WESTERN SYDNEY
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URBAN HEAT MITIGATION IN SYDNEY, AUSTRALIA – TREE EFFECTS AND POLICY CONTEXT

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Statement of Authentication

The work presented in this thesis is, to the best of my knowledge and belief, original except as acknowledged in the text. I hereby declare that I have not submitted this material, either in full or in part, for a degree at this or any other institution.

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Signature

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List of Abbreviations

ABS	Australian Bureau of Statistics
A_C	Vertically Projected Crown Area (m^2)
AEST	Australian Eastern Standard Time
ATLAS	Advanced Thermal and Land Applications Sensor
BoM	Bureau of Meteorology
CBD	Central Business District
CDD	Cooling Degree Day
CO_2	Carbon Dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DBH	Diameter at Breast Height (cm, 1.3 m above ground)
DCP	Development Control Plan
DP	Development Plan
EPI	Environmental Planning Instruments
ESS	Environmental Sustainability Strategy
GI	Green Infrastructure
GLM	Generalized Linear Model
GSD	Ground Sample Distance (m)
GT_S	Shaded Globe Temperature (°C)
GT_{SL}	Sunlit Globe Temperature (°C)
LA	Local Authorities
LAD	Leaf Area Density
LAI	Leaf Area Index (m^2 m^{-2})
LCZ	Local Climate Zone
LEP	Local Environmental Plan

LGA	Local Government Area
LST	Land Surface Temperature (°C)
NSW	New South Wales
NT	Northern Territory
PAI	Plant Area Index
PET	Physiologically Equivalent Temperature (°C)
QLD	Queensland
SA	South Australia
SEPP	State Environmental Protection Plan
SVF	Sky View Factor (unitless, from 0 to 1)
T_{Abs}	Absolute Maximum Air Temperature (°C)
T_{Dmean}	Mean Day-time Air Temperature (°C)
T_{max}	Mean Maximum Air Temperature (°C)
T_{mean}	Mean Air Temperature (°C)
T_{min}	Mean Minimum Air Temperature (°C)
T_{Nmean}	Mean Night-time Air Temperature (°C)
UF	Urban Forest
UHIE	Urban Heat Island Effect
$UHIE_{atm}$	Atmospheric Urban Heat Island Effect
$UHIE_{sub}$	Sub-surface Urban Heat Island Effect
$UHIE_{surf}$	Surface Urban Heat Island Effect
VIC	Victoria
WSUD	Water Sensitive Urban Design
WSROC	Western Sydney Regional Organization of Councils
ΔT_A	Air Temperature Differential (°C)

ΔT_{AS}	Air Temperature Differential in the Shade (°C)
ΔT_{ASL}	Air Temperature Differential in the Sunlight (°C)
ΔT_{G}	Globe Temperature Differential (°C)
ΔT_{S}	Surface Temperature Differential (°C)
ΔT_{SL}	Surface Temperature Differential in the Sunlight (°C)
ΔT_{SS}	Surface Temperature Differential in the Shade (°C)

Thesis Summary

Rapid urbanization, land use modification and anthropogenic heat emission have accelerated the Urban Heat Island Effect (UHIE) in cities. The UHIE can be defined as the "discernible temperature difference between urban and adjacent rural areas caused by the excess heat emitted and the solar gain trapped by the urbanised environment" (Gartland, 2008). Trees provide cooling through evapotranspiration and surface shading. This thesis takes a transdisciplinary approach to assess the efficacy of trees in cooling urban spaces in Sydney and how well this function is embedded in government policies. The first experimental chapter investigates the effect of tree crown characteristics on surface temperature across a range of common surface materials. Across Greater Sydney, canopy characteristics (leaf area index and vertically projected crown area) were measured in 471 free standing trees that belonged to 13 species. Surface temperatures were recorded under the canopy of each tree in the shade and in full sun next to each tree. Linear regression analysis indicated that there were no significant relationships between canopy characteristics and surface temperature. However, surface materials had a significant impact on surface temperatures ($p < 0.001$). The largest surface temperature differential (ΔT_S) of tree shade was found by shading bark mulch (ΔT_s = -24.8 °C), followed by bare soil (ΔT_s = -22.1 °C), bitumen (ΔT_S = −20.9 °C), grass (ΔT_S = -18.5 °C) and concrete pavers (ΔT_S = -17.5 °C). The present research is novel and useful, since urban planners can take advantage of it when designing more heat-resistant urban landscapes by incorporating cooler surfaces, such as grasses under trees, instead of pavers.

Microclimates result from local variations in the amount of heat or water received or trapped near the surface. Generally, microclimates are warmer than their surroundings since they receive more energy. The second experimental chapter investigates how urban microclimate is influenced by different combinations of surface cover. Temperature loggers were installed in 156 locations and air temperature was recorded at 10-minute intervals during summer from

December 2018 to February 2019. The polygon tool in Nearmap was used to digitize a circle with a 50 m radius around each location where a temperature logger was installed to determine the variability of the surface cover. The findings indicate that tree canopy had the greatest effect on reducing mean air temperature (T_{mean}) and mean day-time air temperature (T_{Dmean}). The analyses revealed that 1 °C cooling of summer T_{mean} could be achieved by increasing tree canopy cover by 40%. The same cooling effect could be achieved for T_{Dmean} by increasing tree canopy cover by 50%, indicating that daytime cooling requires more canopy cover compared to cooling T_{mean}. However, the effect of tree canopy cover on air temperature cooling was limited at night. This limited effect is due to lack of transpirative cooling at night, low sky view factor and trapped warm air underneath tree crowns. Conversely, increasing the proportion of grey infrastructure like buildings and roads contributed to the warming all the time. The results of this research indicate that increasing the area covered by open green spaces with a sparse arrangement of trees (>40%) would be ideal to cooling down the ambient urban summer air temperatures during the day and night.

The third chapter assessed key policies in relation to the best use of urban trees in mitigating UHIE. A thematic policy analysis was conducted by coding five policy documents from Parramatta Council (New South Wales), nine from Cumberland Council (New South Wales) and four from The Cities of Unley and Mitcham (both South Australia). Provisions linking urban trees and heat mitigation were not present in the statutory planning documents of Parramatta and Cumberland councils whereas the Development Plans (DPs) of The Cities of Unley and Mitcham contained such provisions. The Tree Strategy document of The City of Unley stood out among all analysed strategic documents due to its exceptionally well-designed action plans to increase tree canopy cover. Unley's urban tree strategy included key directions for increasing and protecting canopy cover by garnering the collective support of all relevant stakeholders. Furthermore, they conduct regular tree audits to check the health of the trees, maintain an asset management plan for trees, and encourage private landowners by offering attractive incentives. The policy analysis enabled formulation of recommendations that could improve the status of urban trees as important assets for heat mitigation in the two analysed local governments in New South Wales and densely populated urban landscapes elsewhere. Most importantly, the Local Environmental Plans should integrate science-based evidence of tree cooling to broadly elevate the importance of urban trees as cooling devices in warming cities. Development of an overarching tree management plan, regular tree audits and establishment of a tree data repository would further strengthen the role of urban trees in strategic asset management. Councils should also design attractive incentive schemes to encourage landowners to plant and retain trees on private land.

Overall, this research showed that both science and policy play a key role in the pathway to achieve urban cooling. Effective urban heat management must be guided by comprehensive urban planning policies. Therefore, the key planning policies of local and state government agencies should contain a standalone provision for urban heat management. While there are numerous scientific studies conducted in Australia on UHIE, their integration within strategic planning at local and state government levels is currently inadequate. Surprisingly, none of the councils examined in the study had firm canopy cover targets associated with expected cooling benefits. This indicates that policy makers at all government levels need to have a deeper understanding about urban heat and how to reduce it or adapt to it. This research provides new strategic guidance to better understand spatial and temporal variability of urban heat and offers improvements to existing practices for planting and managing urban trees.

Chapter 1: Introduction

1.1 Urbanisation

At present, the global human population stands at 7.8 billion and is increasing at a rapid pace (United Nations, 2019). It is estimated that 70% of the world's population will be living in cities by 2050 (United Nations, 2019). Migration from rural to the urban areas, higher birth rates compared to deaths and urbanization of formerly rural areas are the primary drivers to population growth in cities (Lerch, 2017). Since 2007, more people live in urban compared to rural settings for the first time in human history. However, urbanization patterns of developed regions are markedly different (e.g., slower) from the less developed regions (e.g., faster) in the world (Fig. 1.1). By 2050, less developed regions will host nearly 83% of the world's urban population and 87% of total world population.

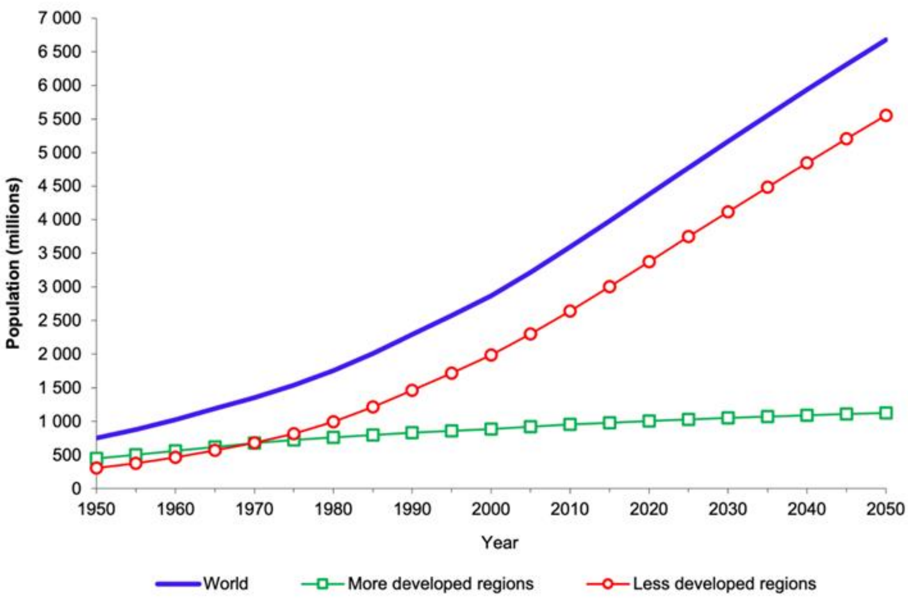

Figure 1.1: Historic and projected urban population in the world in more developed and less developed regions from 1950 to 2050. By 2050, with 5.6 billion urban dwellers, the less developed regions are projected to have 83% of the world's urban population and 87% of the total world population. (Image © United Nations, 2019)

Urbanization will be responsible for an expansion of urban land by 1.2 million km^2 between 2000 and 2030 (Seto et al., 2014; Angel et al., 2011). Urbanization affects culture, lifestyle, consumption patterns and behaviours of urban dwellers (Montgomery et al., 2013). It also creates economic opportunities, improves transportation, and results in more accessible infrastructure. Yet, urbanization and the resulting human activities account for nearly 80% of the global carbon dioxide (CO_2) emissions (UN Habitat, 2011). Given that CO_2 is a powerful greenhouse gas, it is reasonable to state that urbanization and cities as dynamic and growing entities are major drivers of human-induced climate change.

1.2 Urban heat

While all cities contribute to climate change, some cities are highly vulnerable to it through sea-level rise and extreme weather events (heatwaves, cold waves, floods, cyclones, hurricane) than others (While & Whitehead, 2013). Extreme weather events are also becoming more common and many cities across the world are affected. In June 2021, a number of cities in the United States were impacted by the Pacific Northwest Heatwave. During the heatwave, Seattle (WA) and Portland (OR) reached record high air temperatures exceeding 45 °C. This heatwave caused 1800 hospitalizations and more than 500 deaths (Silberner, 2021). The UK experienced a record-breaking heatwave in July 2019. The average temperature across the UK exceeded 35 °C and caused nearly 900 deaths related to regional heatwaves (Met Office, 2019). The 2003 European heatwave took more than 70,000 lives (Robine et al., 2008), of which many were lost in cities.

Across the Australian continent, the near surface air temperature has increased on average by 1.44 °C ± 0.24 since 1910 (Commonwealth Scientific and Industrial Research Organisation (CSIRO), 2020). This widespread warming has resulted in more frequent extreme heat events, and it is predicted that the frequency, intensity, and duration of heatwaves in

Australia will increase further (CSIRO, 2020). In December 2019, a total of 11 days had a national area-averaged maximum of 40 °C or above, seven of them were recorded consecutively from 23 to 29 December (Fig. 1.2) (Bureau of Meteorology (BoM), 2020a). Penrith, New South Wales (NSW) recorded the highest known temperature (48.9 °C) in the Sydney Basin on 4 January 2020 (BoM, 2020a). This is the new record maximum value measured by an official weather station for any metropolitan area in Australia. Researchers recorded near-surface air temperatures as high as 52.0 °C in the region during this extreme event (Pfautsch et al., 2020).

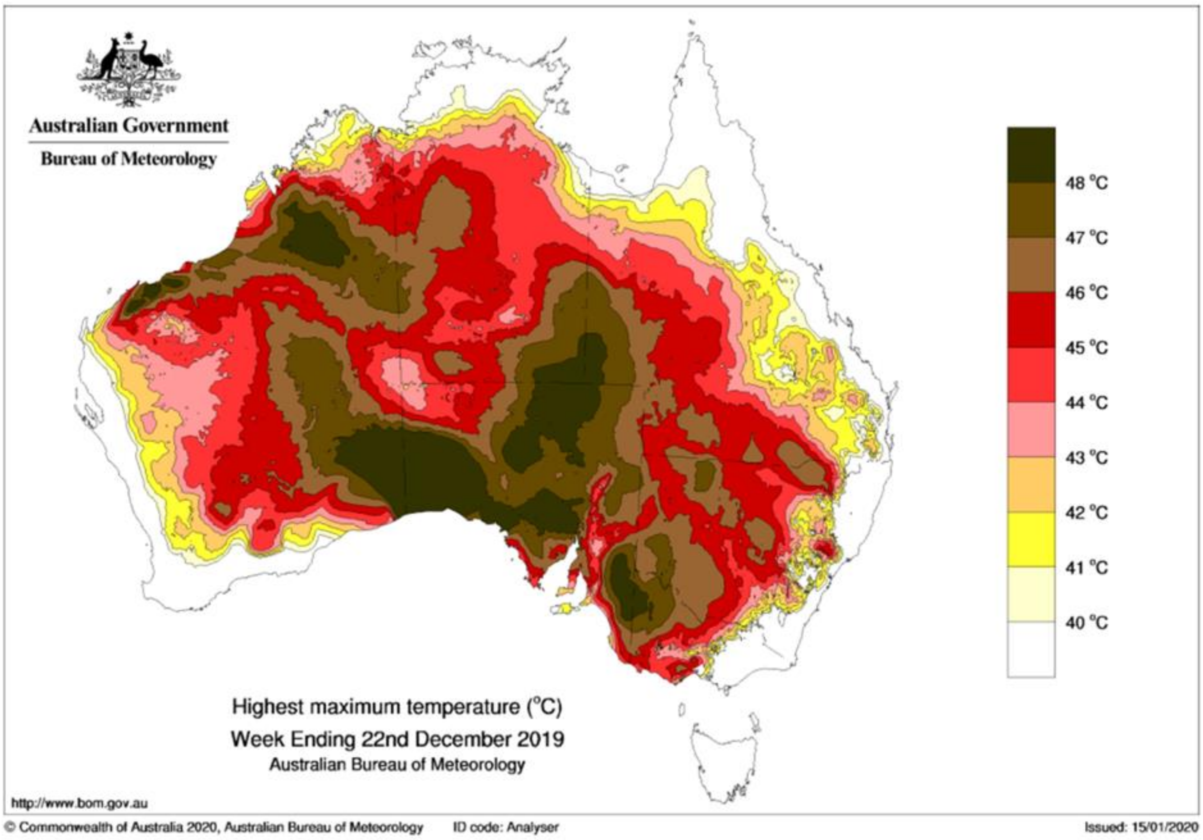

Figure 1.2: Map of Australia showing widespread and extreme heat across the entire continent. Temperatures shown are the highest daily maximum temperatures from 16–22 December 2019. (Image © BoM, 2020a)

The Australian Bureau of Meteorology (BoM) defines a heatwave as “three or more consecutive days when both daytime and night-time air temperatures are unusually high in relation to the local long-term climate and the recent past" (BoM, 2021). Heatwaves are climate dependent, meaning that the same meteorological conditions can constitute a heatwave in one place but not another (McGregor et al., 2015). The BoM classifies heatwaves into three types namely, low-intensity heatwaves, severe heatwaves and extreme heatwaves (BoM, 2021). This classification system is based on the level of impact that heatwaves have upon the community. Low-intensity heatwaves are more frequent during summer and most people can cope with weather conditions during these heatwaves. Severe heatwaves are less frequent and are likely to be more challenging for vulnerable people such as the elderly, particularly those with medical conditions. Even healthy people may suffer severe health issues if they do not take precautions during extreme heatwaves. People who work or exercise outdoors are also at greater risk of being affected by extreme heatwaves.

It is expected that the average annual number of heatwave days in Australia will increase from 10, as occurred in the 20th century, to 25 by the middle of the 21st century (PWC, 2011). In 2019, 43 extremely hot days (>40 °C) were observed in several parts of Australia which is more than triple the number during any of the years prior to 2000. This increasing trend is observed at locations across all of Australia (CSIRO, 2020). Major cities in Australia and their populations face similarly challenging heat conditions, with doubling of very hot days (>35 °C) by 2070 as a result of climate change (Zuo et al., 2015). Heatwaves have not only a significant negative impact on people's health and wellbeing, but importantly also on infrastructure performance and energy demand (Tong et al., 2017; Wu et al., 2012; Hanna et al., 2016).

Historically, heatwaves in Australia lead to more deaths compared to those caused by other natural hazards like floods, storms, bushfires and tropical storms combined (Changnon et al., 1996; Coates, 1996; Nairn et al., 2015). The January 2009 heatwave in Victoria killed over 370 people (Alexander & Tebaldi, 2012; Perkins-Kirkpatrick et al., 2016) with an insured loss of US$1.3 billion (Perkins-Kirkpatrick et al., 2016). Further, Australia was ranked within the top one-third of countries in a global assessment of heat-related morbidity risks (Li et al., 2015). In the recent past, the number of heatwave days in Australia has increased by 2 days per decade (Perkins-Kirkpatrick et al., 2016) and all-cause mortality during summer compared to winter has increased during the last 40 years (Bennett et al., 2014). These increases are attributed to more frequent and intense heatwaves. In addition, many households may not have the necessary disposable income to afford the use of air conditioners, which puts public health at risk during extreme heatwave events. Additionally, the poor thermal efficiency of Australian buildings has a greater impact on marginalised and disadvantaged communities (Byrne et al., 2016). However, improvements in medical care, advanced technologies and heatwave management have significantly reduced heatwave related death tolls compared to the past (Coates et al. 2014; Bi & Walker, 2001).

1.3 Urban Heat Island Effect (UHIE)

Effects of heatwaves are amplified by the Urban Heat Island Effect (UHIE) in cities (Habeeb et al., 2015). The UHIE can be defined as the "discernible temperature difference between urban and adjacent rural areas caused by the excess heat emitted and the solar gain trapped by the urbanised environment" (Gartland, 2008). The UHIE is often associated with buildings and other urban structures that have low reflectivity, also termed '*albedo coefficient*'. Albedo is the ratio of reflected radiation to incident radiation from a surface. Low albedo can result in high absorption of solar radiation by buildings and other urban infrastructure from where it is re-radiated as sensible heat (Giuseppe & D'Orazio, 2015) (Fig. 1.3). In addition, UHIE is influenced by meteorological parameters like humidity, wind speed, clouds and location-specific microclimatic conditions (Santamouris et al., 2015a). People living in urban areas are likely to depend on air-conditioned buildings, artificial lighting, and air-conditioned transport. The additional heat generated by this lifestyle further contributes to the UHIE (Salamanca et al., 2014; Gartland 2008; Priyadarsini, 2009).

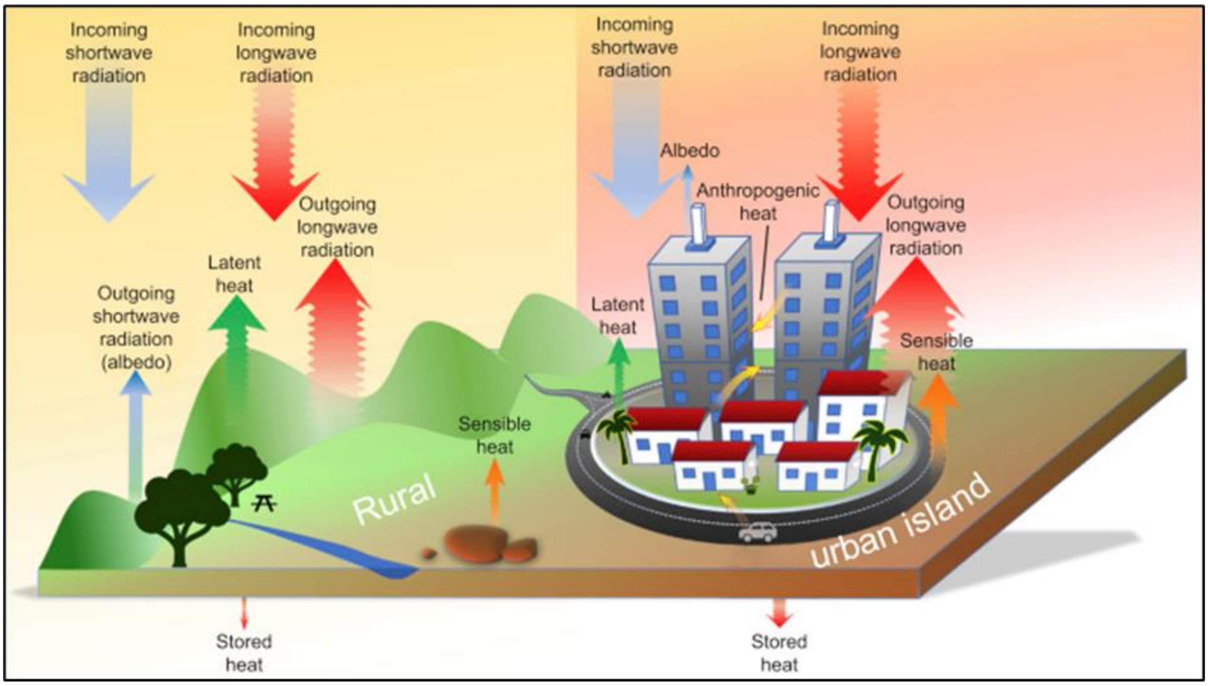

Figure 1.3: Schematic illustration of energy fluxes in rural and urban areas. The combined effect of lower albedo, lower latent heat flux, more stored heat, larger sensible heat emissions and additional anthropogenic sources of sensible heat leads to warming of cities compared to rural landscapes. (Image © Jamei & Tapper, 2019)

Modifications to natural surfaces as result of urbanization is the main cause for UHIE (Kukulska-Kozieł et al., 2019; Sultana & Satyanarayana, 2020; Sherafati et al., 2018; Zhou et al., 2014), which can be evaluated using two different temperature metrics. The air temperature data collected at weather stations in urban and rural areas (Oke, 1973) is used to derive atmospheric UHIE ($UHIE_{atm}$) while the UHIE derived from remotely sensed Land Surface Temperatures (LSTs) is known as surface UHIE ($UHIE_{surf}$) (Li et al., 2011; Sachindra et al., 2016). On average urban-rural air temperature differences are usually 4 ºC but can increase up to 10 ºC (Oke, 2006; Manoli et al., 2019). The UHIE is more pronounced at night (Sachindra et al., 2016). This is because buildings and roads in urban areas retain more heat during the daytime than trees and at night, these structures slowly emit the stored heat making the air warmer. Tall and narrow urban canyons can further contribute to UHIE at night by trapping this warm air. For example, built-up, densely populated areas in central Paris showed a very high nocturnal $UHIE_{surf}$ of up to 2.5–3.0 ºC (Lemonsu et al., 2015) (Fig. 1.4). Yet, the daytime $UHIE_{surf}$ was much less intense (between 1.0 and 1.5 °C) and spread over a much larger area (Lemonsu et al., 2015).

