THE ROLE OF URBAN VEGETATION FOR CLIMATE ADAPTATION IN CITIES
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Introduction

One of the main climate change challenges in urban centres is the combined patterns of high density human habitation with increasing urban heat patterns. This is especially true of the urban heat island, where urban areas tend to have higher air and surface temperatures than their rural surroundings because urban form and materials store and trap heat (Oke, 1997). Prolonged urban heat events have also been highlighted as a factor in exacerbating several health problems within cities—including cardiovascular disease and diabetes (Kovats and Hajat, 2008). Additionally, heatwaves have been identified as a major climate change impact in cities and are often associated with increased human morbidity and mortality (Bambrick et al., 2011).

Green infrastructure, which typically refers to an interconnected network of multifunctional green spaces, strategically planned and managed to provide a range of ecological, social, and economic benefits (Wright, 2011), provides many benefits to cities in the context of climate adaptation (Shashua-Bar et al., 2009). Green infrastructure has a key role to play in reducing the amount of solar radiation that is absorbed into building materials such as walls, roofs and pavements during the day and released at night (Rizwan et al., 2008), and modelling studies show that increasing the proportion of tree canopy cover in the urban environment can reduce both surface and air temperatures (Alexandri and Jones, 2008). Empirical evidence highlights that temperatures under trees are lower than areas without trees (Shashua-Bar et al., 2009). Furthermore, strategically located trees adjacent to residential buildings can reduce the energy required for household cooling during hot weather through the provision of shade (McPherson et al., 2011; Pandit and Laband, 2010).

The combined issues of urban densification and urban heat island are particularly pertinent in Sydney, Australia, where the major planning paradigm is for increased residential densities through more compact urban form (Gray et al., 2010). The population of Sydney is projected to grow from 4.3 million to 5.6 million people by 2031 requiring an additional 545,000 homes and associated urban infrastructure (NSW Government, 2013). The majority of this growth is expected to occur within existing urban areas through urban consolidation. This process is transforming Australian suburbs, which typically are low density and characterised by single detached houses.

There are clearly many questions around the compatibility of strategies to increase green infrastructure in urban areas to reduce the urban heat island effect, given the trend for more compact and dense urban form, especially as houses built on smaller blocks of land tend to have smaller yards and less area for tree cover around homes (Hall, 2010). Here, we present a series of analyses undertaken in Sydney, Australia, where decision-makers are grappling with these issues of how to adapt to the likely impacts of climate change, while at the same time planning for a growing population. We report on summary findings of three interrelated investigations examining the relationships between tree and vegetation cover and thermal patterns of land surface temperature at the city, neighbourhood, and residential house scale to identify spatial relationships that affect the distribution of climate regulation benefits and the heat-related health risks to Sydney’s population.
Socio-spatial inequities of tree cover distribution across Sydney

Urban population growth is leading to growing concerns about land use change, green infrastructure provision and the loss of beneficial ecosystem services. Human and environmental health is supported by services such as climate regulation, air filtration and flood mitigation. However, maintaining these services within cities requires the retention and equitable distribution of green infrastructure near where people live. This study investigates the spatial distribution of green infrastructure within Sydney to determine how patterns of green infrastructure vary according to land use, residential density, as well as socio-economic advantage.

Initial investigations used Landsat 5 satellite imagery to investigate the distribution of vegetation and land surface temperature in Sydney. This broadly showed that vegetation cover, derived using the Normalized Difference Vegetation Index (NDVI) was the most important factor explaining variation in land surface temperature (LST), with LST negatively related to NDVI (Figure 1, Barnett et al. 2013). In other words, the hottest areas typically have little vegetation cover.

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<tr>
<th>Land surface temperature (LST)</th>
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<td>LST (°C)</td>
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Figure 1. LST and NDVI maps for Sydney derived from Landsat 5 satellite imagery captured on 2 February 2011 and clipped to Sydney’s urban boundary. Analyses of urban form and other environmental factors showed that the most important factor driving LST patterns across Sydney was NDVI (Barnett et al. 2013).

Distribution of vegetation cover across land uses

Although high levels of NDVI may indicate areas of lower LST, and potentially where climate regulation benefits are the greatest, relatively little is known about the distribution of vegetation cover in Sydney and if it is benefitting the most sensitive and vulnerable populations. Thus, an environmental stratification was conducted to identify the relationships between land use, residential dwelling density, tree canopy cover and areas of parkland across Sydney, using data sourced from the 2011 Australian Bureau of Statistics Census of Population and Housing and remote sensed data.

