TREES PROVIDE ENERGY SAVING BENEFITS TO ADJACENT BUILDINGS FOR A SMALL WATER COST

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INTRODUCTION

Urban centres are a major source of greenhouse gas emissions and energy use. In Australia, Building energy use is responsible for 23% of greenhouse gas (GHG) emissions, more than half of which comes from the residential sector (CIE, 2007). In Australian residential homes, about two thirds of energy is used for heating and cooling (incl. water) (CIE, 2007). Residential (and commercial) space cooling is forecast to rapidly increase by up to 16% per annum (DEWHA, 2008), but will still only represent 4% of total residential energy consumption in 2020. However, the problem of space cooling on hot summer days is a key issue to sustained electricity provision at times of peak demand.

The urban heat island and extreme summer heat waves both intensify the cooling load that residential, office and commercial buildings experience, and consequently that the occupiers may experience. Trees can reduce the cooling load through direct shade, and cool the external micro-climate through transpiration. Trees require rainfall or irrigation to provide these benefits, otherwise these benefits are limited and tree health suffers.

There have been several key studies investigating the cooling energy savings achieved through tree shade (Simpson and McPherson, 1996; Akbari *et al*. 1997; Donovan and Butry, 2009; Pandit and Laband, 2009). These studies document the impact of tree shade on the cooling energy demand through small-scale empirical data collection, large-scale modelling and large-scale surveys. Akbari *et al*., (1997) measured seasonal cooling of two full-scale residential buildings provided energy savings of up to 30% (4 kWh per day) and estimated peak energy demand savings of 0.7 kW for each of the houses. Simpson and McPherson (1996) reported that shading on the west side of houses showed the highest reduction in cooling energy demand and that adding two shade trees on the west would reduced annual cooling costs for the house by between 10-50%. Pandit and Laband (2009) through a broad survey of 160 households in Auburn Alabama and economic analysis of behavioural energy use estimated that 50% shade could reduce power use by almost 20% in a “typical” residential house. Similarly, Donald and Butry (2009) used energy bills from 460 households in Sacramento, California alongside their levels of tree shade to estimate that tree shade was reducing electricity use by 5.2%. The simulations Akbari *et al*., (1997) performed subsequent to their field measures underestimated the energy savings by up to 50%. This indicates the complexity of modelling the impact of tree canopy processes and the problem of inherent assumptions and approximations. The thermal load reduction and energy saving benefits of trees is not due simply to the direct shade effect, in fact the transpirative cooling process can provide the greatest benefit in warm dry climates (Akbari *et al*. 2009). This highlights the important realtionship between tree shade and tree water availability to realise the maximum thermal and energy savings.

Comparable studies on the impact of tree shade upon builing thermal loads and energy use have been undertaken in the southern states of North America. This climate typically produces hotter summers and colder winters than those expereinced in Melbourne, Victoria. It can be assumed that the energy savings from the presence of trees shading a building will be smaller. Similarly, many of these studies have investigate the energy saving benefits of deciduous trees as it is assumed they provide the greatest annual benefit, through deep summer shade whilst enabling some solar gain in winter months. However, in Australia evergreen native canopies are found throughout our urban landscape and comparative research is required to place their benefits in context.

The aim of this study is to directly quantify the reduction in cooling loads upon external walls from the presence of deciduous exotic or evergreen native trees in a Melbourne climatic context. The water use of these trees will be quantified concurrently to gauge temperature reduction benefit in consideration of water uptake cost. Several hypotheses were contructed to be tested:

- Deciduous tree shade will provide greatest reduction in summer thermal load and inward heat transfer.

- Deciduous trees will enable greater winter warming of external wall temperatures and reduced outward heat transfer.
- Tree water use and external wall temperatures will directly relate to daily solar radiation received.

External wall temperatures and wall heat transfer rates were measured on three single-room weatherboard buildings at the Burnley campus of The University of Melbourne: i) evergree native trees placed on the west and north walls, ii) exotic deciduous trees placed on the west and north walls, and iii) no trees (control).