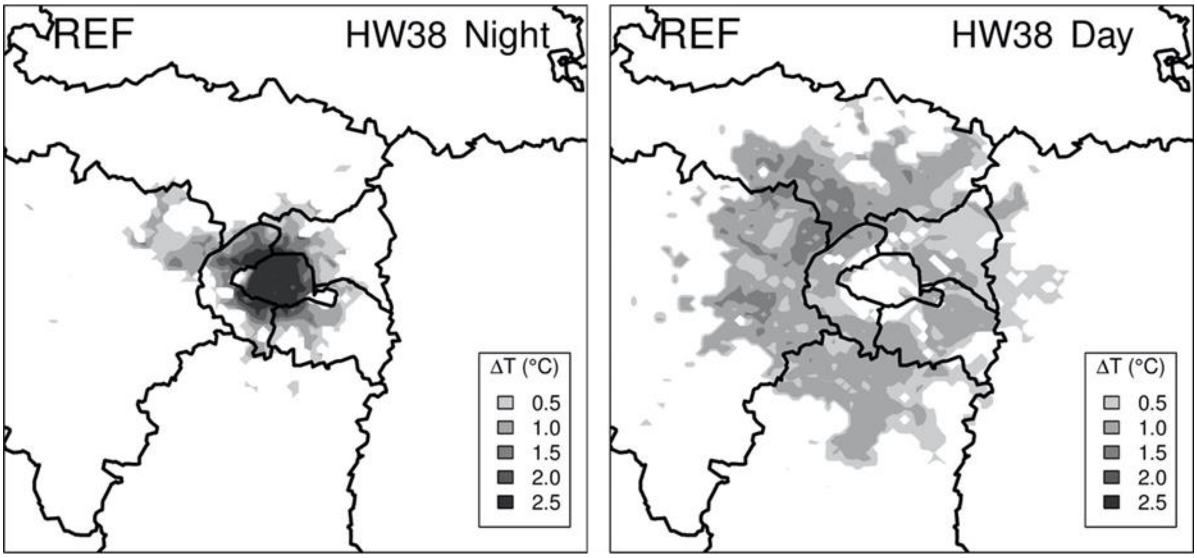

Figure 1.4: Spatial representation of the nocturnal and diurnal Urban Heat Island Effect (UHIE) in Paris (France). (Image © Lemonsu et al., 2015).

Returning briefly to heatwaves, $UHIE_{surf}$ during such extreme conditions were 0.4 °C to 2.8 °C higher compared to non-heatwave periods in 50 cities of the United States (Zhao et al., 2018). In Athens (Greece), the $UHIE_{atm}$ during a heatwave was 3.5 °C stronger than during non-heatwave periods (Founda & Santamouris, 2017a). Also in Australia, a warmer $UHIE_{atm}$ (1.4 °C and 1.2 °C) at night during heatwave periods compared to non-heatwave periods was documented in Melbourne and Adelaide (Rogers et al., 2019). On the contrary, night-time $UHIE_{atm}$ was 1.3 °C cooler during heatwave periods at night compared to non-heatwave periods in Perth (Rogers et al., 2019).

Urban activities also largely contribute to the development of UHIE (Radhi & Sharples, 2013). For example, higher diurnal and nocturnal air temperatures observed in an industrial compared to a residential area of Athens (Greece) was attributed to the increased urbanisation, industrialisation, increased anthropogenic heat flows and the lack of vegetation (Giannopolulou et al., 2011). Similarly, industrial areas showed the highest daytime land surface temperature (LST) followed by commercial locations, airports, residential and park areas in Singapore (Jusuf et al., 2007). Furthermore, significantly higher LSTs were observed in commercial/industrial areas compared to parks/recreational land and waterbodies in Toronto (Canada) (Rinner & Hussain, 2011). The elevated surface temperature in commercial/industrial areas were attributed to high proportion of built-up surfaces and lack of vegetated areas.

There are several studies from Australia that have determined the UHIE in major cities. Climate data obtained from six meteorological stations spanning the interval between 2005 and 2015 showed that the atmospheric UHIE across Sydney mainly developed in the summer and its magnitude varied between 1 °C and 11 °C (Santamouris et al., 2017a). Another study assessing the surface UHIE in Sydney used Terra/Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) LST time series data from 2003 to 2015 (Sidiqui et al., 2016) and found that the magnitude of daytime surface UHIE varied between 7–8 °C in summer while the night-time surface UHIE was much less pronounced during any season. Climate data collected from four country towns in the state of Victoria showed a smaller, yet significant atmospheric UHIE with an average magnitude of 1.2 °C (Torok et al., 2001).

1.4 Land cover and surface temperature

The UHIE has become more prominent with rapid urbanization and accompanying conversion of land (Leal Filho et al., 2018). Macroscale studies have been conducted to investigate urban and rural temperature differences. Most of these studies have incorporated satellite remote sensing methods to capture the LSTs of different landscapes (Kaplan, 2019). ASTER (Del Pozo et al., 2020), Landsat TM (Surawar & Kotharkar, 2017; Tsou et al., 2017; Zhang et al., 2017) and MODIS (Del Pozo et al., 2020; Das et al., 2020) are the commonly used satellite sensing instruments to map the UHIE. Generally, LST values are retrieved from satellite images by converting the digital information to radiance, which then is used to acquire at-satellite brightness temperature (Estoque et al., 2017; Chander et al., 2009). Fig. 1.5 shows the LST maps of Nanchang City (China) (Zhang et al., 2017). The LST map of September 15 (left) was derived using Landsat 5 TM images while the map for October 5 (right) used Landsat 8 OLI/TIRS images.

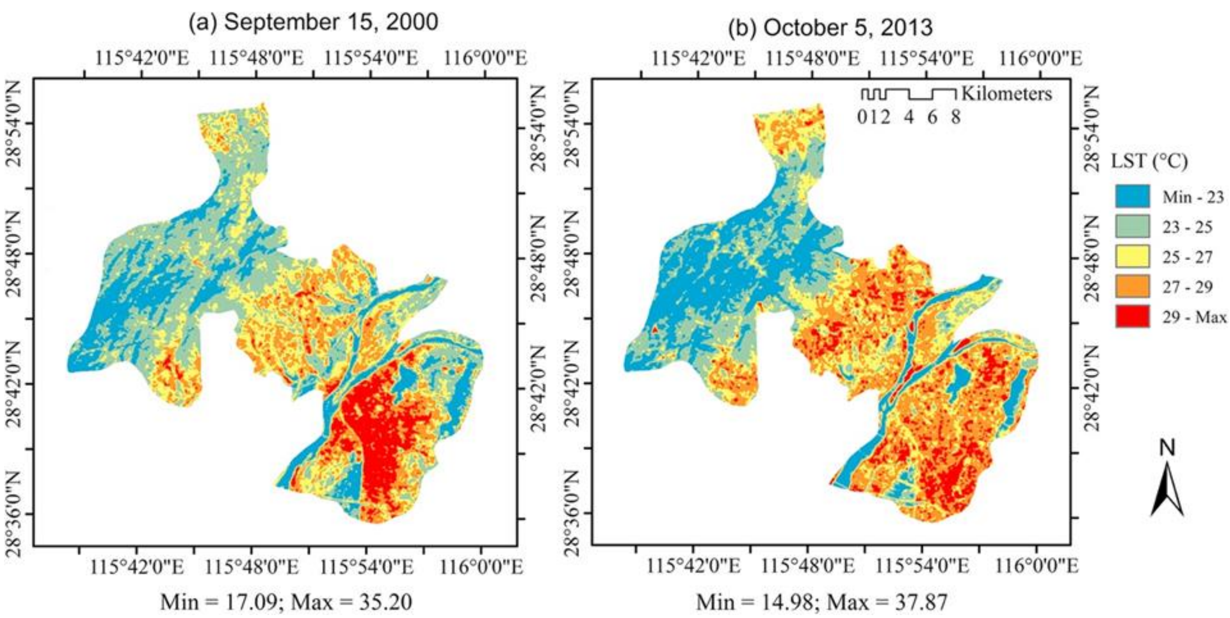

Figure 1.5: Land Surface Temperature (LST) maps of Nanchang City (China) in (a) 2000 and (b) 2013. (Image © Zhang et al., 2017)

Overall, the mean LST of Nanchang City, China had increased by 1.64 °C from 2000 to 2013 (Zhang et al., 2017) and this temporal variation was attributed to the rapid urbanization and land use modification in the area. Similarly, the LSTs had increased by 2.32 °C in Zhengzhou City (China) between 2000 and 2014 and was positively correlated with an increased area covered by impervious surfaces (Zhao et al., 2020). Seasonal LSTs extracted from Landsat 8 images confirmed that urban green spaces are highly effective in reducing LST in Beijing (China) and this cooling effect was greatest during the warmer seasons (Yao et al., 2020). Further, increasing urban forestcanopy cover was found to be the best way to mitigate the UHIE in urban areas with limited open space (Yao et al., 2020). An urban forest encompasses the trees and shrubs in an urban area, including trees in yards, along streets and utility corridors, in protected areas, and in watersheds (Escobedo et al., 2011). Higher LSTs (captured with MODIS) were recorded in built-up areas compared to the surrounding vegetated areas across Srinagar City (India) (Shafi et al., 2019). Countless studies have emphasised the role of green infrastructure in moderating urban heat and specifically the cooling effect of trees. Green infrastructure (GI) refers to all of the vegetation that provides environmental, economic and social benefits such as clean air and water, climate regulation, food provision, erosion control and places for recreation (CSIRO, 2021).

1.5 Urban ecosystems and services

As defined by Moll & Petit (1994), an ecosystem is a collection of species that interact with their non-biological environment to sustain life. It is possible to view the urban environment either as a single ecosystem or as a collection of numerous individual ecosystems, such as parks and lakes (Rebele, 1994). As Bolund & Hunhammar (1999) identified, there are at least seven different urban ecosystems that we refer to as "natural," even though almost all areas in cities have been manipulated or managed by humans. Among the ecosystems are street trees, lawns/parks, urban forests, cultivated land, wetlands, lakes, and streams. Normally, street trees are standing trees surrounded by paved ground. Parks/lawns consist of a mixture of grass, larger trees, and other plants. This category also includes areas such as playgrounds and golf courses. Urban forests consist of less managed areas with a higher tree density than parks. Gardens and cultivated land are used for growing a variety of food items. Swamps and marshes are examples of wetlands. Streams are characterized by flowing water, while lakes/seas include areas of open water. According to Costanza et al. (1997), ecosystem services are defined as "the benefits that humans derive, directly or indirectly, from ecosystem functions.". They also identify 17 major categories of ecosystem services.

This thesis examines the ecosystem services provided by urban trees, with particular emphasis on their cooling properties. The ecosystem services provided by trees include carbon sequestration (Domke et al., 2020), air purification (Nowak, 2002), stormwater management (Zhang & Dong, 2018), energy savings (Nowak et al., 2017), increased real estate value (Staats & Swain, 2020; Wang et al., 2018), and improved mental and physical health. It is expected that 70% of the world's population will live in urban areas by 2050 (United Nations, 2019), and urban ecosystems and their services are increasingly being taken into account in both policy and research (Elmqvist et al., 2013). In recent years, there has been an increased interest in incorporating ecosystem services into urban planning (Hansen & Pauleit, 2014). Furthermore, the discussion of urban ecosystem services provides an extension of the environmental impact assessment of urban land use transitions (Nuissl et al., 2009) and particularly for the social–ecological context of different land use decisions (Andersson et al., 2014).

Using various urban policies throughout LGAs, this thesis examines how local governments incorporate trees and their ecosystem services into their policies. In addition, investigated whether the scientific findings around urban cooling are in fact reflected in these policies. Knowledge of ecosystem services is crucial for making informed decisions in urban planning. However, this kind of knowledge is not always taken into account in urban governance and planning, and in particular with respect to the structure and function of urban ecosystems (Boyer & Polasky, 2004, Niemelä et al., 2010, Wilkinson et al., 2013).

1.6 The role of trees in cooling cities

Urban trees seem to be an optimal tool to reduce urban heat and UHIE. They provide cooling through two processes: shading and transpiration. Tree canopies reflect and absorb solar radiation whereby they reduce the amount of solar radiation reaching ground. Shielding buildings, roads and other surfaces from this radiation reduces the amount of energy that is absorbed and re-radiated into the air by these structures (Richards & Edwards, 2017). The result of this effect is that surface temperatures of shaded structures remain cooler during the day (Fig. 1.6).

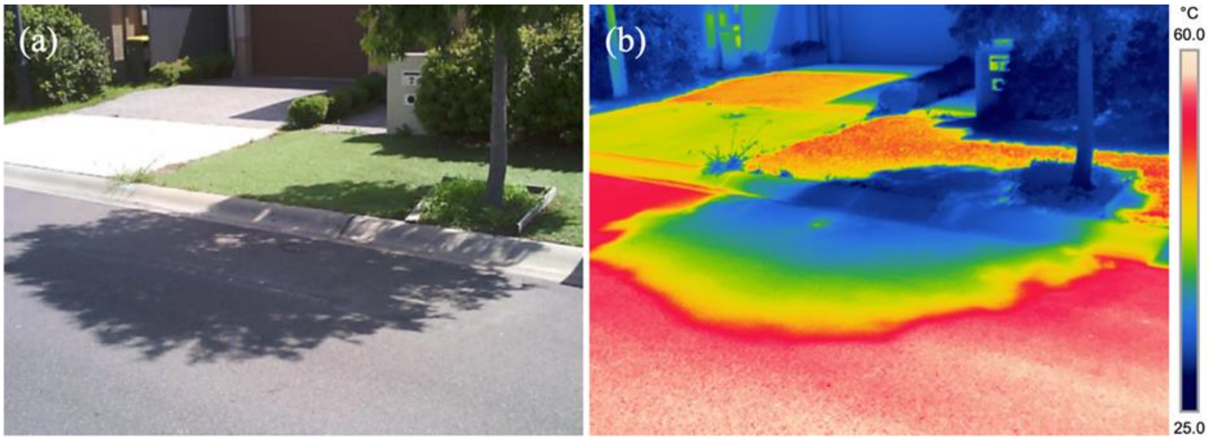

Figure 1.6: Tree shade reduces surface temperatures. The depicted example shows the normal view (a) and infrared view (b) of a road surface temporarily shaded by a small tree. The shade of the tree crown lowered surface temperature of black asphalt by 30°C. (Image © S. Pfautsch)

In addition, tree crowns can cool the air by reducing heat transfer from the ground to the air flowing over it (Brandani et al., 2016). For example, Rahman et al. (2017) reported up to 3.5 °C air temperature reduction within the tree canopy of *Tilia cordata*. However, air temperature reduction may be negligible in conditions of high air turbulence (Petralli et al., 2015). Shading affects human thermal comfort by altering the perceived temperature (Coutts et al., 2016). Human thermal comfort is “the state of mind that expresses satisfaction within the thermal environment” and generally assessed subjectively (ASHRAE, 2004). This perceived temperature is defined as a function of air temperature, humidity, windspeed and other climatic factors (Li et al., 2018a). Human thermal comfort depends more on radiation and less on convection of heat from the local environment towards the human body (Matzarakis et al., 2007; Shashua-Bar et al., 2011). For example, a person standing in the shade feels cooler than a person who is standing in sun when both are surrounded by air of the same temperature.

Transpiration is a process by which a plant transpires water in the form of vapor from its leaves into the surrounding atmosphere (Pallardy, 2010; Moss et al., 2019). During this process energy contained in solar irradiance is absorbed by leaves to convert liquid water to vapor which reduces the surrounding ambient air temperature (Akbari, 2002). This process is termed latent heat flux cooling (Akbari, 2002). It is found that a large urban tree can transpire up to 370 L of water per day (Akbari, 2009), which can provide substantial latent heat flux cooling. Transpirational cooling may vary with climate, tree species and environmental conditions (Rahman et al., 2015). For example, tree species in dry habitats generally have low transpiration rates compared to species in wetter habitats as they conserve water by closing their stomata, which will reduce their capacity to cool the surrounding air temperature (Rahman et al., 2015).

The cooling capacity of urban trees has been studied for many years and different climate zones. For example, urban trees and building geometry influenced diurnal and nocturnal air temperature in Gothenburg (Sweden) (Konarska et al., 2016). Air temperature data from ten street and park sites with varying cover of green space (trees and other vegetation), grey space (buildings, roads), building geometry and openness was obtained from 2012 to 2013. Findings showed that parks with trees remained cooler than streets (Konarska et al., 2016). Further, an average daytime air temperature reduction of 0.5 °C –1 °C was observed and attributed to cooling effects of trees. Similarly, mobile air temperature measurements collected in Madison (WI) showed that urban trees and impervious areas affect air temperature (Ziter et al., 2019). Day-time air temperature reductions of 0.7 °C–1.5 °C were observed in areas where tree canopy cover was ≥40% compared to areas with lower tree canopy cover (Ziter et al., 2019). In Athens (Greece), the average cooling effect of trees during midday ranged from 0.5 °C to 0.6 °C and during the afternoon from 0.4 °C to 2.2 °C (Tsiros, 2010). This study also documented that the maximum cooling effect was delivered in streets with a large number of trees and minimum traffic load (Tsiros, 2010). Shahidan et al. (2012) investigated the optimum cooling potential of trees in Putrajaya (Malaysia) by analysing field measurements as well as generating computer simulations of air and ground surface temperatures. Findings of this work indicated that the higher the number of trees and the density of their crowns, the greater the cooling benefits. Both the tree shading and transpirative cooling contributed to an average reduction of air temperature by 2.7 °C in that study (Shahidan et al., 2012). Another study showed that the variation of cooling efficiency of trees from 118 cities in the United States varied across a much smaller mean effect size (0.04–0.57 °C) (Wang et al., 2020). Cooling efficiency in that study was defined as the magnitude of temperature reduction by one-unit increase of vegetation abundance (number of plants per area) (Zhou et al., 2017). Cities in climate zones with dense, broadleaf urban forests had significantly higher cooling efficiency than those where tree crowns were sparser (e.g., trees with open/low density canopy) (Wang et al., 2020). Another study found that *Tilia cordata* trees grown in two street canyons in Munich (Germany) reduced air temperatures up to 3.5 °C (Rahman et al., 2017).

These and many other studies confirmed the cooling capacity of urban trees. However, the cooling capacity apparently varied due to differences in species, meteorological conditions and the composition of the surrounding urban landscape. These studies have primarily been conducted in the northern hemisphere - with only a few from Australia. To better understand the sources of this variation, it is necessary to take a closer look at how species-specific effects of crown architecture, size and other characteristics affect their cooling capacity.

1.6.1 Morphological characteristics of trees in relation to urban cooling

As a result of the importance of urban trees for cooling, a growing number of studies are concerned with the effect of species-specific traits on surface and air cooling. These studies showed that different traits, such as Leaf Area Index (LAI), Plant Area Index (PAI), Leaf Area Density (LAD), foliage density, leaf arrangement, leaf thickness and leaf colour play a key role in cooling air and surface temperatures. The LAI is defined as the total one-sided area of leaf tissue per unit ground surface area (Watson, 1947). The PAI is an estimate of the fraction of ground shaded by vertical projection of tree crowns (Chianucci et al., 2015). The difference between the LAI and PAI is that LAI only focuses on leaves whereas PAI accounts for all physical elements of the canopy such as twigs, branches, flowers, fruits and leaves (de Abreu-Harbich et al., 2015). However, in practice it is difficult to meaningfully distinguish between LAI and PAI, due to the techniques used to measure them. The LAD is a key index for characterizing vertical and horizontal crown structures and is defined as total one-sided leaf area per unit volume of a given tree crown or forest canopy (Oshio et al., 2015).

The LAI influences both the within and below canopy microclimate, controls radiation extinction as well as water and gas exchange with the atmosphere (Breda, 2003). Tree species with higher LAI (e.g., *Crataegus laevigata*, *Pyrus calleryana*) usually provide significantly more cooling than other, comparable-sized tree species (e.g., *Sorbus arnoldiana*, *Prunus* ‘Umineko’, *Malus* ‘Rudolph’) and surface temperature reduction is often positively correlated with LAI (Armson et al., 2013). Similarly, a significant relationship was observed between LAI and surface temperature under trees on asphalt surface in a study conducted in Florence (Italy) (Napoli et al., 2016). Air temperature, solar radiation, Physiologically Equivalent Temperature (PET)and mean radiant temperature, all decreased significantly with increasing PAI (Sunusi et al., 2017). The PET is based on the thermal balance of the human body, and it translates the effects of the thermal environment on humans in terms of thermal heat/cold stress or comfort (Krüge et al., 2017). “The uniform temperature of a hypothetical spherical surface surrounding the subject (emissivity $\varepsilon = 1$) that would result in the same net radiation energy exchange with the subject as the actual, complex radiative environment” (Matzarakis et al., 2007) is the mean radiant temperature. Species with high LAD and high rates of transpiration were more effective in cooling air temperature (Gillner et al., 2015).

A study conducted in Taipei (Taiwan) found that foliage density had the greatest effect on surface cooling followed by leaf thickness, leaf texture and leaf colour (Lin & Lin, 2010). Shape of the tree crown was also a major contributing factor to the reduction of air temperature under a tree canopy. However, trees with a spreading, open crown with droopy and feathery compound leaves were not effective in reducing air and surface temperature as this configuration allowed more solar radiation to pass through the canopy (Tukiran et al., 2016). Additionally, simple leaf arrangement as opposed to compound, crown width and wide umbrella-shaped crowns were found to result in greater air temperature cooling (Speak et al., 2020). Yet, the same study found that leaf shape did not significantly influence the cooling effect. Further, Speak and colleagues found that despite a narrower tree crown, columnar trees like *Cupressus sempervirens* provided a high level of air cooling due to their high crown density. Small-leaved species were more efficient in reducing air temperature than large-leaved species as they maintained lower crown temperatures (Leuzinger et al., 2010). These findings highlight the importance of species choices when urban planners and managers try to reduce summer temperatures in urban environments and mitigate UHIE.

1.7 Urban trees in Greater Sydney

Urban trees provide tangible and intangible benefits such as cooling, air purification, water retention and improved aesthetic value. Jacobs (2016) states in his book *Great Cities* that people consider the most significant factor that makes a great street is street trees. Trees can thrive under altered urban conditions and survive in an entirely human-dominated environment. Urban trees are an asset to cities as they play an important role in making cities liveable, attractive and healthy places (Cavender & Donnelly, 2019).

Today, the metropolitan area of Greater Sydney has an estimated population of 5 million and is growing rapidly. By 2036 its population is expected to reach 6.6 million (NSW Department of Planning, Industry and Environment, 2021a) – a continuous addition of 100,000 new residents every year. As the population is projected to increase, the challenge is to keep Greater Sydney liveable and resilient. Furthermore, the UHIE is very pronounced in Greater Sydney compared to the other parts of Australia (Sidiqui et al., 2016). As a solution, the NSW government has implemented a number of actions and strategic plans to increase tree cover in Greater Sydney to increase the city's resilience against predicted climate change impacts.

The NSW government aims to increase the average urban tree canopy cover across Greater Sydney from under 20% to 40% by 2050 and supports this ambitious goal through its Five Million Trees program (NSW Department of Planning, Industry and Environment, 2021a). This state-funded initiative aims to plant 5 million trees in the Greater Sydney area by 2030 and provides grants for councils, organisations and community groups to plant trees. The highest urban tree canopy cover (54%) in Greater Sydney was recorded in Hornsby Shire in 2016, while the City of Botany Bay and Rockdale Council had the lowest canopy cover (14%) (Amati et al., 2017). The most significant canopy loss was recorded in Pittwater Council (13%) between 2009 and 2016 (Amati et al., 2017). As cities grow, urban planning policies facilitate land divisions and clearing of vegetation for new buildings (Pritchett, 2003; Randolph, 2004). Moreover, across many densely populated local government areas (LGA), including those of Parramatta, Cumberland, Blacktown, Strathfield, Ryde and Liverpool, tree canopy cover was well below 30% in 2016. North Sydney Council reported a decline of its canopy cover by 1.2% since 2017 (North Sydney Council, 2020). They also report that the greatest losses of canopy area appeared on privately owned land which made up 58% of the land area in that specific LGA. Figure 1.7 shows the aerial view of Sydney Botanical Garden where a large relative cover of open space and tree canopy provides cooling and other benefits to the local population and visitors.