More than half of urban Sydney is comprised of residential land use (52%) (Figure 2a). This is more than double the next largest land use, parkland (23%). Not only are residential areas the dominant land use within urban Sydney, they provide a large proportion of Sydney’s green infrastructure with a mean Foliage Projection Cover (FPC) of 43% (Figure 2b).
Foliage Projection Cover, a measure of the percentage of ground area that is covered by the vertical projection of foliage from tall woody vegetation (Walker and Hopkins, 1990), was used to estimate canopy cover in these analyses (NSW Office of Environment and Heritage, 2011). Park and agricultural land each occupy a smaller area, but have a slightly higher proportion of tree cover than residential areas, with a mean FPC of 53% and 45%, respectively. Remaining land uses which include commercial, industrial and education all contribute to Sydney’s green infrastructure, but collectively comprise only one-quarter of the land area taken up by residential land use. Figure 2 highlights the substantial contribution of residential areas and parkland areas to Sydney’s green infrastructure as well as the shared responsibility (public and private) for this green asset.

Figure 2. For urban Sydney, (a) the area (km²) and (b) mean Foliage Projection Cover for six major land use types. Residential land use represents the largest contribution to Sydney’s green infrastructure (52%) and parkland second largest (23%). Parkland has a greater mean FPC (53%) than residential land areas (43%).

Effect of dwelling density on vegetation cover in public and private spaces

We also wanted to understand how residential density affected both public and private green infrastructure (indicated by parks versus residential tree canopy cover measures). There is a widely held view among urban planners that as urban densities are increased, any subsequent loss of private green infrastructure can be offset by increased access to or provision of public green infrastructure (Maat and de Vries, 2006), but there is little evidence this offset is actually occurring in cities around Australia (Byrne et al., 2010).

Residential dwelling density (number of dwellings per hectare of residential land use) was calculated for each suburb in Sydney from population and dwelling counts derived from the 2011 Census of Population and Housing (ABS, 2011) in order to see whether tree cover across Sydney suburbs, expressed by mean FPC, varies with changes in residential dwelling density. The amount of designated parkland in each suburb was also identified to test if there was a higher availability of public green space in areas where private (residential) tree cover was at a lower level. A regression model between the dwelling density (log transformed) and the amount of tree cover (log transformed), expressed as mean Foliage Projection Cover, of residential areas in Sydney suburbs (Figure 3), shows that with greater dwelling density, there is a decrease in the amount of residential tree cover (p<0.0001, t=-9.06, R²=0.269). Results also indicated a small decrease in the area of parkland within a suburb with an increase in dwelling density (p<0.01, t=-2.69, R²=0.034). As such, we found that there is not a greater amount of public parkland in high density residential areas to offset lower amounts of private green cover.
Figure 3. For each suburb in the Sydney UCL (n = 221), the log of residential dwelling density (dwellings/ha of residential land) was compared to (a) the mean Foliage Projection Cover (FPC) of the residential areas (log transformed) and (b) the percentage of land in each suburb that is designated as parkland (ABS 2012).

Distribution of tree cover can lead to inequities in green space access

Availability of private versus public green infrastructure, however, differs according to socio-economic advantage. Areas of high socio-economic advantage have significantly more private green cover, but slightly less public green cover than suburbs of greater disadvantage. In fact, tree cover in public parkland remains relatively high for all decile categories compared to private residential tree cover. In those areas where communities were more disadvantaged, the parkland tree cover provided a larger proportion of overall tree cover in these communities, largely due to the lack of tree cover in private residential areas.

Figure 4. Patterns of socio-economic advantage and disadvantage using the IRSAD Decile Categories defined in the ABS Census of Population and Housing (2011) and presented at SA1 scale in relation to private green cover (FPC of residential land) and public green cover (FPC of parkland). Patterns show an increase in private green cover (p<0.0001) and a slight declining trend in public green cover (p=0.0274) with increasing socio-economic advantage (Lin et al., 2015).
These findings highlight that urban densification can lead to a general loss of two important reservoirs of urban green infrastructure (public parkland and residential tree cover), but disadvantaged communities may have a greater reliance on public green infrastructure in the form of parkland due to a lack of private residential tree cover. This may have important ramifications during extreme heat events, as disadvantaged populations also tend to have a higher prevalence of heat-related health risk factors including the elderly, people living alone, and so on. Resources directed towards future urban greening must consider both public and private land and the equitable distribution of the climate regulation benefits from urban green spaces.

Understanding patterns of tree cover mediated climate regulation at the neighbourhood scale

Although vegetation cover has been associated with lower land surface temperatures, it is important to understand how these patterns play out at the neighbourhood scale, where people live and interact with their environment. Using fine resolution (2x2m scale) hyperspectral and thermal airborne remote sensing imagery, we examined a case study transect (Figure 5) in the northern suburbs of Sydney to sample climate and vegetation gradients and to evaluate how tree cover affects the climate regulation benefit of reduced land surface temperatures at the neighbourhood scale — that is houses, streetscapes, and parklands (Figure 6).