METHODS

The Burnley campus of The University of Melbourne is located in eastern metropolitan Melbourne (37°47′45″S, 145°01′50″E) on the southern bank of the Yarra river. Mean annual rainfall is 681 mm, mean minimum temperature 8.9°C and mean maximum temperature is 19.9°C. Three air-conditioned (thermostat setting: 21°C using Midea, 2.5 kW split heat pump system), single-room dwellings (3.2 x 3.7 x 3.3 m) were instrumented with heat flux sensors (HFS4, Omega Pty Ltd, USA; thermal resistance = 0.004 °C W^{-1} m^{-2}) on all walls, ceiling and floors to directly and continuously measure heat transfer rates (Fig. 1). Two buildings are flanked on the north and west walls by trees, i) nine 3.5 m tall evergreen *Eucalyptus sideroxylon* trees (75L pots) ii) nine 4.0 m deciduous *Fraxinus excelsior* trees. The third buildings has not tree shade. Tree water use is measured continuously for one of both species using two lysimeter balances (300 ± 0.05 kg capacity) (Fig. 2). It is expected that the trees will provide small, but significant, reductions in north/west wall thermal load and heat transfer, but will not shade the roof. The buildings were weatherboard constructions with wall and ceiling insulation but no floor insulation, only a surface carpet with underlay. They were suspended on concrete stump footings, with the entry door and one window facing south and the second window facing north (Fig. 1).

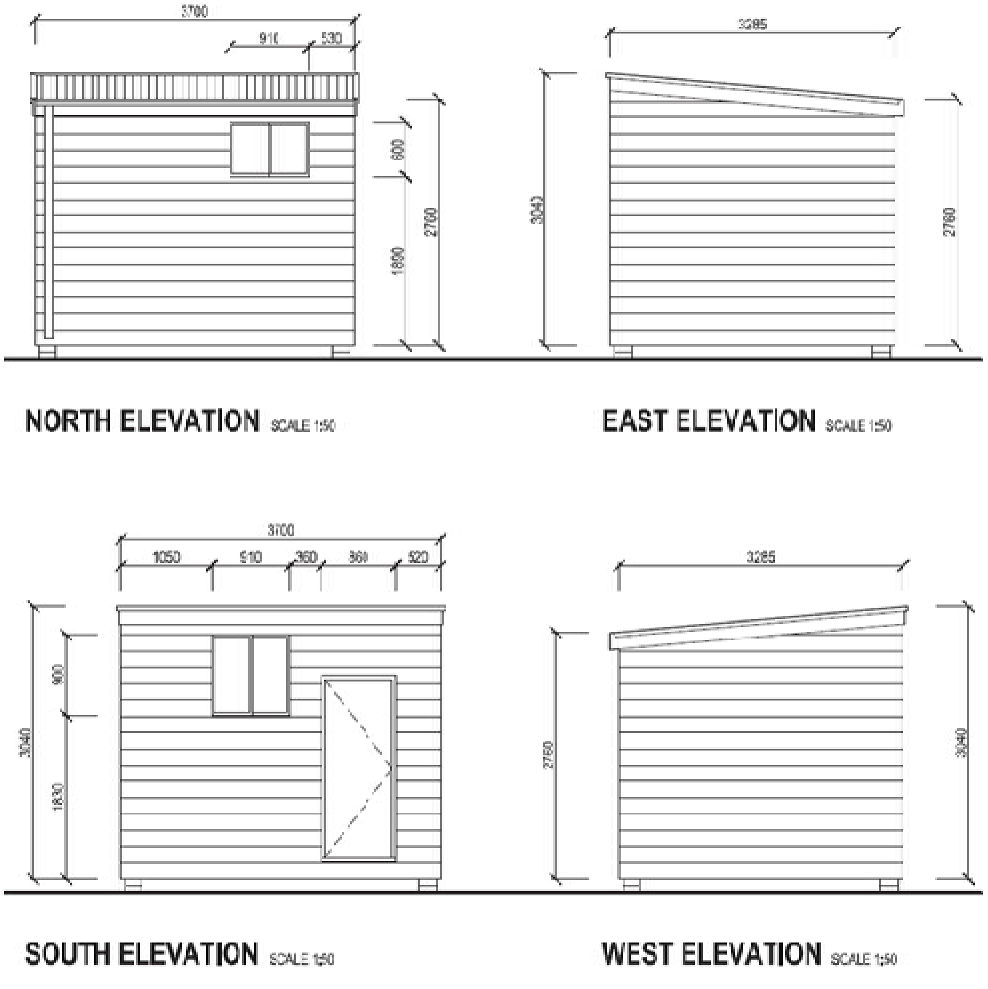

Figure 4. Dimensions for single-room weatherboard buildings.