Figure 1.7: Aerial view of the Sydney Botanical Garden. (Image © The Urban Developer, 2017)

Today there are numerous tree planting projects taking place across Greater Sydney to increase urban tree canopy cover. For example, the City of Parramatta takes its urban heat mapping data into consideration to decide where and what types of trees are to be planted in each location (City of Parramatta, 2021). Hornsby Shire Council has achieved its goal to plant 30,000 trees between 2019 and 2021 (Hornsby Shire Council, 2021). A recent study carried out by the City of Sydney (2013) found that that most of the street trees in this LGA are semi-mature or mature. Table 1.1 shows the most common urban tree species found in Sydney. An assessment of the City of Sydney's Street tree species showed that the family *Myrtaceae*, with many species native to Australia, accounted for more than 40% of the tree population in the city. This finding reflects that street trees in Sydney are dominated by a single family and a lack of young trees to replace potential losses due to age. A lack of species diversity can pose a high risk to pathogen calamities as demonstrated by the impacts of Dutch Elm Disease in the United States (La Porta et al., 2008). Over aging in urban tree populations without the presence of the next cohort of trees in place can lead to a rapid and widespread decline in canopy cover as senescent and defect trees with large crowns will be removed over a relatively short time interval without any replacement.

Table 1.1: List of the most common urban tree species in the City of Sydney. Also shown is the status of species as natives or exotics, leaf habit and height range. (Source: City of Sydney, 2013)

Botanic name	Common name	Native/ Exotic	Evergreen/ Deciduous	Potential Height in Street Environment (m)
Acacia binervia	Coastal myall	Native	Evergreen	8–12
Backhousia citriodora	Lemon-scented myrtle	Native	Evergreen	7–10
Brachychiton acerifolia	Illawarra flame tree	Native	Deciduous	15–20
Brachychiton discolor	Queensland lacebark	Native	Deciduous	15–20
Eucalyptus saligna	Sydney bluegum	Native	Evergreen	20–28
Ficus benjamina	Weeping fig	Exotic	Evergreen	15–20
Ficus macrophylla	Morton bay fig	Native	Evergreen	20–25
Gingko biloba	Maidenhair tree	Exotic	Deciduous	12–18
Gordonia axillaris	Gordonia	Exotic	Evergreen	5–8
Jacaranda mimosifolia	Jacaranda	Exotic	Deciduous	10–15
Lagerstroemia indica	Crepe myrtle	Exotic	Deciduous	8–10
Schinus areira	Peppercorn tree	Exotic	Evergreen	10–12

Several studies have been conducted in Sydney to investigate the microclimatic benefits of urban trees. A decline in near surface air temperature with increasing tree height and canopy density was observed in western Sydney (Wujeska-Klause & Pfautsch, 2020). The study found that near surface air temperatures under 36 park trees were lower under trees with dense canopies and streets with high canopy cover resulted in lower numbers of days with hot (>35 °C) and extreme (>40 °C) air temperatures compared to streets with low tree canopy cover. Another study explored transpirative cooling of two large *Melaleuca* trees located in eastern Sydney where sea breezes dominated the local climate (Gao & Santamouris, 2020). The maximum air temperature difference under trees and adjacent in the full sun was about 2 °C (Gao & Santamouris, 2020). Further, this study revealed that although sea breezes were the primary cooling mechanism, transpirative cooling heavily contributed to lowering air temperatures. However, also the effect of spatial arrangements of urban trees on local cooling was investigated in Sydney. Urban trees in small clusters or rows with well irrigated grass reduced LST by up to 8 °C during day and night (Bartesaghi-Koc et al., 2020). Shade cast by tree canopy heavily influenced surface temperatures of roofs in residential areas in Sydney (Lin et al., 2016). Similarly in streetscapes, both increasing tree cover and green grass showed a significant negative relationship with surface temperature of road pavements (Lin et al., 2016).

1.8 Management policies for urban trees and forests

As mentioned in the previous sections, urban trees play a vital role in keeping cities healthy and liveable. Local Authorities (LAs) like councils and municipalities play a central role in managing urban trees because of their function as planning authorities, and often also as public landowners (van der Jagt & Lawrence, 2019). Proactive and successful urban tree management is strongly influenced by existing local policies related to trees (Galenieks, 2017). Many LAs in various countries have developed and implemented policies to protect trees in urban areas, including maintenance programs, removal regulations, and minimum landscaping area requirements for residential and industrial areas (Sung, 2012; Conway & Ubarni, 2007).

Several studies have investigated the efficacy of government policies, management plans and programmes that LAs put in place to manage urban trees. For example, Urban Forest (UF) programmes in cities across the state of Oregon (United States) included elements like a tree ordinance, a tree advisory committee, and a management plan that described a vision, plan and costed actions (Ries et al., 2007). However, only a limited number of towns and cities had operationalised these elements (Ries et al., 2007). There was also substantial variation among UF policies in Greater Toronto (Canada) (Conway & Ubarni, 2007). The urban forestry management by Scottish LAs was largely reactive due to limited funding, poor knowledge of the scale and state of the UF, fragmented management structures, and the tendency to perceive trees as a liability as opposed to an asset (van der Jagt & Lawrence, 2019).

Rising heat in cities is now one of the main concerns for city planners (Kukulska-Kozieł et al., 2019). A limited number of studies have investigated the effect of the policies related to trees on UHIE mitigation. For example, Woodland in Texas had a tree protection policy which consisted of minimum tree cover requirements and tree removal permits (Sung, 2013). Here, mean LSTs derived from Landsat thermal images were compared between Woodland's neighbourhoods and nearby control neighbourhoods without a tree protection policy (Sung, 2013). Findings showed that the mean surface temperature of Woodland's neighbourhood was 1.5–4 °C lower when compared to a control neighbourhood that was deprived of tree canopy (Sung, 2013). Similarly, McPherson (2011) predicted that the one million tree planting initiative implemented in Los Angeles could reduce the summertime air temperature, yet the authors did not provide an indication for the magnitude of cooling that could be achieved. Although these studies provide evidence that policies related to trees/UF are effective in minimizing the impact of urban heat, most of the policies lack planning, implementation and monitoring methods to assess progress towards UHIE mitigation targets (MacLachlan et al., 2020). However, exceptions can be found where UHIE mitigation policies are integrated into local development and planning requirements (building codes and zoning) (MacLachlan et al., 2020). For example, minimum vegetation requirements (trees and green space) for specific sizes and types of developments are stipulated in the Landscape Ordinance of Baton Rouge (Louisiana) and the Green Factor Policy of the City of Seattle (Washington) (MacLachlan et al., 2020).

1.8.1 Management policies related to urban trees in Sydney

State governments and/or local governments (also known as councils) are responsible for increasing and protecting the urban tree cover in Australian cities. The state government as well as local governments of NSW provide directions to plan and control the development activities and protect and increase the urban tree cover within its administrative boundaries through several policies and plans. These policies and plans and their roles to protect and enhance urban tree canopy will be outlined briefly.

The Environmental Planning and Assessment Act 1979 is the primary land use planning legislative document in the state of NSW which governs matters related to planning instruments, planning administration, development assessments, infrastructure finance, building certification and appeals and enforcement. The Environmental Planning and Assessment Act 1979 allows plans to be made to guide the process of development and to regulate competing land uses. These are known as Environmental Planning Instruments (EPIs). There are three types of EPIs,

1. State Environmental Planning Policies (SEPPs)
2. Local Environmental Plans (LEPs)
3. Development Control Plans (DCPs)

The SEPPs address the land use planning issues such as agriculture and affordable housing, within the state. Some SEPPs are exclusively designed for specific areas or precincts (e.g., Kurnell Peninsula and Kosciuszko National Park). Both the Environmental Planning and Assessment Act 1979 and the SEPPs are prepared by the state government. Currently, there are 38 SEPPs effective within NSW. Examples of some important SEPPs are *SEPP No 19 - Bushland in Urban Areas, SEPP No 33 - Hazardous and Offensive Development, SEPP (Infrastructure) 2007, SEPP (Urban Renewal) 2010* and *SEPP (Vegetation in Non-Rural Areas) 2017*. Importantly, during the time (2018–2021) this thesis was produced, the government of NSW reviewed and reorganised the two most relevant SEPPs for urban tree canopy (*Design and Place SEPP*, *Environment SEPP*). It is anticipated that the role of tree canopy in urban development will be considerably strengthened in the new SEPPs, that will be implemented in 2022/23.

A LEP is a legal document which prescribes development and land use within a particular LGA (NSW Department of Planning, Industry and Environment, 2021b). The LEPs are adopted by the relevant planning and/or consent authority of the area, generally the councils. The difference between the LEPs and the SEPPs is that LEPs are only effective within the LGAs. The SEPPs however can override the LEPs in certain situations, for example when a development project is deemed to be of 'state significance'. All land, whether privately owned, leased or publicly owned within the LGA is subject to the controls set out in the relevant LEP. Currently, there are 35 councils in Greater Sydney who own and implement comprehensive LEPs. The LEPs are highly important in increasing urban tree canopy cover as they control the land use on both private and public land.

Some councils in NSW have DCPs. The DCPs are providing planning and zoning guidelines for relevant council areas; however, unlike SEPPs and LEPs, DCPs are not statutory binding, rather they are planning guidelines, and thus cannot be enforced. They are prepared by councils and provide detailed guidelines which assist a person proposing to undertake a development within the council area. Division 3.6 (Development Control Plans) of the

Environmental Planning and Assessment Act 1979, states that the purpose of a DCP is to provide guidance on:

1. Giving effect to the aims of any environmental planning instrument that applies to the development,
2. Facilitating development that is permissible under any such instrument, and
3. Achieving the objectives of land zones under any such instrument.

Since DCPs are non-statutory documents, they are not published on the NSW legislation websites. A DCP must be consistent with the provisions and objectives of the relevant LEP. Both the LEPs and DCPs are highly important in managing the urban tree population as they provide guidelines for conservation as well as removal of trees.

The State government and the local governments also have other non-statutory documents directly or indirectly aiming at preserving the urban canopy cover with their action plans (Fig. 1.8). The Central City District Plan (2018) is one of the leading documents focussing on improving urban green infrastructure in Sydney. It is a 20-year plan to manage growth in the context of economic, social and environmental matters of Sydney. By addressing the "Planning Priority C:16 Increasing urban tree canopy cover and delivering Green Grid connections" of this plan, councils in the Central City District (e.g., Blacktown, Cumberland, Parramatta, The Hills) meet their commitment to increase the urban canopy cover. Further, the NSW government has identified a network of high-quality green spaces that connect town centres, public transport hubs and major residential areas known as Sydney's Green Grid (2018). This plan highlights the importance of the interconnecting network of green space, riparian corridor, and canopy cover. Additionally, the Western Sydney Regional Organisation of councils (WSROC) introduced the Turn Down the Heat Strategy (2018) which provides strategic direction and actions to increase public awareness around heat and mitigate its impact in western Sydney. It has number of actions proposed to mitigate the UHIE and “Action 8: Urban Forest Strategy” aims at keeping trees healthy and increasing canopy cover to provide cooling on extreme heat days.

Though there are a few different policies and environmental strategies in NSW to control development activities and to protect urban tree cover, integration of UHIE mitigation into these policies is lacking. LEPs and DCPs primarily control the land use at local government level thus have a direct influence on the urban tree canopy cover. However, to date there are no studies available that have investigated whether cooling benefits of urban trees are taken into consideration in the existing policies and environmental strategies in Greater Sydney to improve the city’s resilience against climate change impacts, especially increasing heat.

1.9 Overview of the thesis

Rapid urbanization and land use modification puts increasing pressure on trees in cities. Trees are an integral part of making the cities liveable. Importantly, they influence both air and surface temperatures. While numerous studies have been conducted in the past to assess the relationship between tree morphology and air temperature (Richards et al., 2020; Wu & Chen, 2017; Wang et al., 2018a; Rahman et al., 2017; Wang et al., 2020; Upret et al., 2017; Rashid et al., 2014), the relationship with surface temperature is studied less. Further, studies which assessed the relationship between surface temperature and tree canopy typically rely on remotely sensed thermal data (Del Pozo et al., 2020; Surawar & Kotharkar, 2017; Tsou et al., 2017; Zhang et al., 2017) which cannot be used for microscale analysis. For example, MODIS can only be applied to larger areas due to its low resolution while Landsat and ASTER are more appropriate to capture the UHIE at small city scale (Kaplan et al., 2019). Furthermore, findings of such studies cannot be used to assess the effect of canopy traits on surface temperatures under a tree canopy, as surfaces are obstructed by the canopy itself. While some studies exist for places in Melbourne (Berry et al., 2013; Sanusi et al., 2016), these microscale investigations are very limited for Sydney (Wujeska-Klause & Pfautsch, 2020). Similarly, reliable information about tree species that are more or less effective in cooling urban spaces is lacking for Sydney. This type of information is important for landscape architects and urban planners when selecting tree species to – among other goals – improve microclimate. Hence, is it important to study the effect of tree morphological characteristics (e.g., LAI, tree stem diameter and ground-projected area of the crown) on surface temperature during warm seasons in Sydney. This is the first objective of the present thesis: *to determine how canopy characteristics of urban trees in Greater Sydney assist in cooling common surface materials.*

Another research gap which was identified in the literature review above. It relates to inadequate information about the composition of urban fabric and its relationship to air temperature at the microscale. Microclimate has a direct spatial and temporal relationship with surface materials (He et al., 2019). Though the role of trees in mitigating surface UHIE has been studied widely, trees do not 'act alone' in urban landscapes. Other elements of the urban fabric like roads, buildings, pavements, water bodies and open spaces all contribute to the microclimate of a specific location. Furthermore, findings of existing microscale studies which investigated effects of green cover such as urban parks or impervious surfaces like buildings and paved areas (Taha, 1997; Lin et al., 2008) on variation of air temperature cannot be applied universally because each city has its own urban characteristics and local climate (Aboelata & Sodoudi, 2019). Moreover, microscale analyses are very important in identifying areas with high thermal exposure. Only once identified can targeted interventions be planned and executed to provide effective cooling. Hence, the second objective of this thesis was: *to determine the effects of landscape heterogeneity on air temperature at the microscale.*

Local governments, their policies and environmental strategies play a central role in managing and controlling development activities. Hence, they have a direct influence on how the UHIE is addressed within a given LGA. Furthermore, though there are many actions already being taken to tackle the impacts of urban heat at state government and local government level through initiatives like the Five Million Tree Program in Greater Sydney, the UHIE remains a major environmental and socio-economic challenge across the region. Therefore, it is necessary to determine to what extent existing planning policies and environmental strategies effectively contribute to mitigate the UHIE and whether more needs to be done. Few studies have investigated the policy in relation to urban trees in mitigating UHIE in cities across the world (Sung, 2013; McPherson, 2011; MacLachlan et al., 2020). However, no such studies have been conducted for any local government in Sydney. Responding to this, the third objective of this thesis was: *to use a policy gap analysis to identify where the role of urban trees in mitigating UHIE can be strengthened in existing policies and environmental strategies.*

This research primarily contributes to the field of urban and regional planning. The focus of this field is on the environmental, economic, and equity components of development patterns over the long term. As cities growing in size and density, the ecosystem services provided by greenery and green infrastructure are becoming increasingly important for maintaining a healthy and sustainable urban environment. In a city that is densely populated, it is difficult to retain and maximize urban greenery. Councils can address these challenges by developing and implementing policies which are based on research like this. In addition to this, my thesis contributes to other areas such as landscape design, urban resilience, and management of urban green infrastructure. Chapter 2 and 3 directly address urban resilience and green infrastructure while Chapter 4 integrates urban planning policies and contributes to urban and regional planning.

The following three experimental chapters were designed to address the aforementioned objectives (Fig. 1.8):

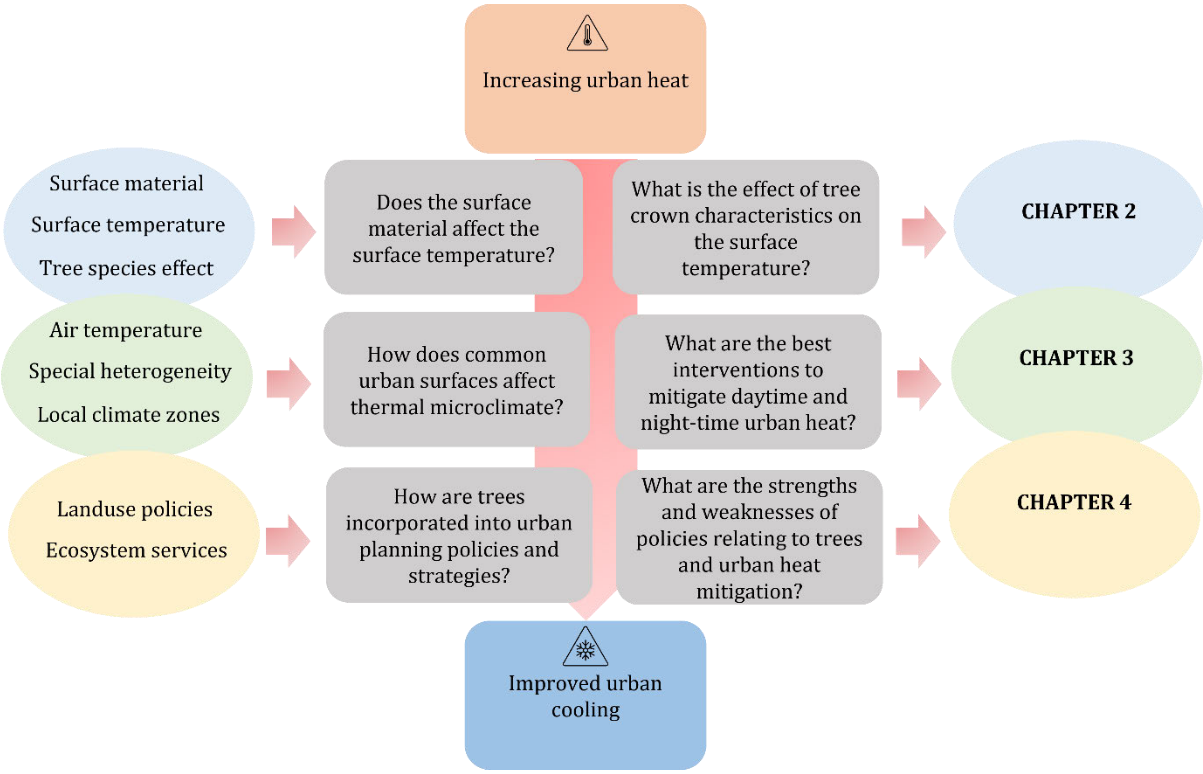

Figure 1.8: Diagram illustrating the sequencing of the experimental and policy chapters of the thesis, with research questions that address different aspects of urban heat to achieve improved urban cooling in western Sydney.

1.9.1 Overview of the Methods

A mixed-method approach was used in this research where quantitative and qualitative methods were combined. According to Tashakori & Creswell (2007), mixed methods research is defined as "research in which the investigator collects and analyses data, combines findings, and draws conclusions using both qualitative and quantitative approaches". A combined qualitative and quantitative approach can be used to create an overall understanding of the findings, whereas a singular approach is not possible. For example, an empirical study may find, for instance, that certain percentages of canopy cover may reduce the temperature. For the findings to be applied to the actual urban landscape, it is necessary to examine existing policies and landuse plans and to engage stakeholders to identify challenges and opportunities.

Mixed methods studies should clearly explain why qualitative and quantitative methods are being used and how findings should be integrated, if at all (O'Cathain et al., 2008; Onwuegbuzie &Teddlie, 2003). One characteristic of mixed methods studies is their integration of qualitative and quantitative findings at some point in the research process, such as during data collection, post-analysis, or interpretation stages (Andrew & Halcomb 2009). Using multiple data sets can help the researcher gain a better understanding of the issue and provide more complete evidence. Moreover, it can strengthen the findings of the study. Researchers who use mixed methods also develop their skills, which is particularly important for those who are in the early stages of their career. Mixed methods are not without their limitations, however. As an example, the resources and skills required - one researcher may not have expertise in both qualitative and quantitative methods and may require the help of another person or have to invest time to learn the skills by themselves. By focusing on the actual landscape, the thesis addresses one of the most significant environmental issues in the western Sydney. Besides affecting human health and wellbeing, urban heat also has a detrimental effect on the infrastructure and overall livability of the city. The inherent complexity of this phenomenon as well as its widespread application in the urban landscape dictates that such a study should utilize a mixed-method approach to identify all aspects relating to mitigate urban heat. In this study, the mixed-method approach was applied at the stage of data analysis and interpretation. While Chapters 2 and 3 use a quantitative approach, Chapter 4 employs a qualitative approach.

- **Chapter 2 – Reduction of surface temperatures through tree shading depends on surface type not tree species**

This Chapter has been published in *Forests,* a peer-reviewed journal.

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In this experimental Chapter, I investigate the effect of tree canopy characteristics on surface temperature across several widely used surface materials (grass, bark mulch, pavers, bare soil). Diameter at breast height, LAI and ground projected crown area was measured for 471 free standing trees belonging to 13 species growing in urban locations across Sydney. I also measured the surface temperature under the crown of each tree in the shade and in full sun next to each tree between noon (daylight saving time) and 3:00 pm to determine the difference between adjacent sunlit and shaded surfaces (DTs). A linear regression analysis was used to analyse the relationships between the physical characteristics of the trees and the temperature measurements. Relationships among LAI, ground projected crown area, surface, globe temperature, and surface types were evaluated using Generalized Linear Models (GLM).

- **Chapter 3 – Influence of surface cover on microclimate in Sydney**

Urbanization causes biophysical changes in the composition of the landscape. Such changes impact on microclimate. This chapter was designed to investigate the variation of air temperature at microscale (50 m radius) with respect to the spatial variation of surface cover in two LGAs (Parramatta and Cumberland) in western Sydney. Air temperatures were measured at 156 locations and a range of air temperature derivatives calculated from the resulting data were correlated to the relative presence of surface types and tree canopy in the vicinity (50 m radius) around each of the measurement locations. Every location was classified into Local Climate Zones (LCZ) based on the relative cover of each surface type.

- **Chapter 4 – Policy analysis of the role of trees in heat mitigation**

Scientific findings should be incorporated into land-use policies in order to effectively mitigate urban heat. It is imperative that existing policies are thoroughly reviewed in order to identify any gaps, opportunities and challenges. Significant discoveries were made in Chapters 2 and 3 that are critical to urban heat resilience. It is however impossible to evaluate the existing policies without reviewing them in order to determine what the councils are currently doing and what more can be done in the future. An in-depth analysis of policy was therefore undertaken in order to identify planning provisions around trees. As outlined above, policy in relation to urban trees in mitigating UHIE is not researched in Australia so far. To address this gap, a thematic policy gap analysis was conducted by investigating Local Environmental Plans, Development Plans and other policy and strategy documents from four local governments in Australia. My analysis is focussed on five policy documents from Parramatta (Sydney, NSW), nine from Cumberland (Sydney, NSW), and four from each local government of Unley and Mitcham (both Adelaide, South Australia).

1.9.2 Data availability

The raw data that support the findings of this study are available on request to the author.

Chapter 2: Temperature Reduction in Urban Surface Materials Through Tree Shading Depends on Surface Type Not Tree Species

2.1 Abstract

Trees play a vital role in urban cooling. The present study tested if key canopy characteristics related to tree shade could be used to predict the cooling potential across a range of urban surface materials. During the austral summer of 2018/19 tree and canopy characteristics of 471 trees from 13 species were recorded across Greater Sydney, Australia. Stem girth and tree height, as well as leaf area index and ground-projected crown area was measured for every tree. Surface temperatures were recorded between noon (day light saving time) to 3:00 pm under the canopy of each tree in the shade and in full sun to calculate the temperature differential between adjacent sunlit and shaded surfaces (ΔT_s). Analyses revealed that no systematic relationship existed among canopy characteristics and ΔT_s for any surface type. However, highly significant differences ($p < 0.001$) in ΔT_s existed among surface materials. The largest cooling potential of tree shade was found by shading bark mulch (ΔT_s = -24.8 °C ±7.1), followed by bare soil (ΔT_s = -22.1 °C ± 5.5), bitumen (ΔT_s = -20.9 °C ± 5.8), grass (ΔT_s = -18.5 °C ± 4.8) and concrete pavers (ΔT_s = -17.5 °C ± 6.0). Results indicate that surface material, but not the tree species matters for shade cooling of common urban surface materials. Shading bark mulch, bare soil or bitumen will provide the largest reductions of surface temperature which in turn results in effective mitigation of radiant heat. This refined understanding of the capacity of trees to reduce thermal loads in urban space can increase the effectiveness of urban cooling strategies.