Figure 5. The location of the airborne remote sensing flight transect across northern Sydney, which was conducted on 6 August 2012 between noon and 2:00 PM. Also shown is the Mesh Block land use classification that is described by the Australian Statistical Geography Standard (ABS, 2010) (from Lin et al., in press).
Residential homes

Thirty houses were selected for the analysis of roof surface temperatures. To control for variation in the size of residential land parcels, properties were selected from within a range of 650–750 m², approximately the median parcel size within the transect. Google Earth was then used to perform a visual assessment, identifying houses with similar roof colour (grey-brown) and roof construction material (tile). By choosing similarly sized houses with similar roof types, in general, the houses have a similar development style. Only houses with tree canopy cover located on the north and north-western sides of the house were selected for inclusion in the analysis, ensuring maximum and consistent tree shadow given the direction of the sun during the time of the data collection flight (from true north the sun was 358° at noon and 317.5° at 2 PM).

Based on the analysis of the thirty houses sampled, a proxy measure of percentage tree canopy cover (defined by NDVI > 0.3) within a 15 m buffer centred on the north-western corner was used to assess the influence of tree canopy cover in the vicinity of the house (Figure 7). Mean roof temperature was reduced with an increase in tree cover to the north and west of the roofline. The model shows that a 10 percent increase in vegetation cover (NDVI > 0.3) decreases mean roof surface temperature by 0.74 °C ± 0.2 °C. The NDVI measure is considered to be a better measure than direct canopy cover as it includes tree canopy cover that is located beyond the immediate rooftop of the house, but able to cast shadows across the roof throughout the day.
Figure 7. Direct canopy cover footprints digitized in Google Earth to capture canopy over roofs. This was used to distinguish roof cover from tree cover in the temperature measurement. Building footprints were overlaid on land surface temperature thermal data in ArcGIS and green canopy areas were excluded from the thermal sampling on rooftops as they would represent cool areas not indicative of roof temperature.

Roads and streetscape

Road corridors were another dominant feature examined at neighbourhood scale. Road corridors not only comprise roads, but also a significant amount of road verge utilised for footpaths and street tree plantings.

Figure 8. Road side vegetation can provide benefits for both private space (additional shade canopy for cooling residential houses) as well as public space (cooling of streets for walking and parking of vehicles).
When looking at the road corridor analyses \( (n = 1353) \), the proxy measure for tree canopy cover (NDVI > 0.3) had a highly significant negative relationship with the mean and maximum surface temperature of the non-vegetated ground surface (NDVI < 0.1 was considered pavement). The greater the percentage of vegetation within the road corridor, the cooler the surface temperature of the roads and footpaths with lower maximum and mean temperatures \( (p < 0.0001) \) (Figure 8). Based on the regression models that were developed, it was estimated that a 10 percent increase in vegetation cover (NDVI > 0.3) would result in a decrease in the mean road surface temperature by 0.37 °C ± 0.02 °C and maximum road surface temperature by 0.45 °C ± 0.02 °C.

**Parkland areas**

The objective of the park analysis was to determine the influence of vegetation, as expressed by FPC, on land surface temperature (LST). To perform this analysis, 1518 random points were selected within parklands along the transect. Examination of the relationship between vegetation (measured using percent FPC) and surface temperature within parks revealed higher FPC was associated with lower surface temperatures in parks \( (p < 0.001, R^2 = 0.324) \). In parks, the higher the density of tree cover, the lower the surface temperature.

Overall, these analyses at neighbourhood scale have shown that increased tree cover around homes, and in streets and parklands can significantly reduce LST, potentially leading to greater use of outdoor spaces (Takano et al. 2002) and reducing heat-health impacts (Kilbourne et al., 1982; Vdentorren et al., 2006).

**Understanding the potential for tree shade to provide climate regulation services at the household scale**

While numerous studies have investigated the effects of tree shade on the energy requirement for heating and cooling of residential buildings (McPherson et al., 1988; Pandit and Laband, 2010), there has been little consideration of how this influence might vary with climate change. Although all new homes in Australia are required to meet minimum energy and water efficiency standards (Ambrose 2008), much of Australia’s existing housing is 20 years of age or older and built with little thought for climate change or sustainability.

Disadvantaged populations are more likely to reside in older, poorer quality housing, often in locations of high climate change risk, with few resources to invest in climate adaptation. Although air-conditioning is considered a protective solution against heat-related illness (Vdentorren et al., 2003), in low-income households, this solution may often not be utilised due to concerns over the cost (Farbotko et al., 2011).

Passive shading options, including the use of vegetation, can also modify the thermal performance of buildings (McGee and Reardon 2013). The effectiveness of trees for providing shade is determined by a number of factors, including tree size, shape, canopy porosity, and the direction and distance of the tree relative to the building (Simpson and McPherson 1996). As trees block incoming solar radiation, they have the potential to ameliorate the effects of climate change by reducing the energy requirement for artificial cooling of residential buildings as well as the associated heat-related health risk that is posed to occupants.