The buildings were placed so as to not shade each other after 9 am and 3 pm in winter and are placed on turfed ground. On the western wall of all three buildings, an infrared thermocouple (OS36, K type, Omega Pty Ltd, USA) was installed 0.8 m from the wall at a height of 1.5 m. Heat flux sensors were attached to the inner wall (within the wall cavity between the insulation batts and the plasterboard) using epoxy resin (Fig. 2). The infrared thermocouples and heat flux sensors were logged continuously at 20 s intervals using a Datataker DT85 (Datataker Pty Ltd, Australia) linked to the internet and an 80 W laptop computer. Supporting climate data (total solar radiation on horizontal plane, wind speed & direction, ambient air temperature, ambient air relative humidity, rainfall) was collected from a weather station (Hobo Pty Ltd, USA) mounted to Building B. The air conditioner was manually switched from heating to cooling in early Spring 2010, and from cooling to heating in early Autumn. Building lights are always off, windows always closed and internal blinds fully drawned. Door use is minimised, and shut when researchers are inside.
Trees are automatically irrigated for 2 mintues every Tuesday and Friday at midnight. Pots are kept weed free and covered with coarse porous gravel to minimise surface evaporation. All pots are placed on paving slabs to prevent root exporation outside of the pot.

Figure 2. Schematic of one building instrumented with heat flux sensors, a heat pump and flanked on one wall by trees with one place on a lysimeter balance.

Data is presented from three 10 day periods in December 2010 (early summer), March 2011 (early autumn) and June 2011 (winter). Data collected ath the buildings are logged at 20 s interval and the weather data is logged at 10 min integrations. These are aggregated to hourly intervals and graphically presented. The lysimeter balance logs at 60 s intervals that are aggregated to an hourly scale to accommodate the heightened variability due to wind over short time periods. Daily water use is estimated from the sum of the hourly changes in tree (and pot) mass between 06:00 and 21:00. Daily total solar radiation received on horizontal plane (kW m^{-2}) is estimated from the sum of hourly radiation (W m^{-2}). The surface temperature of external west walls and the heat transfer rate through these west walls is presented for all three buildings at hourly intervals in these 10 day periods.

RESULTS AND DISCUSSION

Solar radiation understandable decreased from December > March > June and this is refelcted in overall patterns of estimated daily tree water use for both tree species (Figs 3 and 4). On days where there is rainfall, very often canopy interception and pot rainfall gain leads to a negative (mass gain) or reduced estimation of water use. Regardless, there was often a strong relationship between the patterns of hourly total solar radiation received on horizontal plane and hourly change in tree (and pot) mass and therefore daily tree water use (negative estimates not presented) (Figs 3 and 4).

In December, *E. sideroxylon* tree were using up to 6 L d^{-1}, and even in winter months, between 1 and 3 L d^{-1} (Fig. 3). Similarly, *F. excelsior* was using up to 6 L d^{-1} in December but after leaf loss during March this had decreased to approximately 0.3 L d^{-1}. This small water loss in winter, when ambient relative humidity is low, is due more to unavoidable evaporation from the pot soil surface (Fig. 4). It appears that in March 2011, there was greater water use by *E. sideroxylon* than *F. excelsior* under the same solar radiation conditions.