Keywords: Urban heat island, surface temperature, green space, western Sydney, microclimate, thermal management

2.2 Introduction

The Urban Heat Island Effect (UHIE) is one of the most prominent impacts of urbanisation and is accelerated by climate change (Parsaee et al., 2019; Iping et al., 2019). The UHIE can be defined as the discernible temperature difference between urban and adjacent rural areas caused by emission of excess heat and the solar energy trapped by infrastructure (Gartland, 2008). Mitigation of urban heat has become a pressing issue as more than half of the world's population is currently living in cities (Hopkins & Goodwin, 2011). People that live in urban areas highly depend on air-conditioned buildings, artificial lighting and (air conditioned) transport. The additional waste heat generated by this lifestyle further contributes to the UHIE (Gartland, 2008; Salamanca et al., 2014; Priyadarsini, 2009). Increased night-time temperatures in urban settings are mainly caused by buildings and paved areas with low albedo and high heat storage capacity (Yang et al., 2011). Buildings and paved areas are made from concrete, asphalt, bricks and tiles which absorb short wave solar radiation during daytime and re-radiate long-wave radiation in the night, thereby increasing air temperatures at night.

Retaining existing trees and planting additional trees is one of the most effective strategies to mitigate UHIE. Urban trees provide surface cooling through shading and additional cooling benefits can be generated by latent heat removal through evapotranspiration (Zhao et al., 2017). Shade from tree canopies reduces the amount of sunlight absorbed by infrastructure, such as buildings and pavement and thus decreases the amount of energy that is re-radiated into the surrounding environment. The cooling effect of tree canopies on single domestic dwellings has been known for decades (Akbari et al., 1997). A recent study revealed that the cooling effect provided by shading from trees is more significant than that by evapotranspiration (Wang, 2016a). It was estimated that urban trees in the United States reduce the national residential energy consumption by 7.2% per year and provide a reduction of 38.8 million MWh of electricity (worth US$4.7 billion) (Nowak et al., 2017). The presence of trees is also linked with higher property values (Wang et al., 2018b; Staats et al., 2020; Zhang & Dong, 2018). As a direct effect on the human body, tree shade alters the perceived temperature which depends more on radiation and less on convection of heat from the local environment (Matzarakis et al., 2006). Hence, reducing radiant heat loads through shade from tree canopies improves human thermal comfort and can have a positive effect on public health (Astell-Burt & Feng, 2020; Jennings et al., 2019).

Shade provided by a tree has a quantitative and a qualitative dimension. The quantity of shade is dependent on the size of the tree crown and can be approximated by projecting the crown perimeter onto the ground surface. The quality of tree shade depends on the density of the canopy. The Leaf Area Index (LAI) can be used to determine the canopy density (Fahmy et al., 2010). LAI is defined as the total projected area of leaves of a single tree or group of trees over a unit of land (m^2 m^{-2}) and is known to have a direct influence on microclimate below the canopy (Lin & Lin, 2010; Sanusi et al., 2017). A low LAI indicates a more open canopy arrangement that provides a lower quality of shade, whereas a high LAI indicates a dense canopy which provides very high quality of shade. The canopy characteristics vary among tree species, age and location and thus, could influence air and surface temperature below the canopy (Armson et al., 2012). However, the shading efficiency of tree canopies is likely the result of a combination of the density and size of tree crowns. Surface temperature under a tree with a wide but open crown may be higher compared to that under a tree with a narrower but dense crown.

Although there are numerous studies on the effect of tree canopy cover on air temperature in urban settings (Feyisa et al., 2014; Tan et al., 2016) far fewer studies have assessed the influence of tree canopies or species differences in shading efficiency on surface temperatures at a microscale. Moreover, studies that do assess the relationship between surface temperature and urban tree canopy cover regularly use remotely sensed infrared data (Tusof et al., 2019;

Yuan & Bauer, 2007; Barbierato et al., 2019), which cannot be used to assess the impact of shading on temperature of surface materials under tree canopies. However, it is this type of information that urban planners, landscape architects and land managers often seek when selecting tree species to improve microclimates and reduce radiant heat loads.

Further, albedo of a surface material plays a significant role in UHIE. The albedo can be defined as the fraction of shortwave radiative energy reflected from a surface (Trlica et al., 2017) Light coloured surfaces with high albedo generally absorb less solar radiation than dark colour ones with low albedo (Santamouris et al., 2017b). Consequently, decreases in albedo increase the radiative energy absorption by the urban land surface, lead to increased air and surface temperature and contribute to the UHIE (Santamouris et al., 2017b; Zhou et al., 2014). Typical albedo values range from 0.10 to 0.50, with higher values usually associated with metallic surfaces (Santamouris et al., 2017b).

Here we present surface temperature measurements of common urban surface types under tree shade and adjacent sunlit areas and investigate species-specific relationships between tree size, using the stem diameter at breast height (DBH), LAI and the vertical projection of the crown area (A_C). A range of common urban tree species planted throughout Greater Sydney were tested for this purpose and we hypothesised (1) that species with higher LAI and larger A_C are most effective in reducing surface temperature, (2) that the surface temperature underneath tree canopies also depend on the surface material and (3) that darker surface materials with low albedo would exhibit higher surface temperatures compared to surface materials with high albedo.

2.3 Materials and methods

2.3.1 Study area

Greater Sydney in the state of New South Wales (NSW), Australia, was selected as the study area for this project. The area has a temperate climate with dry winters and hot summers. A natural rainfall gradient exists along an east (coastal)/west (inland) gradient where mean annual precipitation declines from 1300 mm to 880 mm (BoM, 2020b). Mean annual air temperature of the area is around 18 °C. Greater Sydney, especially the western part experiences extreme heatwave conditions annually with a peak temperature of 48.9 °C in January 2020 (BoM, 2020c). Moreover, Parramatta, a city in the geographic centre of Greater Sydney has been identified to have the highest UHIE in NSW (ABS, 2020). On average, Parramatta experiences 13 days each year with air temperatures of 35 °C and above (Sidiqui et al., 2016). The frequency of hot and extreme heat days is increasing in Parramatta and western Sydney more broadly (Greater Sydney Commission, 2019). Additionally, urban development has transformed rural land in the west of Greater Sydney to residential suburbs (Amati et al., 2017). Estimated population of this part of Greater Sydney in 2018 is 2.2 million which is 10% higher compared to 2011 (The Urban Developer, 2020). It is expected that the population of western Sydney will reach 2.9 million by 2036, representing more than 50% of the total population of Grater Sydney. Due to continued urbanisation in the region, canopy cover in the western part of Greater Sydney decreased by 0.83% from 2009 to 2016, a rate more than twice as high as what was observed across the State of NSW (Sidiqui et al., 2016).

2.3.2 Tree morphological measurements

For the present work, 471 healthy and well-established trees belonging to 13 different species were sampled from November 2018 to March 2019 across Greater Sydney. Sampled trees included (●)native, (○)exotic, (■)evergreen and (□)deciduous species that are widely planted in parks and streets across Greater Sydney, namely: ●,■Australian pine (*Casuarina equisetifolia*), ○,□camphor tree (*Camphor laurel*), ○,■chinese banyan (*Ficus macrocarpa*), ○,□crepe myrtle (*Lagerstroemia*), ○,□flowering pear (*Pyrus calleryana*), ○,□jacaranda (,*Jacaranda mimosifolia*), ●,■lemon-scented gum (*Corymbia citriodora*), ●,■lilly pilly (*Waterhousea floribunda*), ●,■paperbark (*Melaleuca quinquenervia*), ○,□planetree (*Platanus acerifolia*), ●,■queensland box (*Lophostemon confertus*), ○,□sweetgum (*Liquidambar styraciflua*) and ●,■Sydney blue gum (*Eucalyptus saligna*). Physical characteristics of the studied trees are shown in Table 2.1.

Stem diameter at breast height (DBH) was measured for each individual tree using a diameter tape. Here we used DBH as rough indicator of tree age. A clinometer (Suunto Tandem 360PC/360RDG, Australia) was used to measure tree and crown height. Crown radii (r) in six sub cardinal directions were measured using an optical laser (DISTO D810, Leica Geosystems, Australia). For this purpose, a perpendicular was dropped at the edge of the canopy from where the laser was pointed to the centre of the stem at parallel height to the ground surface. Half of the DBH (e.g., the stem radius) was added to each measurement to represent the distance from the crown edge to the centre of the stem. To estimate A_C we used the following modified equation (Pfautsch et al., 2013).

$$A_C = \sum_{i=1}^{6} \frac{r_i \times r_{i+1} \times \sin(60°)}{2}$$

where r_i and r_{i+1} are adjacent radii. LAI was measured using a digital canopy analyser (CI-110 Plant Canopy Imager, Bio Science Inc., USA). Two independent measurements were taken at randomly selected positions under each tree canopy. All images were collected under appropriate light conditions. During post-processing of the images, the Otsu method was applied for image thresholding and gap fraction analysis. This method was selected, because of its robustness in image segmentation, using a least square method based on a grey-scale histogram (Fang et al., 2006). Zenith and azimuth divisions of canopy images were selected manually for each image to ensure an accurate calculation of LAI.

2.3.3 Surface and globe temperature measurements

Surface and black globe temperatures were recorded between 12:00 and 15:00 (local daylight-saving time) under each tree canopy and in full sun adjacent to each tree. Black globe temperature is an indirect measurement of radiant heat load of the environment obtained with a thermometer installed inside a hollow copper sphere painted in matte black (da Silva et al., 2019).

A tripod-mounted weather station (Kestrel 5400, Kestrel Meters, USA) was used to record globe temperature at 30-second intervals. The air temperature sensor of the weather station was shielded from direct solar radiation and was well aspirated. The weather station was first positioned under the tree for 15 minutes before moving it into the sun adjacent to the tree for another 15 minutes. Data for the last 3 minutes of each measurement interval were averaged, to ensure only data was used after the weather station had adjusted to ambient conditions.

An infrared (IR) camera (FLIR C3, FLIR Systems Inc., USA) was used to record surface temperature at five random locations under the canopy and in full sun adjacent to each tree. The IR camera was held horizontally at 1m above the surface when taking the image. Different surface types of grass, bark mulch, bare soil, concrete pavers and bitumen were found under tree canopies as well as in sunlit areas adjacent to trees. Surface temperature was recorded for each of these individual surface types in both tree shade and full sun. Each individual tree had different types of surfaces and some trees had multiple surface types; 414 locations had grass, 135 bitumen, 69 bark mulch, 62 pavers and 28 bare soil. FLIR Tools+ software was used to extract five random point measurements from each image to calculate a representative surface temperature for each image. Measurements of air temperature were used to normalized surface and black globe temperatures. For surface and black globe temperatures differentials (ΔT_S and ΔT_G) were calculated by subtracting temperatures measured in the shade from those measured in the sun. To represent the effect of shading as 'cooling effect', all delta values are presented with a negative prefix.

To document the warm summer conditions during which the black globe and surface temperatures were collected, we provide information about mean, minimum and maximum ambient air temperatures measured in the sunlight (T_{ASL}) and in the shade of trees (T_{AS}) and their differential (ΔT_A) as supplementary materials. Table S3 provides these temperatures according to tree species while Table S4 provides this information according to the five surface types we investigated (e.g., bare soil, bark mulch, bitumen, grass, and concrete pavers).

2.3.4 Data analysis

All statistical tests were done using JMP software (SAS Institute Inc, USA). All data were first tested for normal distribution. Mean values were calculated for A_C and LAI for each tree species. Surface and globe temperature data were normalized to account for day-to-day variation in air temperatures. Surface temperature normalization was done for each surface type separately by using the following equation:

$$T' = \frac{T_O - T_{min}}{T_{max} - T_{min}}$$

where T´ is the normalized temperature, T_O is the observed temperature, T_{min} is the minimum recorded temperature and T_{max} is the maximum recorded temperature. Linear regression analysis was performed between tree physical traits and all the temperature measurements. Generalized Linear Models (GLM) were used to determine relationships among A_C, LAI, surface, globe temperature and surface types.

2.4 Results

2.4.1 Relationships of physical traits

Of the 471 urban trees that we sampled, *Casuarina equisetifolia* accounted for the most trees of a single species (n = 58) followed by *Lagerstroemia* (n = 55) and *Lophostemon confertus* (n = 49), while *Liquidambar styraciflua* had the lowest representation (n = 13) (Table 2.1). DBH of the sampled tree population ranged from 0.03 m (*Lagerstroemia*) to 1.6 m (*Melaleuca quinquenervia*) and tree height varied from 3.84 m (*Casuarina equisetifolia*) to 35.32 m (*Eucalyptus saligna*) (Table 2.1).

Table 2.1: Alphabetic list of tree species with their mean diameter at breast height (DBH), total height, vertical crown projected area (A_C) and leaf area index (LAI). N denotes number of trees. Minimum and maximum values for DBH and height, as well as 1 Standard Deviation (SD) are shown.

Species	N	Mean DBH ±SD (m)	Min /Max DBH (m)	Mean tree height ±SD (m)	Min/Max tree height (m)	Mean A_C ±SD (m^2)	Mean LAI ±SD (m^2m^{-2})
Camphor laurel	48	0.72 ±0.20	0.48/1.31	13.3 ±2.7	9.80/22.34	74.54 ±26.34	1.9 ±0.5
Casuarina equisetifolia	58	0.45 ±0.24	0.06/1.12	14.0 ±5.9	3.84/22.77	59.05 ±39.64	1.7 ±0.5
Corymbia citriodora	15	0.31 ±0.20	0.09/0.70	11.0 ±4.4	5.74/21.01	24.17 ±10.25	0.9 ±0.2
Eucalyptus saligna	19	0.64 ±0.22	0.38/1.30	26.3 ±4.3	17.77/35.32	92.30 ±46.93	1.4 ±0.3
Ficus macrocarpa	48	0.26 ±0.17	0.06/0.93	9.3 ±4.4	4.10/20.95	29.55 ±22.56	3.4 ±0.5
Jacaranda mimosifolia	40	0.51 ±0.26	0.09/0.96	13.5 ±4.5	5.57/22.74	99.47 ±85.45	2.0 ±0.6
Lagerstroemia	55	0.12 ±0.05	0.03/0.25	8.2 ±2.8	3.91/13.48	12.88 ±8.55	2.6 ±0.4
Liquidambar styraciflua	13	0.59 ±0.30	0.10/1.12	16.8 ±5.7	5.63/27.94	95.50 ±74.43	2.5 ±0.3
Lophostemon confertus	49	0.35 ±0.33	0.04/1.26	12.5 ±6.9	4.61/28.00	36.09 ±43.35	2.1 ±0.4
Melaleuca quinquenervia	19	0.84 ±0.33	0.34/1.60	17.1 ±2.5	13.79/24.03	55.14 ±23.43	2.1 ±0.3
Platanus acerifolia	17	0.52 ±0.26	0.08/0.97	16.8 ±5.1	4.27/24.80	96.50 ±44.52	2.8 ±0.4
Pyrus calleryana	46	0.19 ±0.13	0.04/0.68	8.0 ±2.2	4.45/13.33	17.76 ±18.38	2.6 ±0.8
Waterhousea floribunda	44	0.13 ±0.07	0.04/0.29	7.3 ±1.8	4.01/12.23	9.42 ±6.85	2.9 ±0.5

Jacaranda mimosifolia trees generally had the largest A_C (99.47 m^2 ± 85.74; ±1 Standard Deviation) followed by *Platanus acerifolia* (96.50 m^2 ± 44.52) and *Liquidambar styraciflua* (95.50 m^2 ± 73.43) while *Waterhousea floribunda* had the smallest A_C (9.42 m^2 ± 6.85) among all sampled species (Table 2.1). Furthermore, *Ficus macrocarpa* was the species with the highest LAI (3.4 m^2 ± 0.5) and *Waterhousea floribunda* had the second largest LAI (2.9 m^2 ± 0.5). In contrast, *Corymbia citriodora* had the lowest LAI (0.9 m^2 ± 0.2) among the sampled tree species (Table 2.1).

Across all species, tree height and DBH followed a clear positive trajectory (R^2=0.68, p <0.001), as did A_C (R^2 = 0.75, p <0.001) (Figure 2.1). At the individual tree level, there were no significant relationships between LAI and DBH or A_C. Tree species with dense canopies and medium height (e.g., *Ficus macrocarpa*, *Lagerstroemia*) had a smaller A_C and higher LAI compared to tall, species with more open canopies (e.g., *Casuarina equisetifolia*, *Corymbia citriodora*) (Table 2.1).

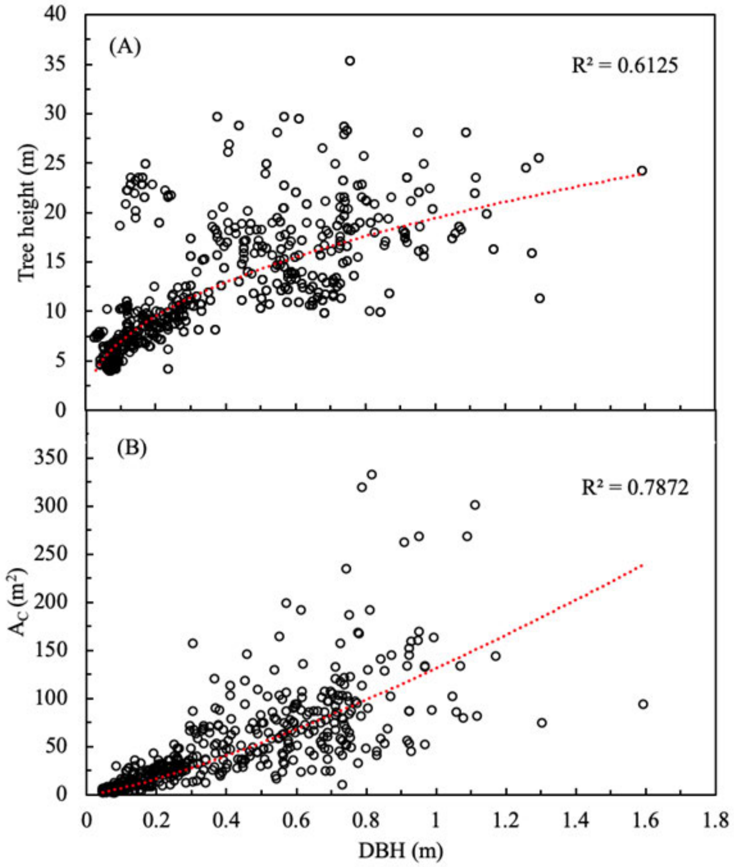
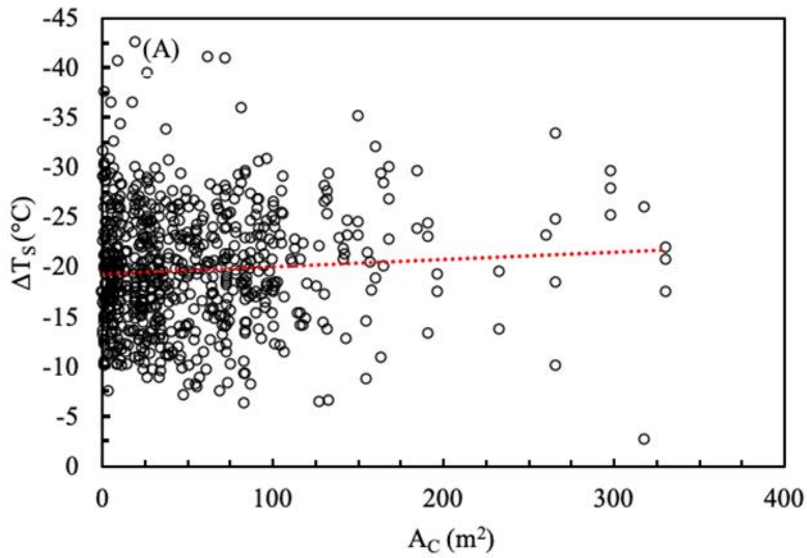


Figure 2.1: Relationships between stem diameter at breast height (DBH) and total tree height (panel A) and vertically projected crown area (A_C; panel B) of 471 trees from 13 species growing in urban environments across greater Sydney, Australia. Dotted lines show best-fit functions (A: Tree height = 19.38 x $DBH^{0.46}$; B: A_C = 136.23 x $DBH^{1.29}$). Coefficients of determination are shown.

2.4.2 Influence of urban trees on different types of temperature

No significant effect of A_C or LAI on the shaded surface temperature (T_{SS}) or surface temperature differential (ΔT_S) ($p > 0.05$) was found (Figure 2.2). Figure 2.3 shows the distribution of ΔT_S and LAI for each species, further demonstrating that there was no relationship between LAI and ΔT_S among the investigated tree species. Species-specific measurements for mean, minimum, maximum and the differential of surface temperatures measured in the shade and sun are provided in Table S1.



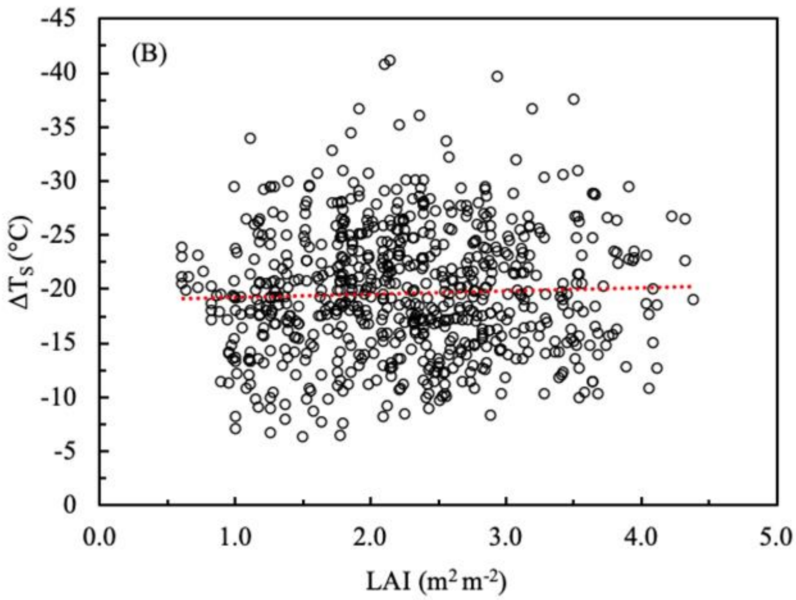


Figure 2.2: Relationships between tree crown characteristics and surface cooling, calculated as differential between the surface temperature in the sun and shade of a given surface type (ΔT_S). Panel A: vertical crown projected area (A_C) and surface temperature dif ΔT_S); panel B: Leaf Area Index (LAI) and surface temperature differential (ΔT_S). Data are shown for 471 individual trees from 13 species growing in urban environments across greater Sydney, Australia. Dotted lines show linear fits.