Little is known about the impacts of tree shade on the thermal performance of housing under projected climate change. Here we explore how differing tree size, differing leaf-fall habits (deciduous and evergreen), and differing planting strategies (distance from and orientation to the house) may affect building thermal performance. We present results of computer simulations for one house (referred to as House 1), which represents a three bedroom, fibrous cement sheet house with a gross floor area of 101.5 m² (Figure 9). It is assumed no ceiling insulation is installed and windows are single-glazed with aluminium frames. House 1 has a thermal performance of 0.8 stars assessed using the Australian Nationwide House Energy Rating Scheme (NatHERS). It represents one of several common low-income house types (Barnett et al. 2013).
Building thermal performance was simulated for House 1 using AccuRate, a benchmark house energy rating tool commonly used in Australia (Delsante 2005). The software calculates the energy requirements and thermal comfort of residential buildings for every hour in a year (n = 8760). Simulations were repeated for climates centred on the years 2000, 2030 and 2070. Changes in the annual heating and cooling (H/C) energy requirement were estimated using common assumptions about thermostat settings for mechanical heating and cooling (ABCB 2006). Heat-related health risk was estimated using the Discomfort Index (DI) developed by Epstein and Moran (2006), with values above 28 representing a severe level of health risk. AccuRate uses information on tree size and height, canopy porosity, distance to house, sun angle, and various wall surface information (including windows and doors) to simulate the influence of tree shade on buildings (Figure 10).

Twenty individual tree shade simulations were run in AccuRate for House 1, with variations of trees that were either large evergreen or large deciduous and positioned 15 m from the house, or small evergreen or small deciduous located 5 m from the house. Results from individual tree scenarios were used to develop mixed tree scenarios to determine the influence of multiple trees on building thermal performance. The mixed scenarios were based on the individual scenarios that were most effective at reducing H/C energy requirement (Figure 11).
Results from the mixed tree scenarios were compared to baseline ‘no trees’ scenarios to identify how tree shade alters building thermal performance. The results of the ‘no trees’ scenarios are presented in Figure 12. What these results show is that for the climate baseline in the year 2000, H/C energy demand for House 1 was substantially heating dominated, by 2030 was almost balanced in heating and cooling requirements, and by 2070 was primarily cooling dominated. This means that irrespective of tree shade, the performance of House 1 will change with climate change. This is also the case in terms of the Discomfort Index, with the annual hours DI exceeds the threshold value of 28 increasing substantially in 2030 and again in 2070.

Results for the mixed tree scenarios are presented in Figure 13. In the year 2000, House 1 has savings of less than 2% of H/C energy when trees are planted to the east and west (M1), but requires more energy if trees are also planted to the north (M2) as shown in Figure 11. The additional heating that is required in winter negates any savings due to the reduced need for cooling in summer. By 2030, House 1 achieves savings of 3.3% with the addition of trees to the north (M2). In 2070, the scenario with the most amount of shade (M2) delivers H/C energy savings of 5.8%. What this reveals is that there is an optimal pattern to staging the planting of multiple trees around a house to avoid increased costs and to maximise savings on heating and cooling, but this staging varies with climate change as the heating to cooling ratios change (Figure 11).
Figure 13. Change to heating, cooling and total annual energy requirement when compared to a ‘no trees’ scenario. The climate data is centred on the years 2000, 2030 and 2070 and results presented for House 1.

In the current Sydney climate, tree planting for the provision of shade to buildings should be staged over time. Initially, trees are best located to the east and west of the house, allowing solar access in winter while blocking solar heat gain in summer. As the climate warms, trees to the north will provide increasing benefit. To reduce the heat-related health risk to occupants, the more trees that are located around houses with poor thermal performance the better, but air-conditioning may still be required to attain safe levels of comfort. Tree shade can reduce heat-related health risk, but will not fully compensate for climate change.

Conclusions

Such research highlights the extent to which vegetation can contribute to climate regulation benefits across a city, within public and private neighbourhood areas, as well as within homes. Although the overall pattern of vegetation cover has a significant effect on urban microclimates, vegetation cover across Sydney is not evenly distributed. Because vegetation cover is skewed towards residential land use and areas of greater socio-economic advantage, it is important to consider the future distribution of green infrastructure planning in public areas as well as more disadvantaged areas. Within neighbourhood areas, we show that tree cover can have a significant impact on rooftops, streetscapes, as well as parklands. Strategic planning of tree cover throughout a neighbourhood could have significant benefits in providing cool pathways for walking and social interaction where people live and recreate. Additionally, tree shade around homes, to the east and west, and increasingly to the north, will be important in Sydney under a warming climate.

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References