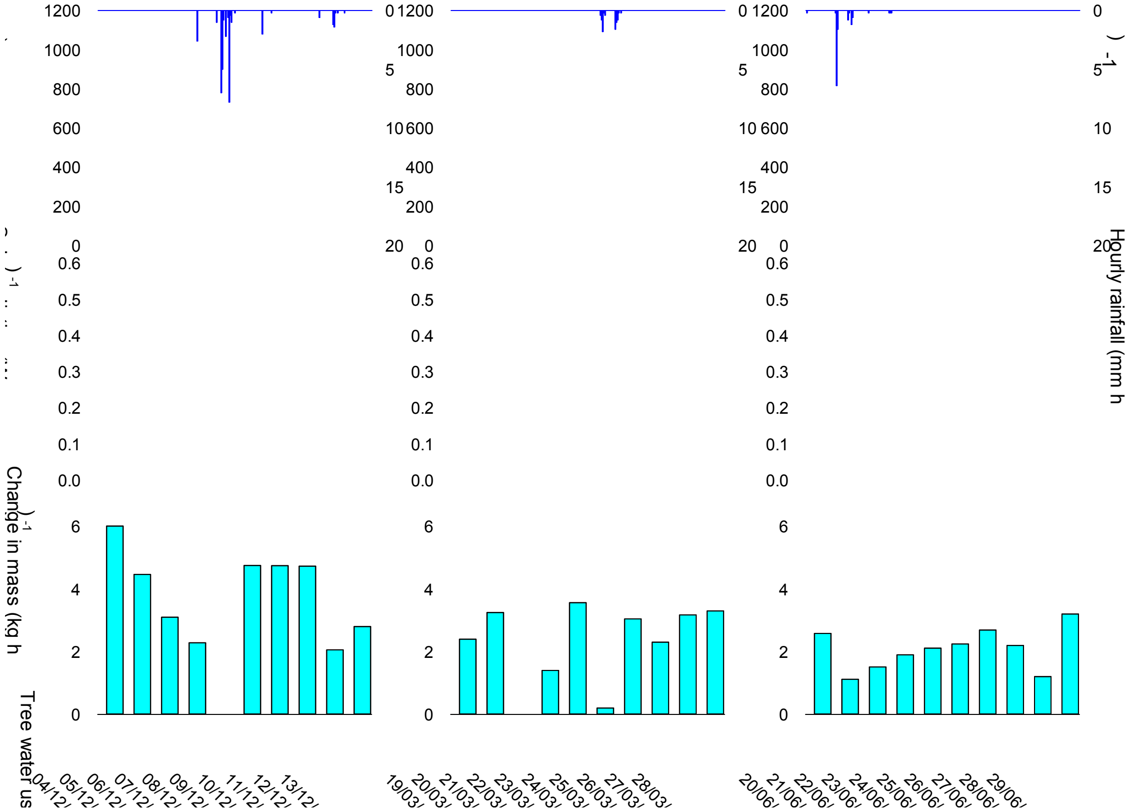

Figure 3. Solar radiation in relation to hourly change in tree (and pot) mass and therefore daily tree water use over 10 day periods in December 2010, March 2011 and June 2011 for a building with nine small Eucalyptus sideroxylon trees (3.5 m tall) placed along north and west aspects.