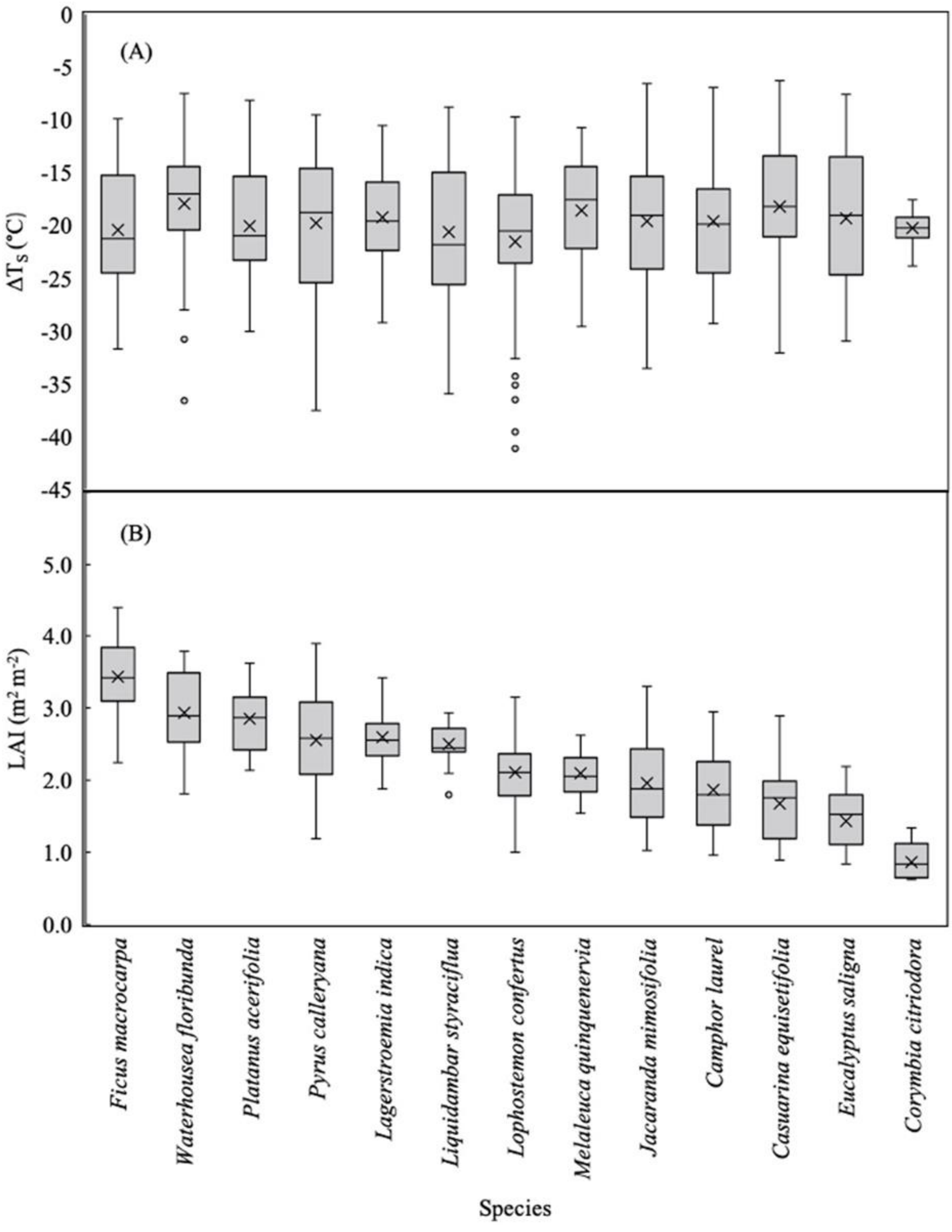


Figure 2.3: Distribution of the surface temperature differential (ΔT_S; panel A) and Leaf Area Index (LAI; panel B) in each tree species. Distribution of LAI in each species is arranged from the highest mean LAI to the lowest mean LAI. The lower and upper line of the box shows the first and third quartile; the line and cross inside the box show the median and mean; the whiskers show minimum and maximum values.

However, the effect of surface type on T_{SS}, T_{SL} and ΔT_S was highly significant ($p < 0.001$). T_{SS} ranged from 20.4 °C to 54.7 °C and bitumen had the highest mean T_{SS} (33.5 °C ± 4.2) followed by bark mulch (33.4 °C ± 3.1), concrete pavers (33.1°C ± 4.8), bare soil (33.0 °C ± 2.9°) and grass (31.0 °C ± 2.7) (Table 2.2). T_{SL} ranged from 30.1 °C to 76.9 °C and bark mulch had the highest mean T_{SL} (58.2 °C ± 8.1) followed by bare soil (55.2 °C ± 5.9), bitumen (54.5 °C ± 6.2) and grass (49.4 °C ± 5.1). Bark mulch showed the largest ΔT_S (-24.8 °C ± 7.1) followed by bare soil (-22.1 °C ± 5.6), bitumen (-20.9 °C ± 5.8) and grass (-18.5 °C ± 4.8) respectively. Concrete pavers showed the smallest ΔT_S (-17.5 °C ± 6.0).

Table 2.2: Mean, minimum and maximum shaded surface temperature (T_{SS}), sunlit surface temperature (T_{SL}) and surface temperature differential (ΔT_S) recorded on bare soil, grass, bark mulch, concrete pavers and bitumen.

Surface types	Mean T_{SS}±SD (°C)	Min /Max T_{SS} (°C)	Mean T_{SL}±SD (°C)	Min/Max T_{SL} (°C)	Mean ΔT_S±SD (°C)	Min/Max ΔT_S (°C)
Bare soil	33.0 ±2.9	27.5/40.4	55.2 ±5.9	44.8/69.9	-22.1 ±5.5	-9.9/-34.3
Grass	31.0 ±2.7	22.5/40.2	49.4 ±5.1	30.1/64.0	-18.5 ±4.8	-6.3/-30.9
Bark mulch	33.4 ±3.1	27.6/42.5	58.2 ±8.1	42.8/76.9	-24.8 ±7.1	-8.2/-41.1
Pavers	33.1 ±4.8	20.4/54.7	50.1 ±5.6	33.6/60.5	-17.5 ±6.0	-7.0/-32.0
Bitumen	33.5 ±4.2	25.9/44.9	54.5 ±6.2	40.7/69.6	-20.9 ±5.8	-8.6/-35.9

A Tukey HSD test revealed that T_{SL} was significantly different between all surface types except between bark mulch and bare soil, bitumen and bare soil and pavers and grass (Figure 2.4). Similarly, T_{SS} was significantly different between grass and bitumen, grass and bark mulch, grass and pavers and also between grass and bare soil. Further, ΔT_S were significantly different between all the surface types except bark mulch and bare soil, bitumen and bare soil and grass and pavers (Table 2.3).

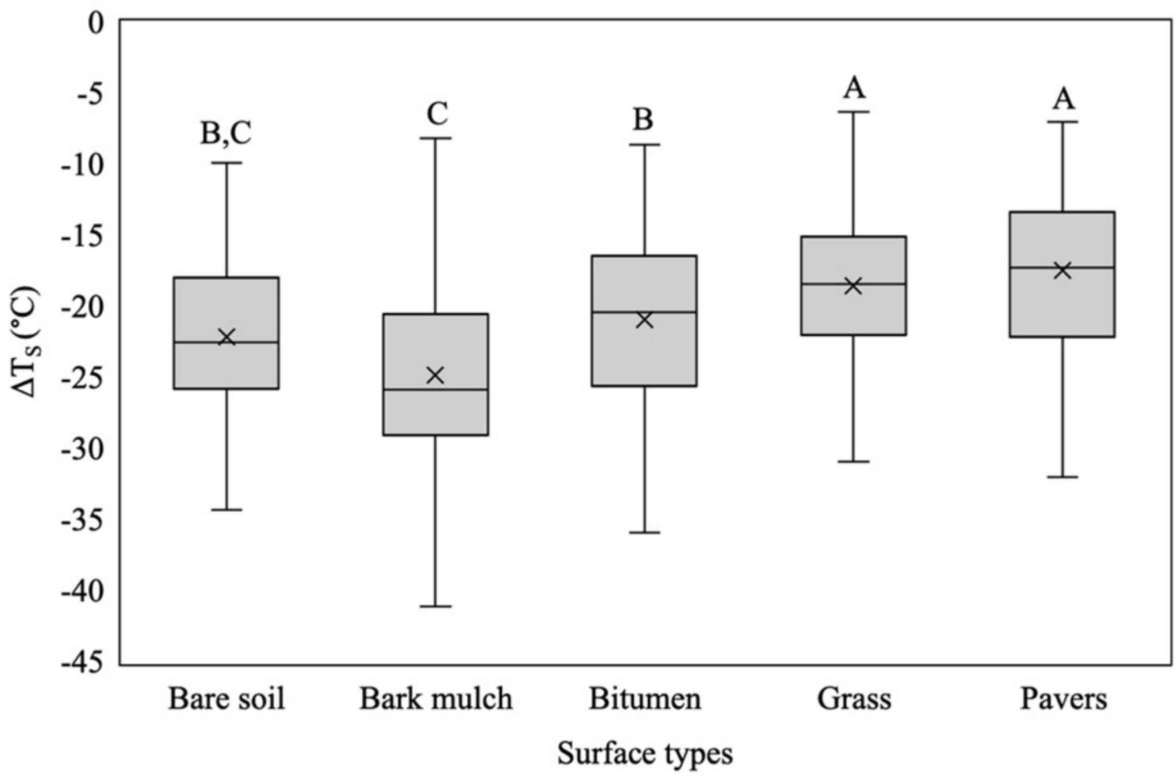


Figure 2.4: Box whisker plot illustrates the distribution of surface temperature differential (ΔT_S) in surface types (bare soil, bark mulch, bitumen, grass and pavers). Levels not connected by the same letter are significantly different. The lower and upper line of the box shows the first and third quartile; the line and cross inside the box show the median and mean; the whiskers show minimum and maximum values.

Table 2.3: Tukey's HSD pairwise comparison of the surface temperature differential (ΔT_S) and black globe temperature differential (ΔT_G) observed between the five surface types: pavers, grass, bitumen, bark mulch and bare soil.

	Pavers	*Grass*	*Bitumen*	*Bark mulch*	*Bare soil*
(a) Surface temperature differential (ΔT_S)					
Pavers		0.5917	0.2432	**<0.0001**	**<0.0001**
Grass	0.5917		**<0.0001**	**<0.0001**	**0.0187**
Bitumen	0.2432	**<0.0001**		**<0.0001**	0.8692
Bark mulch	**<0.0001**	**<0.0001**	**<0.0001**		**<0.0001**
Bare soil	**<0.0001**	**0.0187**	0.8692	**<0.0001**	
(b) Black globe temperature differential (ΔT_G)					
Pavers		**<0.0001**	**<0.0001**	**0.0096**	**<0.0001**
Grass	**<0.0001**		**<0.0001**	**<0.0001**	**<0.0001**
Bitumen	**<0.0001**	**<0.0001**		**<0.0001**	**0.0166**
Bark mulch	**0.0096**	**<0.0001**	**<0.0001**		**<0.0001**
Bare soil	**<0.0001**	**<0.0001**	0.**0166**	**<0.0001**	

Shaded globe temperature (GT_S) and globe temperature differential (ΔT_G) did not show any significant relationship with the tree morphological parameters ($p > 0.05$). Data for species-specific globe temperature measurements collected in the shade and sun, as well as ΔT_G are provided in Table S2. Absolute GT_S ranged from 26.3 °C to 44.5 °C and bark mulch had the highest mean GT_S (37.9 °C ± 2.8) followed by bitumen (36.9 °C ± 2.2), pavers (36.1 °C ± 2.4), bare soil (34.4 °C ± 2.2) and grass (33.3 °C ± 3.2) (Table 2.4). Absolute globe temperature in the sun light (GT_{SL}) ranged from 28.4 °C to 54.1 °C and consistently with rankings found in the shade, bark mulch had the highest mean GT_{SL} (48.8 °C ± 2.8) followed by bitumen (46.1 °C ± 2.2), bare soil (41.5 °C ± 2.2), pavers (40.4 °C ± 2.4) and grass (36.5 °C ± 3.2). Bark mulch showed the largest ΔT_G (-10.9 °C ± 0.5) and grass showed the lowest ΔT_G (-3.2 °C ± 0.2). The effect of surface types on GT_S, GT_{SL} and ΔT_G was highly significant ($p < 0.001$). Tukey's HSD test showed that GT_S was significantly different among all the surface types except bitumen-bare soil. Similarly, GT_{SL} was significantly different between all surface types except bitumen-pavers, pavers-bare soil and bitumen-bare soil. Further, ΔT_G significantly different between all surface types ($p < 0.001$) (see Table 2.3).

Table 2.4: Mean, minimum and maximum shaded globe temperature (GT_S), sunlit globe temperature (GT_{SL}), and globe temperature differential (ΔT_G) recorded in bare soil, grass, bark mulch, pavers and bitumen.

Surface types	Mean GT_S±SD (°C)	Min /Max GT_S (°C)	Mean GT_{SL}±SD (°C)	Min/Max GT_{SL} (°C)	Mean ΔT_G±SD (°C)	Min/Max ΔT_G (°C)
Bare soil	34.4 ±2.2	26.3/41.5	41.5 ±2.2	33.4/48.6	-7.2 ±0.1	-7.3/-7.0
Grass	33.3 ±3.2	25.3/43.1	36.5 ±3.2	28.4/46.3	-3.2 ±0.1	-3.4/-3.0
Bark mulch	37.9 ±2.8	32.2/43.0	48.8 ±2.8	39.3/58.3	-10.9 ±0.3	-10.3/-11.5
Pavers	36.1 ±2.4	29.6/39.6	40.4 ±2.4	33.8/43.9	-4.3 ±0.1	-4.3/-4.3
Bitumen	36.9 ±2.2	33.4/44.5	46.1 ±2.2	38.1/54.1	-9.5 ±0.2	-10.5/-8.5

2.5 Discussion

2.5.1 Influence of urban trees on surface and globe temperature

Tree shade reduced the surface temperatures by 20 °C on average and species like *Lophostemon confertus, Ficus macrocarpa and Liquidambar styraciflua* provided greater surface temperature reduction. Although this can be due to having a comparatively larger LAI, the correlation analysis between A_C, LAI and the ΔT_S did not show a strong significant relationship. For example, *Waterhousea floribunda* had the second largest LAI among the sampled tree species, however, it had the lowest average ΔT_S. Similar results were found in the globe temperature measurements. There is a globe temperature reduction up to 13 °C from the sun to the tree shade. Nevertheless, results do not support that LAI or the A_C have an influence on this temperature reduction. Despite of having both the largest LAI, *Ficus macrocarpa* accounted for the highest GT_S.

Our findings are different from the findings of other studies. For example, the study conducted by (Hardin et al., 2007) in Terre Haute, Indiana, USA, on the effect of urban leaf area on summertime urban surface temperatures found that urban leaf area index and urban surface temperature were negatively correlated. In this study, LAI accounted for 62% of variation in surface temperature (Pretzsch et al., 2015). Moreover, a study by (Yusof et al., 2019) suggested that surface temperature reduction is positively correlated with LAI. They also found that tree shade reduces the surface temperature by average of 12 °C. A study carried out in Suzhou Industrial Park, Shanghai, China by (Xiao et al., 2018) concluded that cooling effect of green areas was positively correlated with the LAI. Similar findings were presented by (Napoli et al., 2016) where they found a strong relationship between ΔT_S on asphalt and LAI and a weaker relationship between ΔT_S on grass and LAI. Studies have found that the amount of solar radiation blocked by tree shade is strongly related to size of the crown and height of the tree (Gillner et al., 2015; Gómez-Muñoz et al., 2010) and thereby improves the surface cooling. In this study, we were unable to build such a relationship with tree height or A_C. There is no doubt that tree shade reduces the amount of heat absorbed by the surface's underneath during the daytime; however, our study provided evidence that microclimate underneath the trees and the temperature of surface material greatly depend on the type of surface material.

2.5.2 Effect of surface types on surface and globe temperature

Results showed that grass had the lowest recorded surface temperature and globe temperature both in shade and sun. This can be due to the combined effects of evapotranspiration and albedo of surface materials. Albedo can be defined as the fraction of the incident sunlight that the surface reflects (Coakley, 2003; Akbari, 2009). Grass has the highest albedo (0.3–0.25) (Zeman, 2012) of all the surface types thus absorbs less and reflects more radiation than the other surface types. On the contrary, bark mulch had the highest T_{SS} T_{SL} and GT_S. It has a very low albedo 0.05 (Tripathi & Kativar, 1984) compared to others; bare soil (0.26–0.16) (Gascoin, 2009) bitumen (0.2–0.05) and pavers (0.13–0.1) (Zeman, 2012) thus, increases the surface temperature by absorbing more radiation. However, it is worth to note that there are other factors such as thermal emissivity and thermal mass of surface materials which influence the surface temperatures (Hulley, 2012) and the extent to which surface materials contribute to the UHIE. Further experimentation is needed to evaluate individual effect of these parameters on surface temperature variations. Largest surface cooling from tree shade was observed for bark mulch followed by bare soil, bitumen, grass and pavers. Results indicated that the surface material has a strong and significant influence on surface temperature. This finding is backed-up by the globe temperature recorded above each surface material; the highest GT_{SL} was recorded in bark mulch whereas lowest was recorded in grass. Black globe temperature has the combined effects of air movement, dry-bulb temperature and radiant heat received from the surfaces (Panagakis, 2011). The novel finding of this study advances understanding of cooling provided by trees. Planting trees with wider canopies and larger LAI does not directly support urban cooling through surface temperature reduction. Rather, surface material has a larger influence in the reducing thermal loads in urban space. This finding should be integrated in urban planning and cooling strategies to mitigate UHIE.

2.5.3 Limitations of the study

The majority of the sampled trees were young, and this is a clear indication that the urban landscape of western Sydney does not accommodate large, mature trees with wide canopies. Research has demonstrated that the shade profile of a tree depends on the maturity, overlapping canopies and canopy extents (Downs et al., 2019a; Downs et al., 2019b; Rahman et al., 2014). The major proportion of our study was comprised of young trees with smaller and separate canopies which can influence the amount of solar radiation reaching the ground.

2.6 Conclusion

This study gave a novel insight to the relationship between surface temperature and canopy characteristics. It showed that canopy characteristics such as LAI, shaded area and crown projected area do not have a strong influence on the temperature loads on surfaces. Although these canopy characteristics varied among the tested species, they were unrelated to surface temperature reductions in shade. Nevertheless, we found that surface types play a significant role in absorbing and reflecting radiation thereby controlling surface temperatures and cooling arising from tree shade. Evapotranspiration will have effect on surface cooling; however, further studies are needed to determine the cumulative effects of surface material and tree evapotranspiration on surface cooling. This novel finding can be integrated in urban cooling and urban planning strategies. Landscape planners and architects should consider choice of surface materials in urban settings as a higher priority than tree species for shade quality alone when implementing urban greening strategies to mitigate urban heat.

2.7 Author contribution

T.U.N.K. collected and analysed the data and wrote the draft manuscript. S.P. designed the study and assisted with analyses of data and writing the manuscript. M.G.T. contributed to data analyses and writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

Chapter 3: Influence of Surface Cover on Microclimate in Sydney

3.1 Abstract

The area covered by metropolitan Sydney has expanded over time and influencing the urban and rural temperature difference. The study reported in this chapter was conducted to determine the effect of urban landscape heterogeneity on air temperature at the microscale. Temperature loggers were deployed in branches of trees that automatically recorded the air temperature at 10-minute intervals from December 2018 to February 2019 at 156 locations across the Local Government Areas of Parramatta City and Cumberland in western Sydney. Six types of temperature derivatives were calculated from the recorded temperature data. A 50-m radius area encircling each location where a temperature logger was installed was manually digitized into six surface categories (Green space, Tree canopy, Roads, Buildings, Blue space, Brown space). Relative cover of each surface category was calculated for each location and all the locations were categorized into Local Climate Zone (LCZ) classes. Linear regression analyses showed that increasing Tree canopy cover by 40% would potentially cool mean air temperature (T_{mean}) by 1 °C. Similarly, increasing Tree canopy cover by 50% would cool the daytime air temperature (6:00 am–7:50 pm) by 1°C. However, Tree canopy was unable to show a significant relationship with night-time air temperature and Grey infrastructure like roads and buildings appeared to have the biggest influence on temperature at night. Compact LCZ classes exhibited higher temperatures (0.2–1.4 °C) compared to more open classes. Increasing Tree canopy cover as well as Green space were equally important to lower the air temperature. However, cluster arrangement of trees could inhibit warm air dissipate into the atmosphere at night. Findings suggest that scattered tree cover may be more effective at reducing air temperature . Based on these and previous analyses, strategic mixing of trees with open and

closed canopy architectures as well as wider spacing among trees are encouraged to maximise cooling potential of urban canopy during day and night. Additionally, as discovered in Chapter 2, grass surfaces under tree canopies would help reduce surface temperatures even more.

3.2 Introduction

3.2.1 Urban Heat Island Effect (UHIE)

The UHIE is a global issue that affects many people living in cities (Mohajerani et al., 2017). The UHIE is a phenomenon when urban areas experience higher air temperature compared to surrounding non-urban areas (Li et al., 2018b; Guo et al., 2020). Studies conducted by the World Meteorological Organisation (1984) revealed that the UHIE can increase air temperature in a city by 2–8 °C (Mohajerani et al., 2017) but other studies have found that it can range between 5 °C and 15 °C (Santamouris et al., 2013; Soltani & Sharifi, 2017; Yue et al., 2019; Manoli et al., 2019). Increased use of human-made materials with low albedo, reduction in vegetation and associated evapotranspiration and increased anthropogenic heat production are the main causes of the UHIE (Rodler & Leduc, 2019). Buildings, roads, and other human-made structures absorb and re-radiate more energy from solar irradiance compared to vegetated surfaces and together with waste heat from anthropogenic activities result in warmer air temperatures (Kelbaugh, 2019; Qaid et al., 2016).

In urban areas, aside from net radiation, anthropogenic heat discharge also causes heat fluxes and this leads to increased temperatures.(Fig 3.1). Net radiation is the balance of energy from incoming solar irradiance and reflected short- and longwave radiation from the atmosphere against the outgoing short- and long-wave radiation emitted from the surface of the land into the atmosphere (Taha, 1997). Human activity, such as manufacturing operations and transportation, generates anthropogenic heat discharge through ground heat, sensible heat, and latent heat. Since the underground temperature is generally lower than the surface temperature during the day, ground heat is conducted into the ground (Kato & Yamaguchi, 2005). The stored heat in the ground is conducted into the atmosphere at night. Latent heat is the energy released or absorbed from a substance during a change in phase between gas to liquid or solid or vice versa. The transpiration of vegetation and evaporation of land surface water produces latent heat (Myrup, 1969; Mirzaei & Haghighat, 2010). Additionally, due to power generation machinery and the generation and supply of hot water, electricity is converted into latent heat through phase changes of water. From land surface to atmosphere, the remaining energy is transferred as sensible heat. Sensible heat is the energy released or absorbed to change the temperature of a substance with no phase change (Takebayashi & Moriyama, 2007). The major sources of anthropogenic sensible heat come from inside urban areas as heated gases that are exhausted, for example, through air conditioning units and through chimneys.

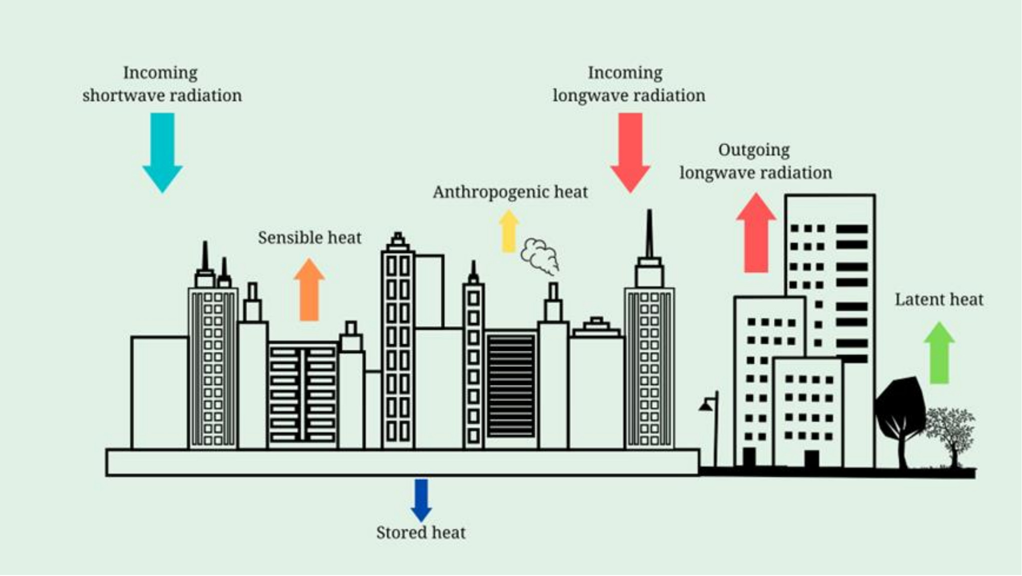


Figure 3.1:Illustration of the radiation and energy fluxes in an urban environment. Sum of the absorbed net radiation and anthropogenic heat in a city equals the outgoing fluxes of heat from the ground, sensible heat, and latent heat. The size of an arrow represents its contribution to the overall energy balance.

