ratio.

The Side of the Street You Walk On: Microclimate and Human Thermal Comfort Benefits

Street orientation also determines the HTC experienced by a pedestrian walking on one or the other side of the street at a given time of the day. For N-S streets, the microclimatic and pedestrian thermal comfort benefits were “time of day” and “side of street” dependent. For these N-S streets, there was higher human thermal stress on the east sidewalk in the morning and higher thermal stress on the west sidewalk in the afternoon. This result confirms the simulation study by Ali-Toudert and Mayer (2007) in Northern Hemisphere street scenarios. This demonstrates that tree shade microclimate benefits may not necessarily be experienced directly beneath the tree canopy, especially not in the early morning and midafternoon in N-S streets. This has considerable implications for the strategic placement of street trees for shade in N-S streets, especially regarding the times of day that pedestrians may be making greatest use of a sidewalk.

The gap between the building and the tree canopy can be another factor that can greatly influence the microclimate (i.e., solar radiation interception) and HTC in N-S streets. The use of external shading facilities on the buildings, such as awnings and retractable canopies, can reduce this gap and improve the street microclimate condition as well as that inside the building (Berry et al., 2013; Porritt et al., 2012). Buildings themselves cast shade, and therefore the aspect ratio of the street (H/W ratio) can influence the street microclimate (Coutts et al., 2015). However, Ali-Toudert and Mayer (2006) point out that street orientation plays a role because even in deep canyon (H/W = 4) streets in an E-W orientation shading from buildings was limited, whereas in N-S orientation such a deep street canyon would significantly lower the PET and periods of human thermal discomfort. As such, if there is tree canopy cover in a deep canyon in a N-S orientation, it will provide less cooling benefit because of self-shading from the buildings themselves (Coutts et al., 2015). Shashua-Bar et al. (2006) modeled that the cooling effect in a street with 70% of tree canopy cover was almost halved when the street canyon H/W was ≥2.0 as compared with a shallow street canyon (H/W = 0.25). In our current study, low H/W ratios for both street orientations (ranging between 0.21 and 0.29) were expected to provide minimal building shade; therefore, the greater cooling effects found on both street orientations were largely determined by the high-percentage tree canopy cover. This further indicates that high-percentage tree canopy cover would be more beneficial when located in canyons with low H/W ratios.

Conclusions

By examining two different street orientations (E-W and N-S) with two different percentage tree canopy covers (high and low), this study leads to the following conclusions: (i) Greater cooling of street microclimate occurs in residential streets with dense, well-developed canopy cover than in streets with a low canopy cover. (ii) In Melbourne’s warm temperate climate, high-percentage tree canopy cover in an E-W street can reduce midday air temperatures

Fig. 4. Air temperature, relative humidity, wind speed, solar radiation, mean radiant temperature (Tmrt), and physiologically equivalent temperature (PET) of high Platanus × acerifolia canopy cover streets comparing both sides of the street. Data collected using spot measurements in north-south (13 Feb. 2013; left column, A) and east-west (6 Mar. 2013; right column, B) orientations are comprised of two different sides of the street in Richmond, Victoria, Australia. Levels of heat stress were presented at the right bottom corner of the graph.
by up to 2.1°C and PET by up to 4.6°C as compared with a similar street with little tree canopy cover. The microclimatic benefits of high-percentage tree canopy cover were less in N-S streets as compared with E-W streets because solar radiation was transmitted under the canopy in the morning and midafternoon. (iii) Greater street tree canopy cover lowered wind speeds but not significantly and not enough to offset the other microclimatic benefits the canopy shade and transpiration provided.

Our study provides an evidence base to urban planners and landscape professionals as to the magnitude of the microclimatic benefits they can gain from increasing tree canopy cover in suburban residential streets. This will help to improve land use planning strategies that consider heat-related health problems during the summer months. These planning strategies should also consider where to plant street trees in high pedestrian areas, such as commercial shopping streets, primary schools, and transport hubs. These planning strategies should consider street orientation and which side of the street is used most by pedestrians and at what time(s) of the day there is greatest pedestrian activity so as to place trees to achieve the greatest microclimatic and HTC benefits.

Acknowledgments
This research was part of the City of Melbourne Research Project Fund. The authors thank the City of Yarra for giving us permission to conduct this research in Richmond, the Statistical Consulting Centre of The University of Melbourne for their help in the data analysis, and the other individuals involved indirectly in this project for their technical assistance and thoughtful suggestions.

References