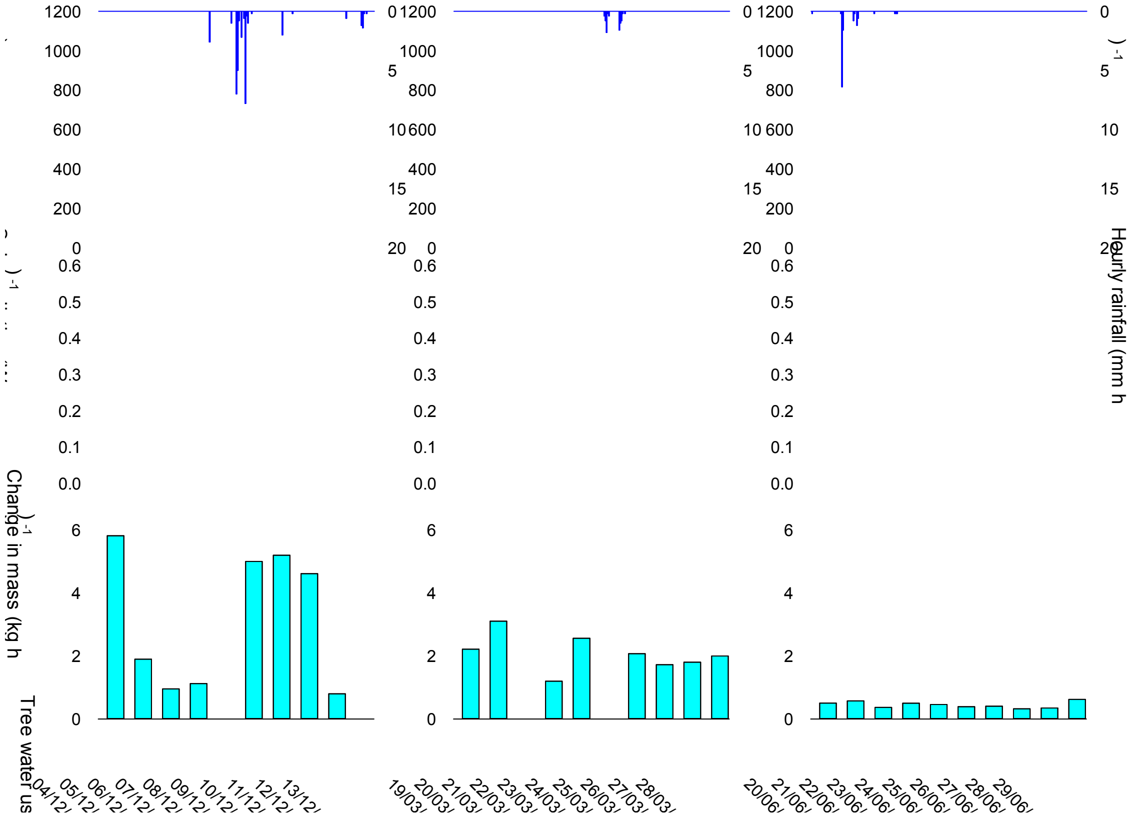

Figure 4. Solar radiation in relation to hourly change in tree (and pot) mass and therefore daily tree water use over 10 day periods in December 2010, March 2011 and June 2011 for a building with nine small Fraxinus excelsior trees (4.0 m tall) placed on the north and west aspects.

For the very same 10 day period it is evident that *F. excelsior* shade is able to singificantly reduce the external surface temperature of the western walls in comparison to the *E. sideroxylon* and no tree buildings in December 2010 (Fig. 5). On warm, high solar radiation days this can be > 10°C and a reduction in thermal load of up to 36% from even this thin Fraxinus canopy in comparison to no tree shade. In the 10 days presented in December 2010, the temperature reductions from *F. excelsior* shade ranged from 4 to 36%, whereas the reductions from *E. sideroxylon* shade ranged from 2 to 22%, in comparison to no tree shade. Akbari *et al.* (1997) reported up to 25% reductions in external wall surface temperatures as a result of shading, which is very similar to the greatest temperature reduction measured in December with the Fraxinus shade in our study. Figure 6 clearly shows that there is a strong direct relationship between solar radiation and external western wall temperatures regardless of canopy shade, except in December (hot summer) when this relationship breaks down, probably because of the impact of canopy shade. This figure also clearly shows that *F. excelsior* provides greater cooling load reduction benefits than *E. sideroxylon* under those higher solar radiation days.

In this study, *E. sideroxylon* has less cooling load reduction benefit, probably because of the lower leaf area and smaller size; i.e. the zenith of the summer sun is able to reach large sections of the northern and western wall in the middle of the day. The thermal load reduction benefits that *F. excelsior* provides are evident on all but he cloudiest of summer days (Fig. 5; left panels).

In March, when the sun's zenith is lower in the sky, *E. sideroxylon* appears to have a greater cooling load reduction benefit as compared to the no trees building. In March, the surface temperatures of the western walls of Eucalyptus and Fraxinus buildings are similar, probably because the Fraxinus trees have also started to loose their leaves (Fig. 5; central panels). In winter (June 2011), there is no obvious difference among the external wall surface temperatures of the three buildings (Fig. 5; right panels).