Aside from the anthropogenic activities, other major contributing factors to the UHIE include:

- **Urban fabric**: Intensity of the UHIE is influenced by the overall distribution of residential, commercial, industrial land use, open space, and parklands (Soltani & Sharifi, 2017).
- **Urban structures**: Building height and compass orientation affect the exposure of urban surfaces to solar radiation (Lin et al., 2010). This also alters the intensity and the pattern of wind flow in urban canyons (Krüger et al., 2011).
- **Surface cover**: Thermal characteristics of urban surface materials (conductivity, specific heat mass, diffusivity), textures and colours can affect the exchange of heat between surfaces and air in urban areas (Karatasou et al., 2013). Conductivity Refers to the intrinsic ability of a material to transfer or conduct heat. It is one of the three methods of heat transfer. The other two are convection and radiation. Specific heat mass Amount of heat per unit mass required to raise the temperature by one degree Celsius. Thermal diffusivity Thermal diffusivity describes the rate of temperature spread through a material.

These factors affect the urban microclimate at the surface layer (land surfaces and buildings), canopy layer (space with variable height (up to 30 m) between the surface and the top of trees) and boundary layer (up to 1500 m above the ground surface) (Oke, 2006). The UHIE occurs at the surface level ($UHIE_{Surf}$), and in the atmosphere ($UHIE_{Atm}$) (Huang et al., 2020). In general, the former occurs below effective roof level and the latter extends along the boundaries of the urban heat plume (Oke, 1984). Urban thermal plumes are characterized by rising air in the lower altitudes of the atmosphere as a result of urban areas being warmer than the surrounding areas (Oke, 1984). Various scales and criteria can be used to categorize the latter, but some commonly used classifications include canopy-layer heat islands and boundary-layer heat islands (Taha, 1997).

Increasing the albedo of materials to minimize the absorption of solar radiation (Yu et al., 2008), planting trees to provide shade and evapotranspiration (Santamouris et al., 2017b), covering roofs and facades with vegetation (Musy et al., 2017) and pavement watering (Azam et al., 2018) are some practices currently used to mitigate the UHIE. Albedo is defined as the proportion of solar radiation reflected by a surface (Qin et al., 2018). Albedo is very low in cities due to the properties of surface materials, including their colour. Urban structures, pavements, and building materials generally have a low albedo. The UHIE occurs where the albedo of the urban area is lower than the albedo of the surrounding rural area. Low vegetation cover, low relative humidity, and low soil moisture content are contributing factors to UHIE in cities. Albedo of dark green leaves is approximately equal to asphalt (0.10-0.15). However, leaves absorb and convert some solar irradiance into chemical energy and produce later heat flux, while asphalt only absorbs solar radiation and emits sensible heat. Besides having low albedo, many surfaces in urban areas like roofs, walls, pavements, streets, and buildings, urban areas also have a lower effective albedo compared to those in rural or surrounding areas (Taha, 1997). Albedo refers to the surface reflectance, which reflects light due to the color, roughness, or other radiative properties of the surface and should be distinguished from effective albedo, which reflects light due to its multiple reflections on the street and walls. According to Bernabé et al. (2015), the urban effective albedo is also related to the intensity of urban heat islands. A street canyon's geometry will result in a higher probability of a photon being absorbed by its surfaces (instead of escaping back to space), lowering its effective albedo (Taha, 1997).

Surface materials used in the urban fabric play a very important role in the urban thermal balance as they absorb incident solar radiation and dissipate a percentage of the absorbed heat through convective and radiative processes into the atmosphere, increasing the ambient air temperature (Morini et al., 2016). Further, the amount of heat released by urban structures such as buildings and paved areas is influenced by the sky view factor (SVF). The SVF is defined as the ratio of the radiation received by a given point on a planar surface to the radiation emitted to the entire hemispheric environment (Zeng et al., 2018). SVF is typically represented by a dimensionless value between 0 and 1, where 0 indicates the sky is completely obstructed and 1 indicates there are no obstructions at all (Brown et al., 2001). A considerable proportion of emitted heat is trapped and retained by urban structures due to limited SVF and thus contributes to the UHIE (Dirksen et al., 2019), especially at night. Even though trees also limit the SVF, they have a limited capacity to store and emit heat due to the physical properties of wood and foliage (Dirksen et al., 2019).

In many cities and suburbs trees are an essential part of the landscape, and they absorb and reflect direct solar radiation and shade man-made materials whereby they cool air and surface temperatures (Gillner et al., 2015). For example, studies have found near surface air temperatures of green space can be 1–3 °C, and sometimes even 5–7 °C cooler than air temperatures above surrounding built-up areas (Zhang et al., 2017). Tree shade was found to lower near-surface air temperature by up to 2 °C in the eastern suburbs of Sydney, Australia (Gao et al., 2020). Trees can also provide a vertical cooling gradient by reducing air temperature 20 m above ground by 4 °C compared to an unshaded area (Wang & Akbari, 2016). During heatwaves in Melbourne, air temperature underneath the canopy of street trees was reduced by more than 6 °C (Taleghani, 2018), and the microclimate of entire tree-lined street canyons was cooled between 0.6 and 1.5 °C (Coutts et al., 2016). Dense shade of street trees can markedly improve human thermal comfort[1] (Sanusi et al., 2016), reducing the perceived

[1] Human thermal comfort is defined as “the condition of mind that expresses satisfaction with the thermal environment” (Rupp et al., 2015).

temperature, measured with globe thermometers, by 5–7 °C (Armson et al., 2012). Recent research from Sydney demonstrated that the area of shade cast by trees onto pedestrian walkways was the least during midday when air temperature was high (Igoe et al., 2020), which highlights the importance of species selection and tree management when the goal is to improve the walkability of urban streets. Beside improved human thermal comfort during summer, shade cast by street trees can reduce the surface temperature of streets and pavements by 20 °C or more compared to unshaded conditions (Armson et al., 2012; Lin et al., 2016; Kaluarachchi et al., 2020).

3.2.2 Urban growth and UHIE in Sydney

Urbanization has led to significant modification in the natural environment leading to land use and land cover changes in cities (Sultana & Satyanarayana, 2020). The human-induced modifications of land cover can increase surface and air temperatures in cities by several degrees compared to surrounding non-urbanized areas leading to UHIE (Sherafati et al., 2018; Bhargava et al., 2017). Similarly, the increasing population of Greater Sydney has resulted in continuous urban encroachment into natural and agricultural landscapes, which from a thermal perspective were significantly cooler (Burgin et al., 2016). Greater Sydney is one of the fastest growing regions in the Asia Pacific Region and its population is projected to increase to 6.6 million by 2036 (Greater Sydney Commission, 2018). The New South Wales Government is planning to add more than 500,000 detached dwellings to the region by 2036 which will ultimately lead to a large-scale transformation of rural to urban land (Burgin et al., 2016).

Over the past two decades, strategic spatial planning has become an increasingly important part of Australian urban planning (Searle, 2013). A spate of metropolitan plans emerged (Bunker & Searle, 2009) after a long period during which such plans were significantly less frequent. Figure 3.2 shows the changes in urban-dwelling density in 1996, 2016 and anticipated changes in 2036. In 1996, most of the urban area comprised of detached low-density housing in the inner suburbs whereas higher density dwellings were limited to the east of the city (Greater Sydney Commission, 2018). By 2016, the density of dwellings had increased across the eastern, central and the western section of Greater Sydney, with particularly high rates of densification in the central and eastern areas. This trend is predicted to continue, leading to increasingly dense urban development in eastern and central Greater Sydney by 2036.

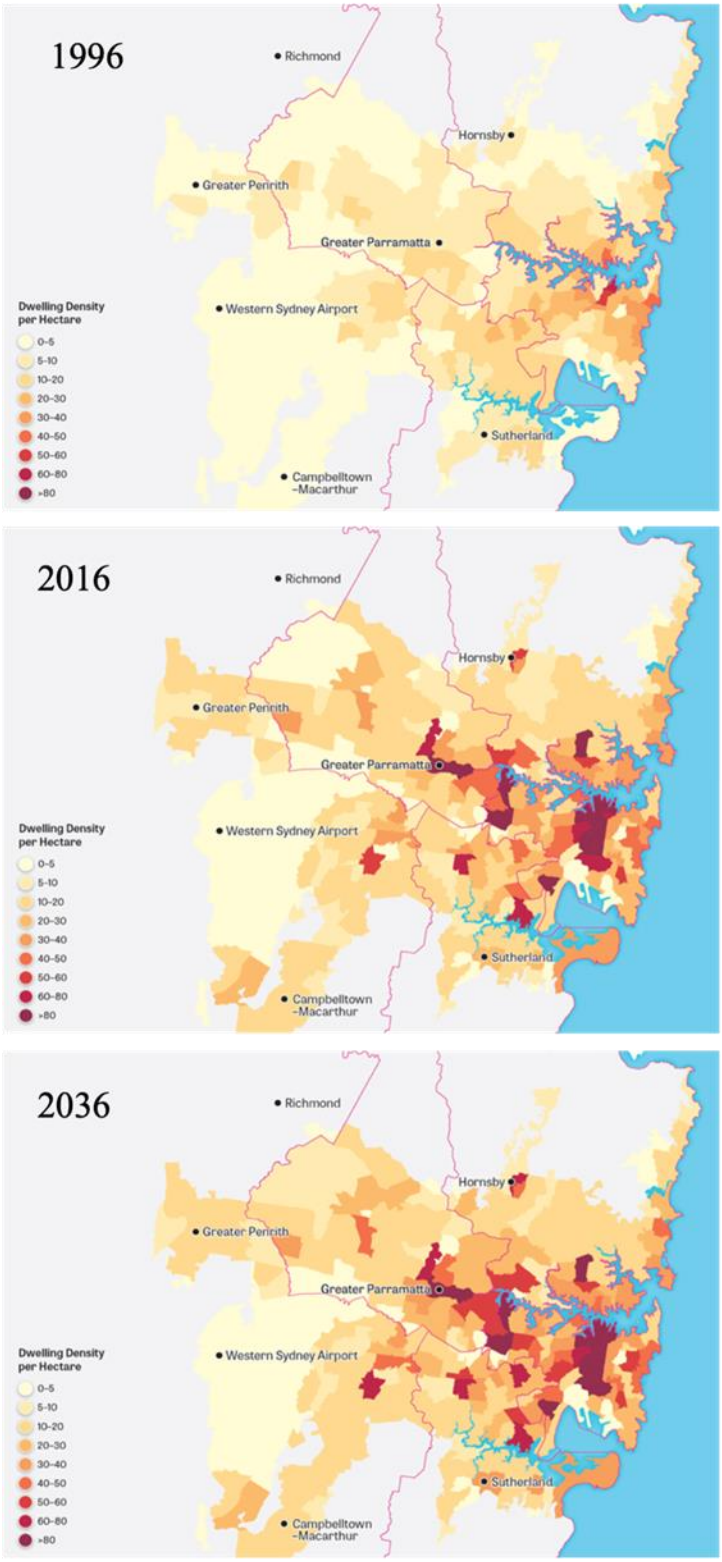


Figure 3.2: Changes in urban dwelling density across Greater Sydney in 1996 (top), 2016 (middle) and 2036 (bottom). 1996: medium density dwelling in the inner suburbs and higher density dwellings are limited to North Sydney, Inner west, City east and Eastern beach 2006: outward spread of intense development from City of Sydney to Chatswood, Strathfield, Parramatta, Hornsby and Liverpool, 2036: further increased development within the existing urban areas is expected. (Image © Greater Sydney Commission, 2018)

Urban densification and expansion results in conversion of land surface cover from pervious to impervious surface, which is a known cause of UHIE. Maheshwari et al. (2020) showed that the climate of Sydney markedly changed during 1986-2011 compared to the reference period of 1960–1985 as a result of continued densification and expansion. In their study, the authors analysed temporal trends in daily maximum and minimum air temperature (T_{max} and T_{min}), evaporation and rainfall data (1960–2011 period) for Sydney to determine whether urbanisation had influenced the urban climate and its longer-term variability.

For Sydney, urbanization increased T_{max} by 1.4 °C and T_{min} by 0.43 °C (Maheshwari et al., 2020). Santamouris et al. (2017) analysed climatic data from six meteorological stations in the Greater Sydney region which covered the decade between 2005 and 2015 and found that the $UHIE_{Surf}$ varied between 0 and 11 °C, as a function of the prevailing weather conditions. It was also found that because of the intense development of the UHIE, Cooling Degree Days (CDDs) in western Sydney are about three times higher than in the eastern coastal zone of Sydney (Santamouris et al., 2017a). The CDD can be defined as the "severity of the climate and the resulting cooling energy demand" (Santamouris et al., 2017a) and in this study CDD index was used because of its correlation with energy consumption and UHIE. In addition, Sidiqui et al. (2016) also found that magnitude of daytime UHIE can vary between 7–8 °C in summer in Sydney. Among all documented UHIE effects in Australian cities, Sydney CBD appears to have the most intense UHIE stretching from east to west. Increased morbidity and mortality are associated with urban heat (Zhang et al., 2018; Bi et al., 2011). Sydney's population appeared to be more vulnerable to urban heat, with a lower susceptibility to heat than some American and European cities (Vaneckova et al., 2008). This observation was based on the findings of the study by Vaneckova et al. (2008). It has been shown that the relationship for heat-related mortality in Sydney is not as strong as that for cities in developed temperate countries and developing subtropical/ tropical countries. There is evidence that heat-related mortality increases less among populations living in subtropical regions during extreme hot events than among populations living in temperate regions.

The report titled “Metropolitan Sydney Climate Change Snapshot” issued by the Office of Environment & Heritage (2014) states that maximum and minimum air temperatures in Greater Sydney are projected to increase by 0.7 °C by 2030 and 2.0 °C by 2070 compared to the baseline modelled climate from 1990 to 2009 (Fig. 3.3). Moreover, the conversion of existing urban and peri-urban forest and grassland in the north-west and south-west of Greater Sydney as a result of urban expansion could double the predicted changes in air temperature as a result of climate change (Livada et al., 2019; Adam et al., 2015).

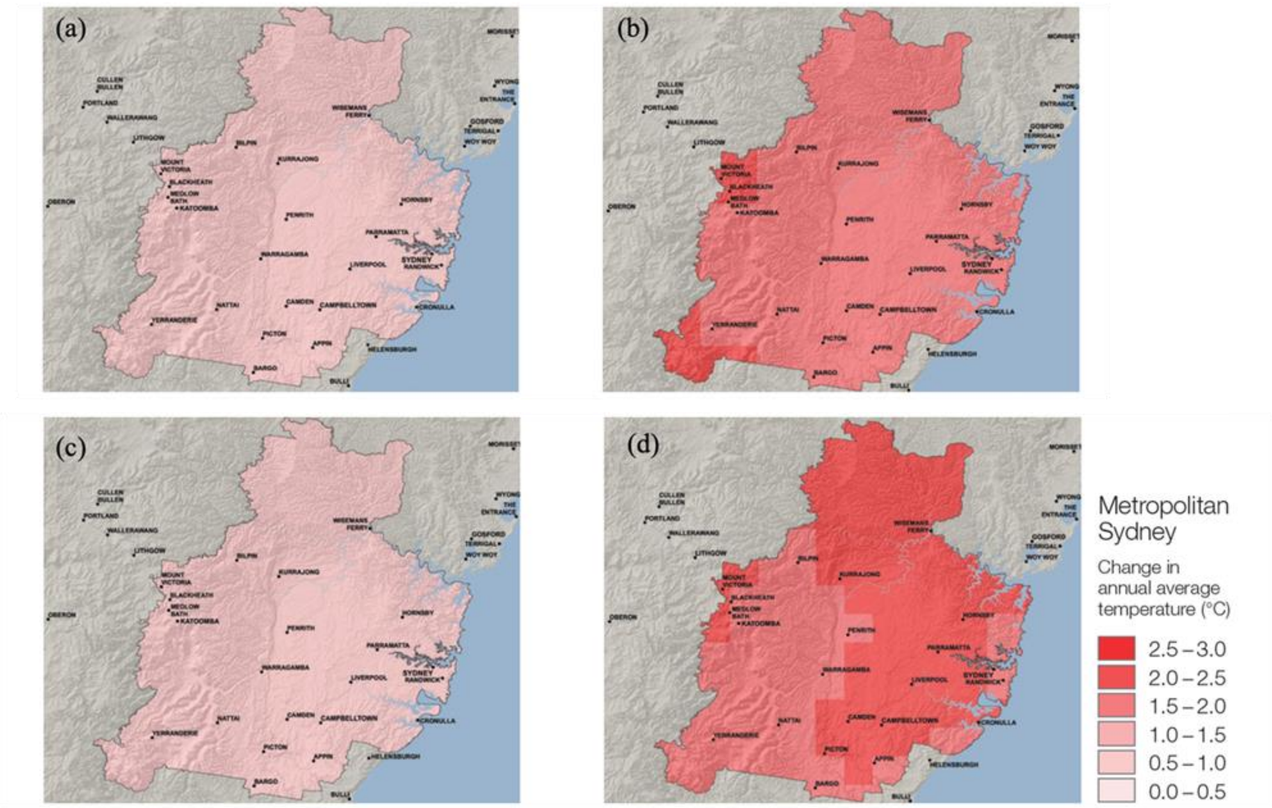


Figure 3.3: Projected changes in air temperature for Greater Sydney for the period of 2020–2039 (panels a and c) and 2060–2079 (panels b and d) compared to the baseline period of 1990–2009. Panels a and b depict anticipated changes in mean maximum air temperatures and panels c and d depict anticipated changes in minimum air temperatures. (Image © Office of Environment & Heritage, 2014)

3.2.3 Research gaps and objectives

As mentioned in the previous sections, researchers have extensively studied the macro-scale causes, magnitude and spatial extent of rural-urban temperature differences. However, the effect of urban landscape heterogeneity on air temperature at the micro-scale (e.g., a single house) and meso-scale (e.g., a precinct) is much less studied. Furthermore, the majority of studies at these smaller scales have predominantly investigated the thermal environments and effects of green cover such as urban parks or impervious surfaces like buildings and paved areas. For example, Taha (1997) reported that air temperature decreased by 0.5 °C in a 33% vegetation cover (grass and trees) scenario and 1 °C in their 67% vegetation cover scenario compared to no vegetation cover. Furthermore, studies have shown that tree canopy cover of 25–40% can reduce the air temperature underneath the canopy by 0.5 °C (Lin et al., 2008; Leuzinger & Körner, 2007). A study conducted in Hong Kong compared five scenarios of urban vegetation cover (0%, 8%, 16%, 34% and 56%) and found out that every scenario had a significant cooling effect, while 56% urban vegetation scenario had the greatest effect (Ng et al., 2012). Moreover, a study conducted in Mexico found that 50% urban vegetation cover can reduce the air temperature by 2.2 °C (Colunga et al., 2015). Onishi et al. (2010) observed a decrease in air temperature of 6.4 °C with 100% grass cover and cooling of air temperature by 9.2 °C with a 70% grass + 30% tree cover. Additionally, Ziter et al. (2019) observed a nonlinear decrease of air temperature with increasing canopy cover from 0 to 90% and greatest cooling was attributed to scenarios where tree canopy cover exceeded 40%.

However, results of these empirical studies cannot universally be applied to cities around the world because each city has its own shape, urban characteristics and local climate (Aboelata & Sodoudi, 2019). Furthermore, the complex environment of cities makes it difficult to accurately separate surface types into pervious and green or impervious and grey areas, but rather demands to integrate them at fine scales (Cadenasso et al., 2007; Zhou et al., 2017).

Contrasting surface types often co-occur (e.g., tree canopy over a road). In addition, many studies that investigated the effects of variability of land surface types on air and surface temperatures have utilized high resolution Advanced Thermal and Land Applications Sensor (ATLAS) data (Weng et al., 2004), Landsat images (Hawkins et al., 2004) or ASTAR satellite data (Mallick et al., 2013). There are several limitations associated with this approach. Mainly, the surface temperatures recorded by the satellite sensors only relates to the spatial patterns of upward thermal radiance received by the sensor (Voogt & Oke, 2003). Besides, the surface UHIE can differ from the atmospheric UHIE due to the effects of turbulence and wind velocity on air temperature (Mirzaei & Haghighat, 2010). A cloudy sky may limit UHIE data collection by satellites owing to limited frequency of sampling of a specific geographic location (Mirzaei & Haghighat, 2010).

Microclimate has a direct spatial and temporal relationship with surface materials (He et al., 2019). Thus, there is a necessity to quantify the effect of surface cover types on urban air temperature by incorporating spatial heterogeneity at a microscale. Moreover, microscale analysis is crucial in identifying the areas with high thermal exposure and to inform site-specific mitigation options. Site-specific mitigatory measures are vital in reducing urban heat and associated health risks (Jenerette et al., 2016; Heaviside, et al., 2017).

The influence of tree morphological characteristics on surface and globe temperature was studied in Chapter 2. I found that surface material had a greater influence on surface and globe temperatures than tree morphological characteristics. Especially since increasing tree canopy cover is viewed as a critical method of reducing deaths due to extreme heat in cities, lowering energy costs, and fostering biodiversity, this important finding raises questions about the role of urban greening. The third chapter deeper into the role of urban greening for cooling by examining how the spatial heterogeneity of these urban surfaces including tree canopy alters the air temperature at a micro-scale.

This study quantifies the influences of surface cover type on daytime and night-time temperature in western Sydney. On-site air temperature measurements were recorded during summer from December 2018 to February 2019 at 156 locations across more than 150 km^2 of urban land. Relative areas of different surface categories were calculated, and regression analysis was used to determine the relationships between air temperature measurements and surface categories. The findings of this study will inform potential strategies to mitigate high air temperatures and heatwaves in cities.

The objectives of the study were as follows:

- To determine the effect of common urban surfaces on thermal microclimate through a range of summertime air temperature metrics,
- To identify the best interventions to mitigate daytime and night-time urban heat.

3.3 Materials and methods

3.3.1 Study area

The local government areas (LGA) of Parramatta City and Cumberland were selected to investigate the spatial variation in microclimate across a range of urban environments. Both LGAs experience extreme heat in summer (Pfautsch & Rouillard, 2019a, b). A practical limitation to assess climatic variation in this part of Greater Sydney is the lack of official weather stations. Only two stations are operated in the area by the Bureau of Meteorology, located at North Parramatta and Sydney Olympic Park. The purpose of these stations is to document synoptic weather patterns at macro-scale, not air temperature variation at micro-scale. To document and assess micro-scale variation it was necessary to distribute a large number of air temperature loggers across all urban typologies present in the LGAs.

Parramatta and Cumberland are located in the Greater western Sydney. The LGAs of Parramatta City and Cumberland City are 24 km west of the Sydney CBD. According to the Australian Bureau of Statistics (2021), 260,000 people live in the Parramatta LGA and 243,000 people live in the Cumberland LGA. At present, Parramatta and Cumberland have population densities of 31 and 34 persons per hectare, respectively (ABS, 2021). Annual mean maximum and mean minimum air temperature in Parramatta is 23.4 °C and 12.2 °C while mean annual rainfall is 966 mm based on data from 1990–2020) (BoM, 2021). Cumberland has an annual mean maximum temperature of 23.6 °C and an annual mean minimum temperature of 13.9 °C (BoM, 2021). It receives on average 912 mm annual rainfall (based on data from 1990-2020) (BoM, 2021).

3.3.2 Temperature logger installation

Bespoke low-cost temperature loggers for continuous measurement of air temperatures were used in this study. Each logger consisted of a temperature sensor (Tempmate ®-S1 V2, Imec Messtechnik, Heilbronn, Germany) and a lightweight, highly reflective white shield made from aluminium to shield the sensor from direct solar radiation and other environmental disturbances. The base of the shield was open, and large holes were drilled into the top of the shield to allow ventilation of the interior air space. The temperature sensor was waterproof and built to record temperature at 10-minute intervals for 110 days with an accuracy of ±0.5 °C (-20 °C / +40 °C) at a resolution of 0.1 °C. Measurement quality was certified through international standards (e.g., CE, EN 12830). Calibration and thermal functionality of the temperature logger is described in Wujeska-Klause & Pfautsch (2020).

Prior to distribution of the temperature loggers in the field, idealised locations were determined using equally spaced grids (1 km^2) to overlay the LGAs of Parramatta and Cumberland. The grids identified a total of 156 locations (Parramatta n = 73, Cumberland n = 83) across both LGAs and adjacent urban landscapes. Once the ideal locations were identified, Google Street View was used to identify the nearest suitable street tree or public park managed by the council to place the temperature loggers in safe locations. The street address of each location was documented, and Goggle Maps was used to calculate ideal routes for installation of blocks of 10–12 locations. Pre-identifying optimal routes for the distribution of temperature loggers was critical, as it helped to avoid the risk of missing or forgetting a logger and to keep a minimal interval between installation of the first logger and the last logger of each route.

With support from both councils, temperature loggers were installed during the austral summer between 26 November and 20 December 2018. The serial number of a temperature sensor was noted before activating and assembling the temperature logger at each location. Each logger was attached to a lower tree branch with no foliage (approx. 2.5–3.5 m above ground) using a step ladder and cable ties and positioned vertically with the open base pointing towards the ground. The loggers were placed in a wide array of locations including residential streets and parks, as well as nature strips, green verges, reserves, playgrounds, industrial areas, commercial centres and other localities (Fig. 3.4). At each location, the GPS coordinates and physical address were noted. A map showing the final distribution of the temperature logger across the adjacent LGAs is shown in Figure 3.5.

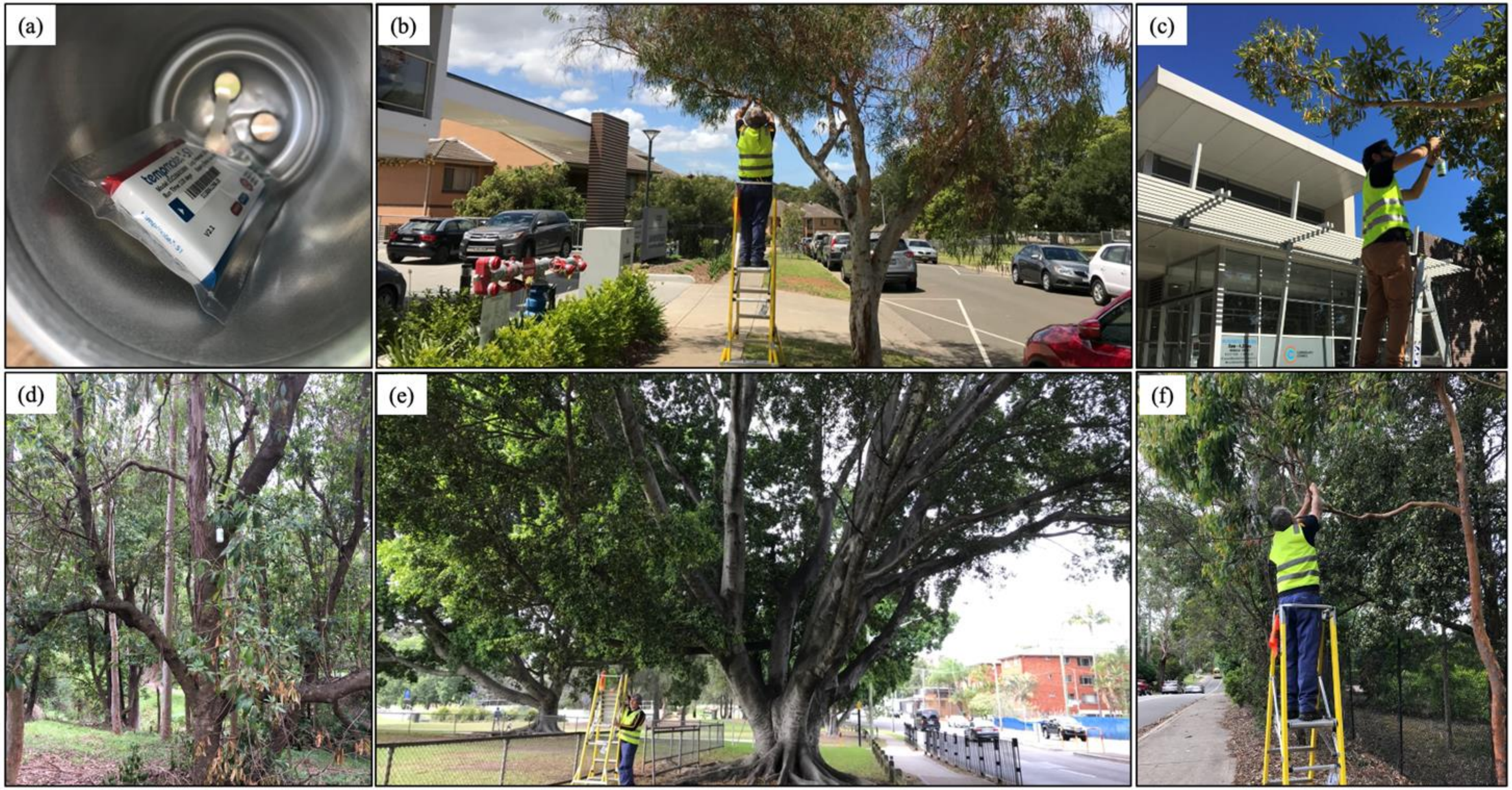


Figure 3.4: Installation of heat sensors around the local government areas of Parramatta Council and Cumberland Council in November and December 2018. (a) Inside view of a temperature logger with sensor, shield and ventilation holes. (b-f) Selection of images showing the diversity of settings where temperature loggers were installed, ranging from nature reserves (d) to residential roads (b) and commercial centres (c).

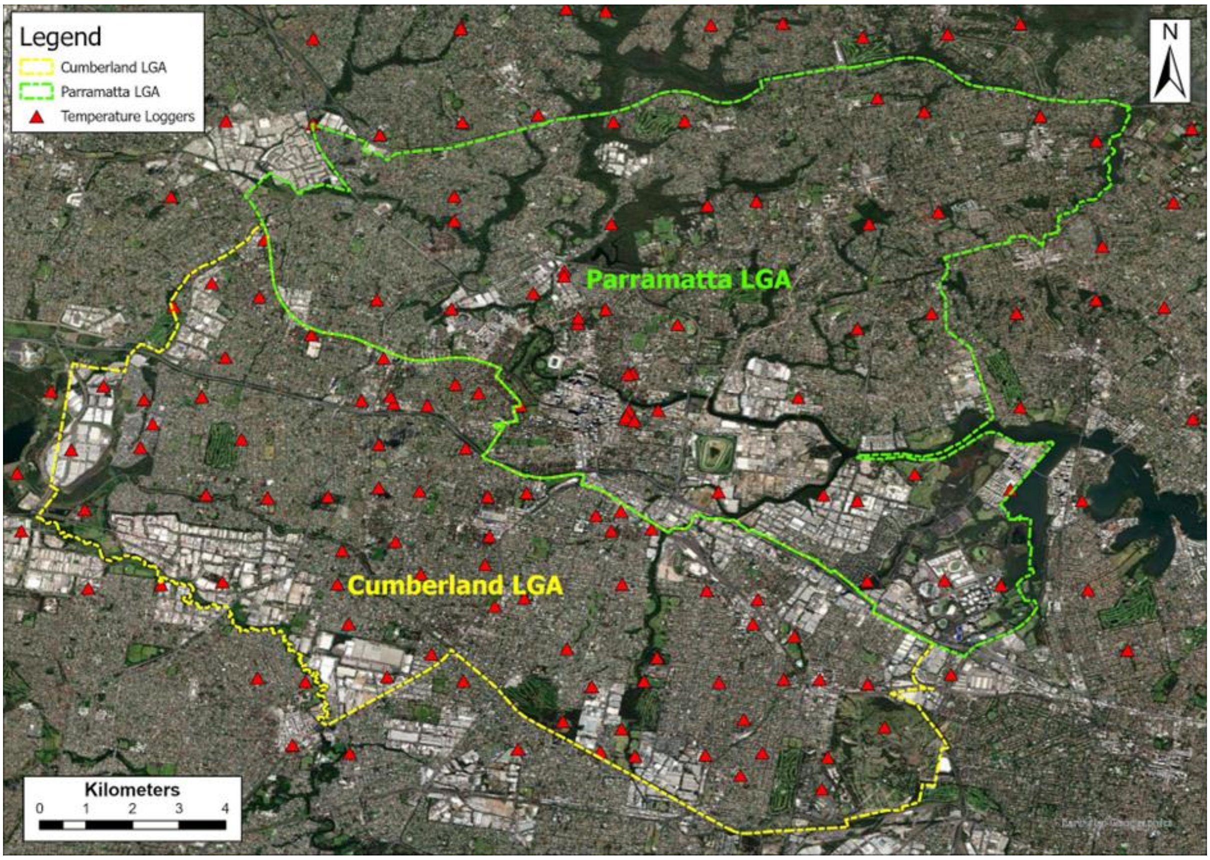


Figure 3.5: Locations of the temperature loggers across the LGAs of Parramatta City and Cumberland in Greater Sydney, Australia. A total of 156 loggers were installed in Parramatta (n = 73) and Cumberland (n = 83).

3.3.3 Data acquisition from temperature loggers

The same driving routes used to distribute the temperature loggers were used to collect them at the end of the experiment in March 2019. The loggers were switched off and brought back to the laboratories of Western Sydney University where data were retrieved from the loggers and stored in a computer. A total of 2,549,125 individual air temperature measurements from the 156 locations across both LGAs were available for analysis. Each dataset had a time stamp which needed to be adjusted to Australian Eastern Standard Time (AEST), (UTC +10). Once the time was adjusted, data were truncated to the period from 00:00 hr on 21 December 2018 to 23:50 hr on 28 February 2019 so that both LGAs had temperature data with a matching start and end point from the same time period. This truncated data set contained 1,594,788 individual measurements.

The following air temperature metrics were calculated/extracted from these data:

- **Mean air temperature (T_{mean})** – The average summertime air temperature between 21 December 2018 and 28 February 2019 at each location in both Cumberland and Parramatta LGAs.
- **Mean maximum air temperature (T_{max})** – The highest recorded daily air temperature averaged across the measurement interval for each location.
- **Mean minimum air temperature (T_{min})** – The lowest recorded daily air temperature averaged across the measurement interval for each location.
- **Mean daytime air temperature (T_{Dmean}) –** The average air temperature recorded between 6.00 am to 7.50 pm at each location. This time window was selected based on the sunrise and sunset times in Sydney in summer. This metric was used to examine the relationship between the day-time air temperature and the surrounding landscape.
- **Mean night-time air temperature (T_{Nmean}) –** This is the average temperature of the air recorded between 8.00 pm to 5.50 am in each location. This time window was selected based on the sunset and sunrise times in Sydney in summer. The UHIE is more dominant in the night due to the release of energy from grey infrastructure like buildings and roads. Higher spatial and temporal UHIE is observed during solar off-peak times (night-time and early morning when solar radiation is not the dominant source of heating) (Memon et al., 2009). Therefore, T_{Nmean} was examined in relationship to the surrounding landscape features.
- **Absolute maximum temperature (T_{Abs}) –** The absolute maximum air temperature was recorded on 31st January 2019 in each location. NSW recorded its peak temperature in multiple locations on 31st January 2019 (BoM, 2021) for the summer of 2018/2019.

3.3.4 Digitizing of surface areas and tree canopy

Nearmap (Nearmap, Barangaroo, Sydney, Australia) was used to obtain high resolution aerial images for the study. Nearmap, a subscription-only service, used mosaics of high-resolution vertical images collected during low altitude flights using light aircraft to generate one large and continuous orthorectified image. On-board camera systems captured data with a ground sample distance (GSD) of 5.5 cm in vertical imagery with a horizontal accuracy of 19.8 cm. GPS locations recorded during the installation of the temperature loggers were used to geolocate the exact position of trees that contained these loggers in Nearmap. Ground-level photos taken during the installation of the temperature loggers were used to further confirm each location. At each location in Nearmap, a circle with a radius of 50 m was drawn around the position where air temperatures were recorded. The 50 m radius was chosen for several reasons. Most studies done in the past have focused on large and central parks, and smaller and local green spaces have been largely overlooked (Aram et al., 2019). Previous studies have indicated either no effect or effects up to 330 m (Aram et al., 2019). The study by Grilo et al. (2020), conducted in Lisbon, Portugal, explored the relationship between microclimate data and land-cover types in the immediate vicinity of the sensors, using buffers of varying radius (5 m, 10 m, 15 m, 30 m, 60 m, 120 m, 150 m, 200 m, 240 m). Based on their findings, the distance from the sensors at which the highest correlation was found between tree canopy area and summer mean temperature and relative humidity was 60 m, indicating this is the distance at which trees produce an influence on summer mean temperature and relative humidity.

Aerial imagery collected in December 2018 was used for this purpose, reflecting the contemporary conditions of surfaces during the collection of air temperature data. The circular area was used to delineate the space where surface cover types and surrounding structures were assessed at very high spatial accuracy (Fig. 3.6). For example, when a temperature logger was installed in a residential area, the 50 m radius would capture the road surface, verge, front yards and houses in the immediate vicinity – all objects that likely influence the microclimate around the point of air temperature measurement.

In a next step, the area covered by the circle was digitised manually using the polygon tool in Nearmap. Six different categories of surfaces were measured separately: *Green space, Tree canopy, Roads, Buildings, Blue space and Brown space*. Green space comprised of gardens, parks and lawns. Tree canopy included all tree canopies above the ground seen in the images. This surface type did not include any bushes or ground cover plants. Figure 3.6 shows images digitized with and without tree canopy.

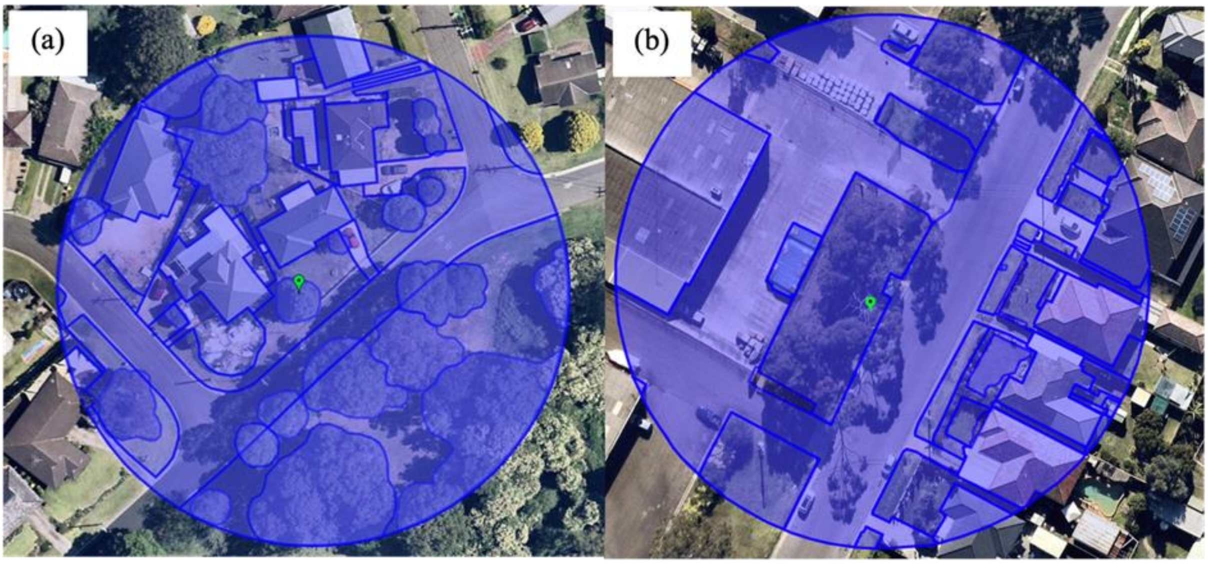


Figure 3.6: Map with a digitized 7850 m^2 encircled area (50 m radius). The green marker in the centre of the circular area indicates the exact location where the temperature logger was placed. a) Image with digitized surface types including tree canopy cover b) Image with digitized surface types not including tree canopy cover. (Images © Nearmap)

Creeks, rivers, lakes and other water bodies such as swimming pools or wetlands were categorised as Blue space. Bare soil was categorised as Brown space. Figure 3.7 shows examples of digitized images with different surface categories. To calculate the area covered by all surface types and canopy cover for the 83 measurement locations in the Cumberland LGA it was necessary to manually draw 5078 polygons. The same process required drawing

6162 polygons for the 73 locations across the Parramatta LGA. The area and surface category or tree canopy cover was noted for each polygon, resulting in extremely accurate measurements of urban surface types around each air temperature measurement point. In total, 11,240 polygons covered 1,224,600 m^2 (1.2 km^2) of complex urban terrain

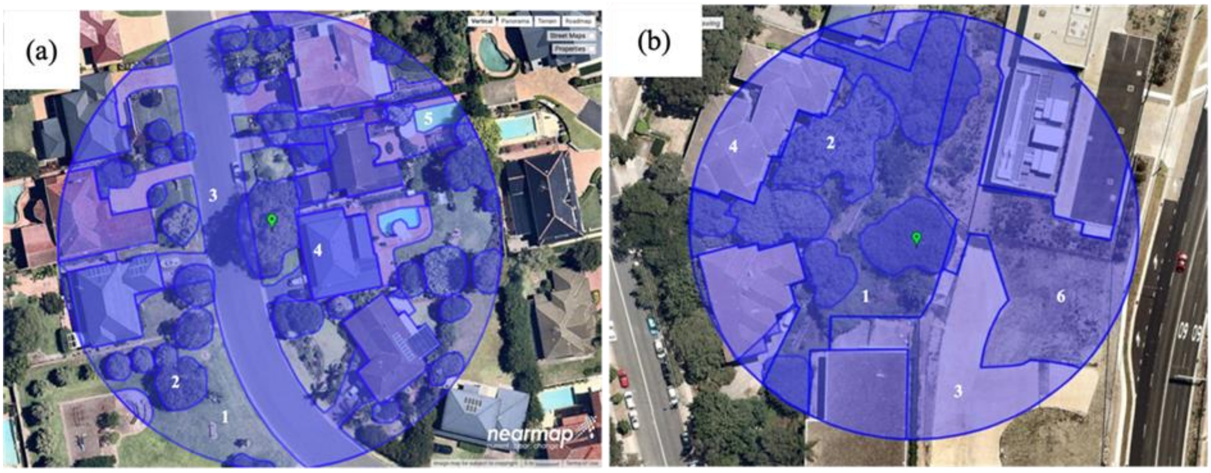


Figure 3.7: Panel a and b illustrate the digitized images of different temperature logger locations with examples of different surface categories found at each location. 1 = Green space, 2 = Tree canopy, 3 = Roads, 4 = Buildings, 5 = Blue space, 6 = Brown space. (Images © Nearmap)

3.3.5 Relative area calculations

The relative area of Green space, Tree canopy, Roads, Buildings, Blue space and Brown space present at each location was calculated by summing all polygon areas for each category and dividing that sum by the total area of the circle drawn (7850 m^2) (Table 3.1). It is important to note that the sum of the percentages per image was greater than 100% because tree canopy was treated as a second, independent layer above the ground surface. Hence, the surface area covered by trees was measured twice: once as overlapping tree canopy and once as the relevant surface category/categories underneath the tree crown.

The investigated surface categories may occur together at a given location in different proportions. Therefore, it was also investigated if predominately cooling or warming surfaces had additive effects on site microclimates. For this reason, composite urban surface categories were created by summing the relative areas of Green infrastructure surface categories (Green space + Tree canopy) and Grey infrastructure surface categories (Roads + Buildings).

Table 3.1: Main types of urban surfaces, elements included and the relative surface area calculation surrounding each temperature logger. Total area is the ground surface area of a 50-m radius circle (7850 m^2) centred on each logger location.

Surface categories	**Elements included**	**Relative area (%)**
Green space	Parks, lawns, home gardens, urban forest	(Area of Green space/ Total area) *100
Tree canopy	Tree canopies (bushes are not included)	(Area of Tree canopy/ Total area) *100
Roads	Roads, footpaths, driveways	(Area of Roads/ Total area) *100
Buildings	Buildings (residential and commercial)	(Area of Buildings/ Total area) *100
Brown space	Surfaces without grass cover, bare soil	(Area of Brown space/ Total area) *100
Blue space	Rivers, swimming pools, wetlands, lakes	(Area of Blue space/ Total area) *100
Green Infrastructure	Green space, Tree canopy	((Area of Green space + Area of Tree canopy)/Total area) *100
Grey Infrastructure	Roads, buildings	((Area of Roads + Area of Buildings)/Total area) *100

3.3.6 Local Climate Zone (LCZ) classification

All digitized locations were categorized into distinct Local Climate Zone (LCZ) classes by using the classification system developed by Stewart & Oke (2012). This system defines an LCZ as a “region of uniform surface cover, structure, material, and human activity that can span tens of meters to several kilometres in horizontal scale”. The LCZ system has 17 zone types at the local scale. Each type is unique in its combination of surface structure, cover, and human activity. Each LCZ has a characteristic screen-height temperature regime (air temperature at 2 m above the ground surface) that is most apparent over dry surfaces, on calm, clear nights, and in areas of simple topographic relief (Stewart & Oke, 2012). These temperature regimes persist year-round and are associated with the homogeneous environments or ecosystems of cities (e.g., parks, commercial centres), natural biomes (e.g., forests, deserts), or agricultural lands (e.g., orchards, cropped fields) (Stewart & Oke, 2012).

The purpose of categorizing the temperature logger locations into LCZs was to investigate temperature variability among the LCZs and determine if the observed variation across the 156 locations in the Cumberland and Parramatta LGAs could be attributed to the land cover within the LCZs. The locations of the present study were classified into the LCZ classes by visual observation of the available ground and Nearmap (aerial) images and comparing the relative areas of buildings and other pervious and impervious surfaces to the values given by Stewart & Oke (2012) (Table 3.2). Figure 3.8 shows the examples of digitized locations belong to each of the LCZ mentioned in the Table 3.2.

Table 3.2: Characteristics and land cover properties of Local Climate Zones (LCZs), based on values stipulated by Stewart & Oke (2012).