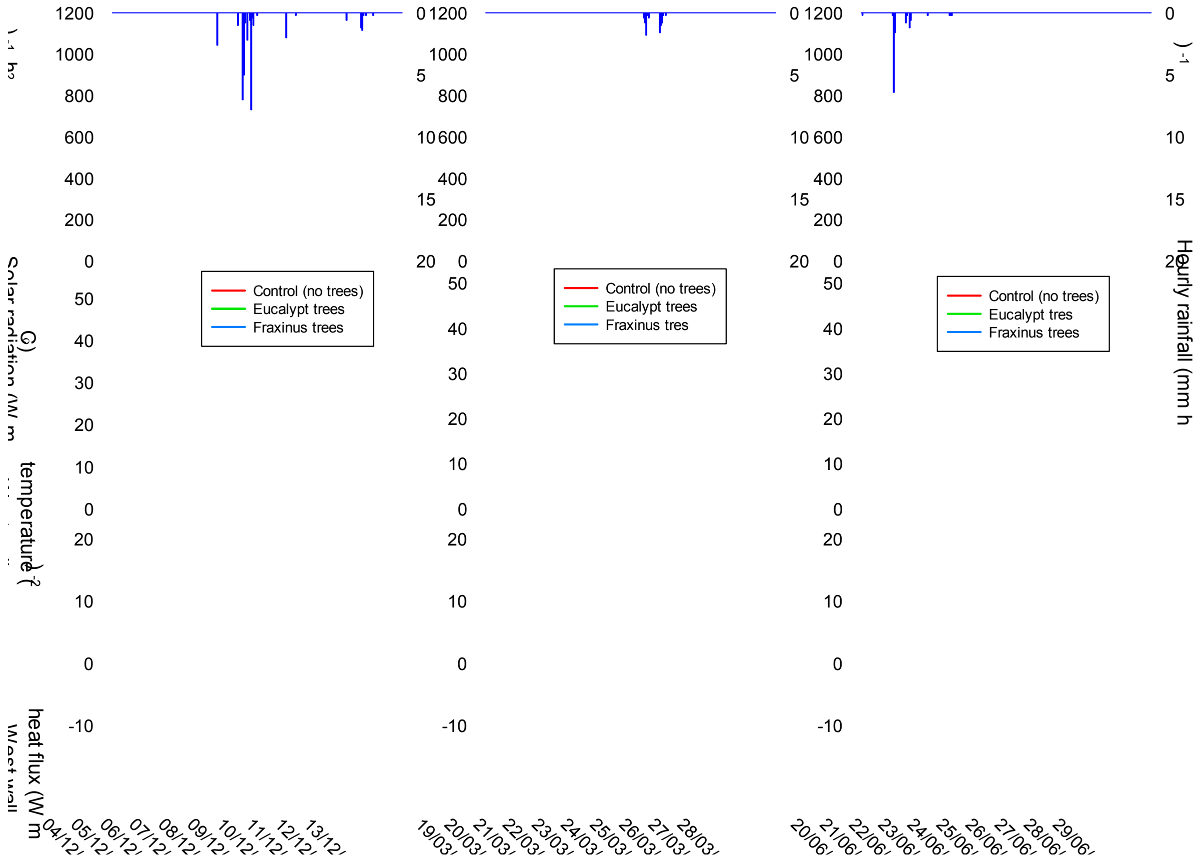

Figure 5. Solar radiation in relation to external western wall surface temperatures and heat flux (in and out) over 10 day periods in December 2010, March and June 2011 for a building with no trees and two buildings with trees (Eucalyptus or Fraxinus) placed on north and west aspects.

Internal wall heat flux closely mirrors the general patterns seen in external wall surface temperatures. In December, there is large inward heat transfer rate on high solar radiation days, when surface wall temperatures exceed 40°C. Inward daytime heat transfer rate is approximately halved by the *F. excelsior* sahde on these >40°C days. At night, all walls expereince outward heat transfer, although less so in the walls shaded by *F. excelsior* (Fig. 5; left panels). Donavan and Butry (2009) provide data that supports these observations stating that morning shade (eastern wall) is of little value as air-conditioning is not typically required at this time, whereas western shade offers the greatest benefit under highest solar radiation in summer.

In March, inward heat transfer rate is more similar among the three buildings during daytime, but there are clear differences at night, when outward heat transfer rate is less for the Fraxinus building and greatest for the Eucalypt building. Wheareas in winter (June 2011), there are minimal differences in heat transfer rate among the three buildings, probably because the heat transfer is invariably from inside the buildings outwards (Fig. 5; right panel).

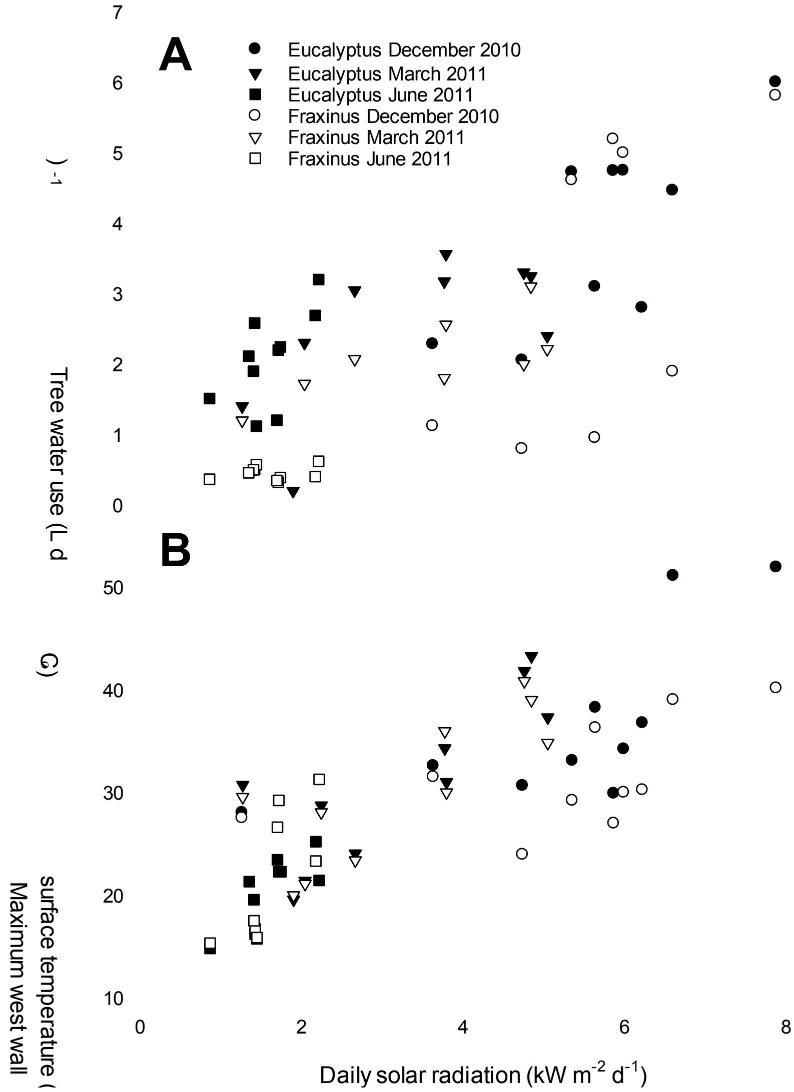

Figure 6. The realtionship between daily solar radiation and tree water use (A) and maximum surface temperature on western walls (B). Eucalypt shaded building data are closed symbols, whereas Fraxinus shaded building data are open symbols. The different months of data presented are indicated by contrasting symbols (●▼■). Note the reductions in external wall surface temperatures in December (●,○) from tree shade, and the considerably greatly reductions with Fraxinus shade (○).

The key differences between our study and those of previous researchers is that these trees no roof shade, which can be expected to greatly increase cooling load reduction and energy saving benefits. The data from this study will help to develop and apply similar mechanistic models of building energy balance to simulate the observed cooling load reductions and construct a full building energy balance with regards to space cooling and heating, and increasingly important part of Australia's building energy demand. Increasing tree canopy cover of buildings, as well as walkways/roadways, is a very cost effective 'urban heat island reduction' strategy or 'climate change adapation strategy' which has been shown to provide considerable energy use reductions at a city-scale for every dollar invested (Rosenzweig *et al.*, 2006). This study goes some way to demonstrating that this cooling load reduction and potential energy saving benefit also comes at a small water cost, an issue that has gained importance from the perspective of local government and the public. This water cost can be met through rainfall inputs for much of the year but may require summer irrigation support. At the rates of tree water use observed over 10 days in December 2010, three months of irrigation at 3.8 L d^{-1} would requie 357 L. Assuming a kilolitre (1000 L) cost of approximately $1.00, this is no cost at all, unless of course potable water reserves are perilously low.

CONCLUSIONS

This study has shown that even moderate tree shade can provide considerable cooling load reductions at the time when they are most needed; high solar radiation days of summer. The first hypothesis that deciduous tree shade would provide greatest reduction in summer cooling load and inward heat transfer was supported with this comparison of *E. sideroxylon* and *F. excelsior*. However, in summer, the most important factor is probably the shaded area by leafs rather than the deciduous or evergreen nature of the tree species.

There was no apparent benefit from winter warming of external western walls under the absent deciduous tree cover, which discounts the second hypothesis. However, the third hypothesis was strongly supported in that tree water use, external wall temperatures (and heat transfer rate) were strongly related to daily solar radiation levels. Importantly there is a negligible water cost required to support this vegetation.

These small scale empirical studies of cooling load and heat transfer at the wall and building scale are important steps in helping to develop, and validate, mechanistic models of building energy balance under different types and forms of vegetation shade. The methods and analytical tools are just as applicable to green walls and facades as to tree shade and hedgerows. Simulating shade cast by vegetation is poorly incorporated in current building simulationmodels (Hes et al., 2011) but this feature offers great potential as a low water cost, low carbon cost strategy to reduce energy use from space cooling and heating of residential and commercial buildings.

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