LCZ Class	Definition	Building surface fraction*	Road surface fraction**	Green infrastructure Brown space & Blue space surface fraction***
LCZ 2 Compact mid-rise	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	40–70	30–50	<20
LCZ 3 Compact low-rise	Dense mix of low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	40–70	20–50	<30
LCZ 5 Open mid-rise	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	20–40	30–50	20–40
LCZ 6 Open low-rise	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.	20–40	20–50	30–60
LCZ 8 Large low-rise	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.	30–50	40–50	<20
LCZ 9 Sparsely built	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).	10–20	<20	60–80
LCZ B Scattered trees	Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.	<10	<20	>90
LCZ D Low plants	Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.	<10	<10	>90

*Ratio of building plan area to total plan area (%)
**Ratio of roads plan area to total plan area (%)
***Ratio of Green infrastructure, Brown space and Blue space to total plan area (%)

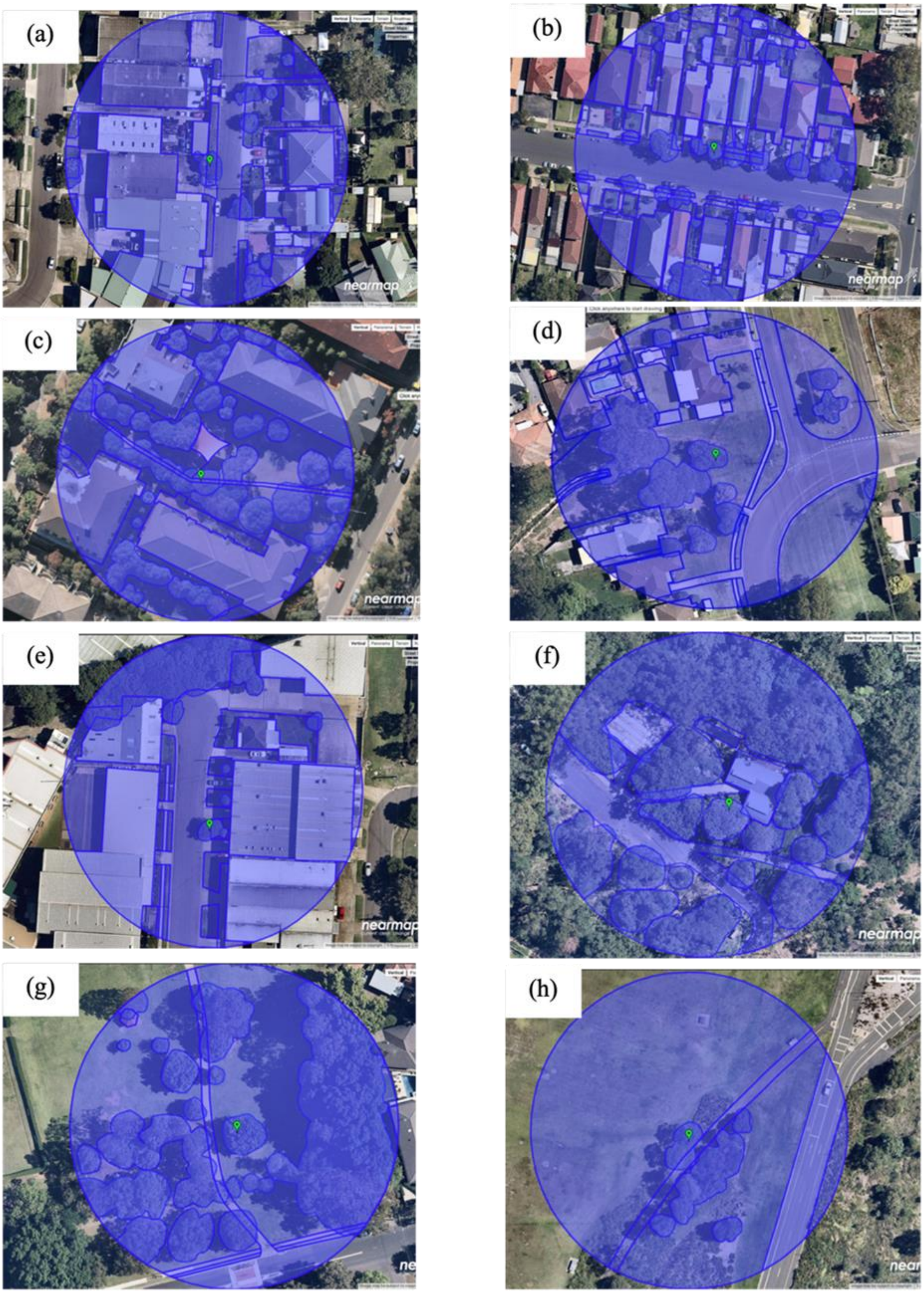


Figure 3.8: Examples of some digitized temperature logger locations belong to different Local Climate Zones (LCZs) (a) LCZ 2 (Compact mid-rise) (b) LCZ 3 (Compact low-rise) (c) LCZ 5 (Open mid-rise) (d) LCZ 6 (Open low-rise) (e) LCZ 8 (Large low-rise) (f) LCZ 9 (Sparsely built) (g) LCZ B (Scattered tree) (h) LCZ D (Low plant). (Images © Nearmap)

3.3.7 Data analysis

All statistical analysis were computed in JMP 16.0.0 (SAS Institute, USA). Linear regression analysis was used to assess the relationships between the relative area covered by surface categories (Green space, Tree canopy, Roads, Buildings, Blue space, Brown space, Green infrastructure, Grey infrastructure) and a specific temperature metric (T_{mean}, T_{max}, T_{min}, T_{Abs}, T_{Dmean}, T_{Nmean}). Coefficients of determination (R^2) were calculated to measure the strength of the relationships between the relative area covered by the different individual and combined surface categories. Multiple linear regression analysis was conducted for temperature derivatives and combinations of all the surface categories to determine any types of interaction between the surfaces and their influence on temperature. T_{mean}, T_{Dmean}, T_{Nmean} were calculated for each LCZ class and relative areas of surface categories were tabulated. One-way analyses of variance (ANOVA) were used to investigate whether these temperature derivatives were significantly different among the LCZs. Tukey's HSD test was performed to pairwise compare the LCZs to see whether a significant difference lies between them.

3.4 Results

3.4.1 Variation of air temperature in summer 2018/2019

The average air temperature (T_{mean}) across all the locations (n = 156) in the two LGAs during summer (from 21 December 2018 to 28 February 2019) was 24.3 °C ± 0.7 (± 1 Standard Deviation). Trongate Street in Granville recorded the absolute T_{max} (45.8 °C) on 29-Dec-2018 at 15:30 and Wetherill Park Nature Reserve recorded the absolute T_{min} (11.3 °C) on 24-Dec-2018 at 05:50. The absolute T_{max} at all locations exceeded 36.5 °C and 123 locations out of 156 had T_{max} ≥40 °C.

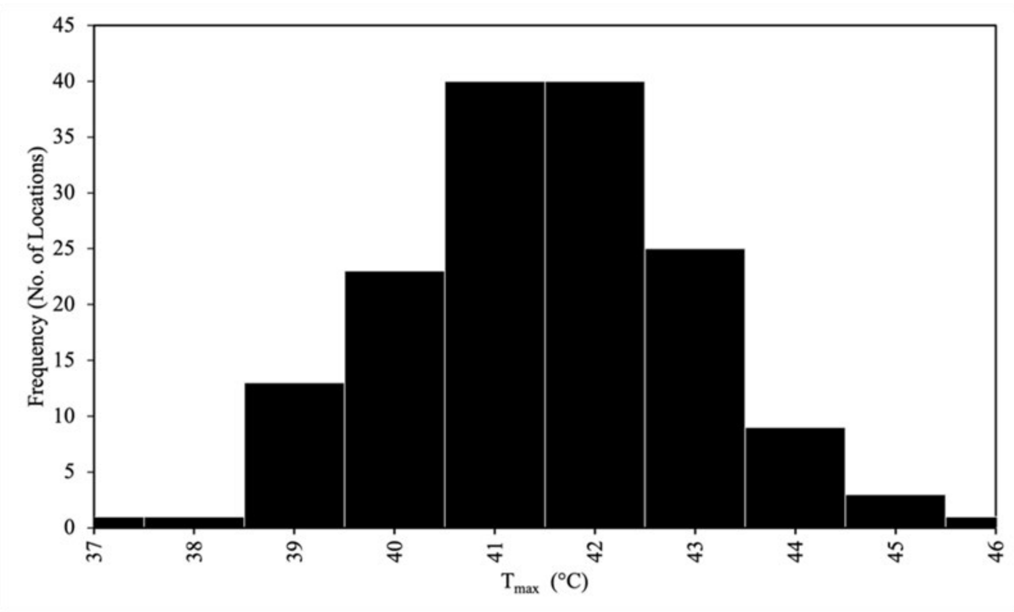


Figure 3.9: Frequency distribution of absolute maximum temperature (T_{max}) in 156 locations.

3.4.2 Relative cover of surface categories across LGAs

Within the assessed circular areas, Green space had the highest representation (45.0% ± 1.7) followed by Roads (32.2% ± 1.1) and Tree canopy (21.0% ± 1.1) among the surface categories in both LGAs (Fig. 3.10). The relative area of Buildings was 19.3% ± 1.1. Blue space accounted for the smallest representation (0.4% ± 0.1) and little bare soil (e.g., Brown space) was present (3.0% ± 0.4) among the surface categories

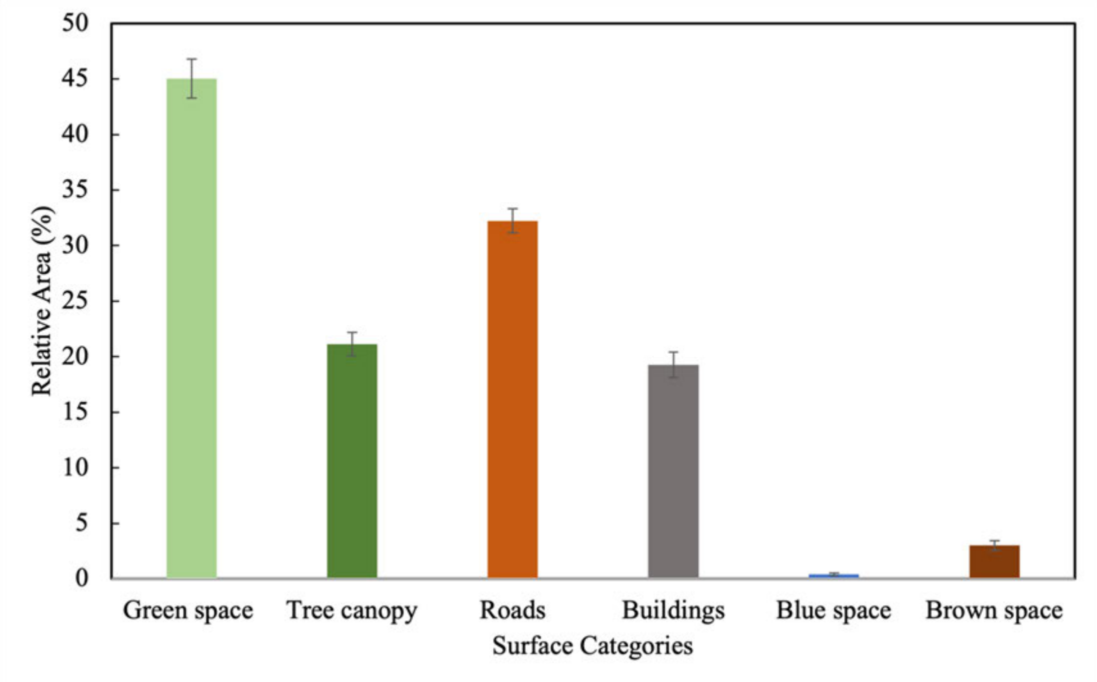


Figure 3.10: Mean relative areas of surface categories (Green space, Tree canopy, Roads, Buildings, Blue space, Brown space) based on temperature logger locations in Parramatta and Cumberland LGAs (n = 156). Error bars show one standard error.

3.4.3 Effect of surface category extent on air temperature

The linear regression analysis indicated that if the surface area covered by Tree canopy increased by 1%, then air temperature would decrease by approximately 0.03°C (T_{mean} = 24.9 - 0.0293*Tree canopy) (Fig. 3.11). Similarly, 1% increase in the Green space and Green infrastructure will increase cooling by approximately 0.01 °C (T_{mean} = 25.1 - 0.0018*Green space) and 0.02 °C (T_{mean} = -25.2 - 0.0137*Green infrastructure) respectively. Green infrastructure showed a highly significant negative relationship with T_{mean} (R^2 = 0.44, p <0.0001). The analysis showed that cooling T_{mean} by 1°C could be achieved if the surface area covered by Green infrastructure was increased from 0 to 60%. Similarly, both Tree canopy and Green space also exhibited highly significant negative relationships with T_{mean} (R^2 = 0.35, p <0.0001 and R^2 = 0.36, p <0.0001 respectively). A 1 °C cooling of T_{mean} was predicted when the surface area covered by Tree canopy would be increased from 0 to 40% and Green space from 0 to 50%.

Roads ($R^2 = 0.25$, $p < 0.0001$), Buildings ($R^2 = 0.21$, $p < 0.0001$) and Grey infrastructure ($R^2 = 0.35$, $p < 0.0001$) had highly significant positive relationships with T_{mean}. Regression analyses showed that if the surface area covered by Roads, Buildings or Grey infrastructure would increase by 1%, then the average air temperature would increase by approximately 0.02 °C ($T_{mean} = 23.6 + 0.0227$*Roads, $T_{mean} = 23.9 + 0.0205$*Buildings and $T_{mean} = 23.4 + 0.0173$*Grey infrastructure respectively). A 1 °C warming of T_{mean} would potentially be achieved by increasing the surface area covered by Grey infrastructure from 0 to 65% whereas the same degree of warming could be expected by increasing the surface area covered by Roads and Buildings from 0 to 45%.

The multiple regression model with all surface categories produced $R^2 = 0.46$ and $p < 0.001$ (Table 3.3). Tree Canopy had significant negative relationship with mean air temperature ($p < 0.001$) indicating that increasing the Tree canopy can reduce T_{mean}, after controlling for the other variables in the model. However, other surface categories did not contribute to either warming or cooling effects in the multiple regression model.

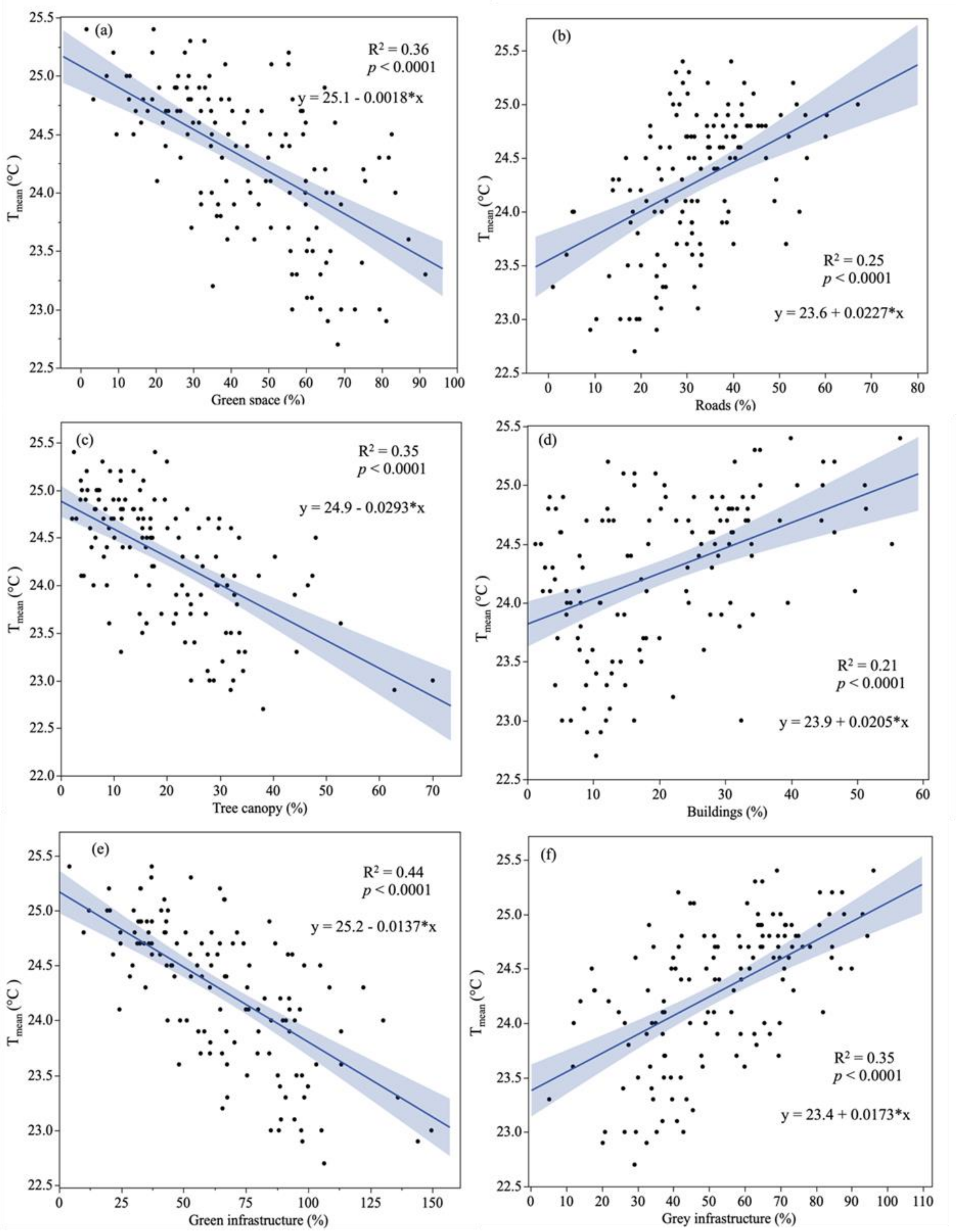


Figure 3.11: Scatterplot with fitted-line linear regression between mean summer temperature (T_{mean}) and surface category (a-f) of all locations (n = 156). Coefficients of determination (R^2) and corresponding p-values and regression equations are given for each relationship. Areas shaded in blue display 95% confidence intervals.

Table 3.3:Standard error and probability (p) values of the multiple regression model of mean air temperature (T_{mean}) and surface categories. Standard error of 0 indicates that the statistic is error-free. The absence of a p value indicates that the data is insufficient to estimate the model.

Surface category	**Standard Error**	**p value**
Green Space	0.0084	0.06
Roads	0.0088	1.00
Buildings	0.0088	0.14
Tree Canopy	0.0048	<0.001
Green Infrastructure	0	-
Grey Infrastructure	0	-
Green Infrastructure*Buildings	0.0004	0.43
Green Infrastructure*Roads	0.0006	0.66
Grey Infrastructure*Green Space	0.0005	0.80
Grey Infrastructure*Tree Canopy	0	-
Tree Canopy*Roads	0.0007	0.67
Tree Canopy*Building	0	-
Green Space*Roads	0	-
Green Space*Buildings	0	-

The effect of different surface types on T_{min} was very limited (Fig. 3.12). Grey infrastructure, Green space and Tree canopy only explained 28%, 24%, 4% of variation in T_{min} respectively. Green space and Green infrastructure exhibited significant negative relationships ($p < 0.001$) with T_{min} while Tree canopy did not show a significant relationship ($p > 0.05$) with this air temperature derivative. Roads, Buildings and Grey infrastructure each show a significant positive relationship ($p < 0.001$) with T_{min}.

Increasing the surface area covered by Green space from 0 to 50% could potentially lower T_{min} by 1 °C. A similar degree of cooling could be achieved by increasing the surface area covered by Green infrastructure from 0 to 90%. A 1 °C warming of T_{min} could result from increasing the surface area covered by Roads from 0 to 40%.

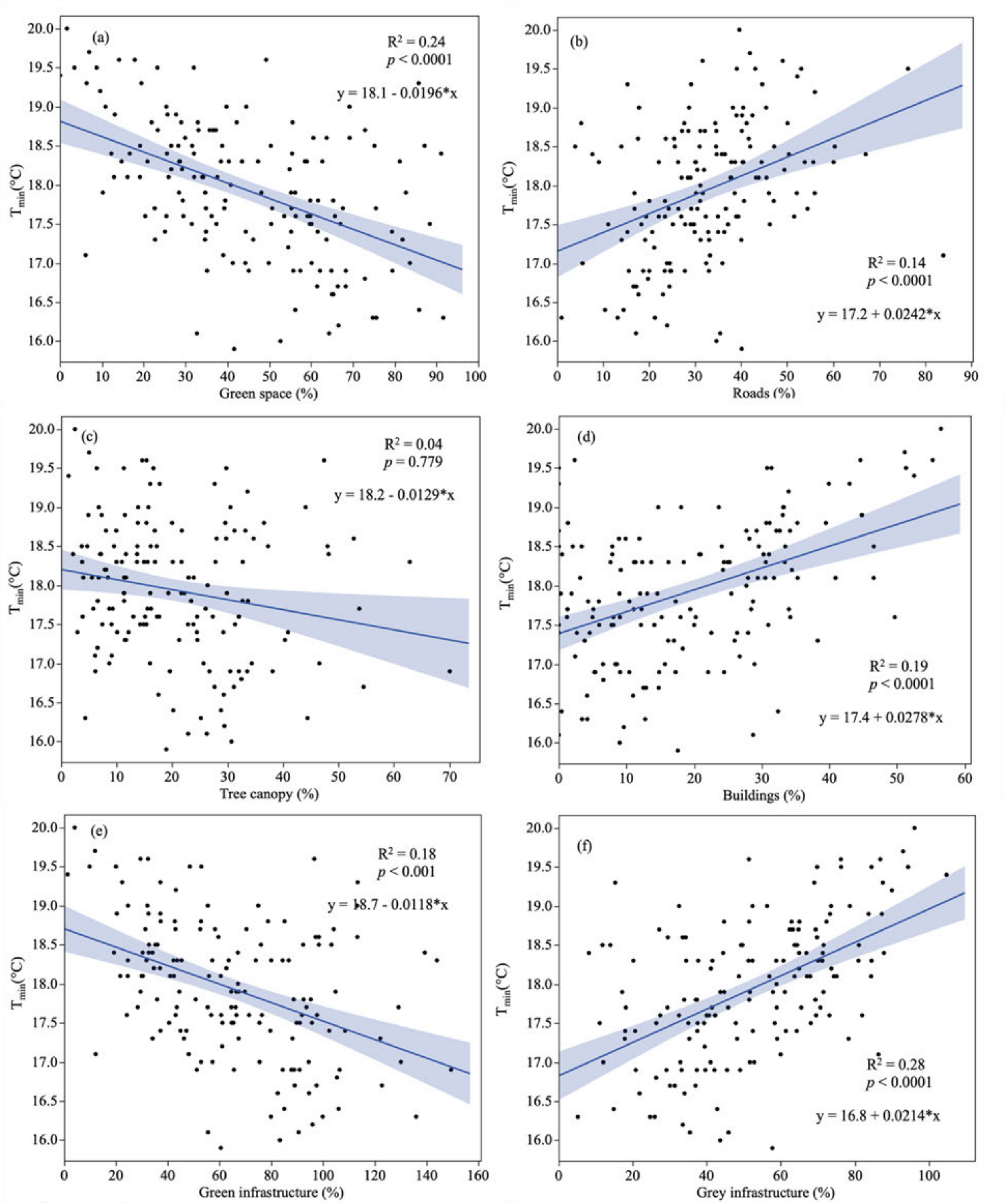


Figure 3.12: Scatterplot with fitted-line linear regression between mean minimum summer temperature (T_{min}) and surface category (a-f) of all locations (n = 156). Coefficients of determination (R^2) and corresponding p-values and regression equations are given for each relationship. Areas shaded in blue display 95% confidence intervals.

The multiple regression model with all surface categories produced $R^2 = 0.34$ and $p < 0.001$ (Table 3.4). Tree Canopy had a significant negative relationship with minimum air temperature ($p < 0.001$) indicating that by increasing the Tree canopy, T_{min} can be reduced after controlling for the other variables in the model. However, other surface categories did not contribute to either warming or cooling effects in the multiple regression model.

Table 3.4: Standard Error and probability values of the multiple regression model of Mean minimum temperature (T_{min}) and surface categories. Standard error of 0 indicates that the statistic is error-free. The absence of a p value indicates that the data is insufficient to estimate the model.

Surface category	**Standard Error**	**p value**
Green Space	0.0114	0.6571
Roads	0.0119	0.1383
Buildings	0.0120	0.1666
Tree Canopy	0.0065	0.0034
Green Infrastructure	0	-
Grey Infrastructure	0	-
Green Infrastructure*Buildings	0.0005	0.3003
Green Infrastructure*Roads	0.0008	0.1194
Grey Infrastructure*Green Space	0.0007	0.0506
Grey Infrastructure*Tree Canopy	0	-
Tree Canopy*Roads	0.0010	0.4624
Tree Canopy*Building	0	-
Green Space*Roads	0	-
Green Space*Buildings	0	-

Similarly, the influence of surface categories on T_{max} was very weak (the highest R^2 was 0.13 for Green infrastructure) (Fig. 3.13). Tree canopy, Green space, Green infrastructure and Roads explained 10–13% of the variation of T_{max}, and all the other surface categories explained <10% of the variation of T_{max}. Nevertheless, Green space, Tree canopy and Green infrastructure showed significant negative ($p < 0.001$) relationships with T_{max} while Roads, Buildings and Grey infrastructure displayed significant positive ($p < 0.05$) trajectories with T_{max}. Increasing surface area covered by Tree canopy from 0 to 30% would result in 1 °C cooling of T_{max} and a similar degree of cooling could be achieved by increasing the surface area covered by Green space from 0 to 60% and Green infrastructure from 0 to 70%. A 1 °C warming could potentially be achieved by increasing the surface area covered by Roads from 0 to 30%, Buildings from 0 to 35% and Grey infrastructure from 0 to 55%.

The multiple regression model with all surface categories produced $R^2 = 0.16$ and $p < 0.05$ (Table 3.5). Tree Canopy had significant negative relationship with maximum air temperature ($p < 0.05$) indicating that increasing the Tree Canopy can reduce T_{max} after controlling for the other variables in the model. However, other surface categories did not contribute to either warming or cooling effects in the multiple regression model.

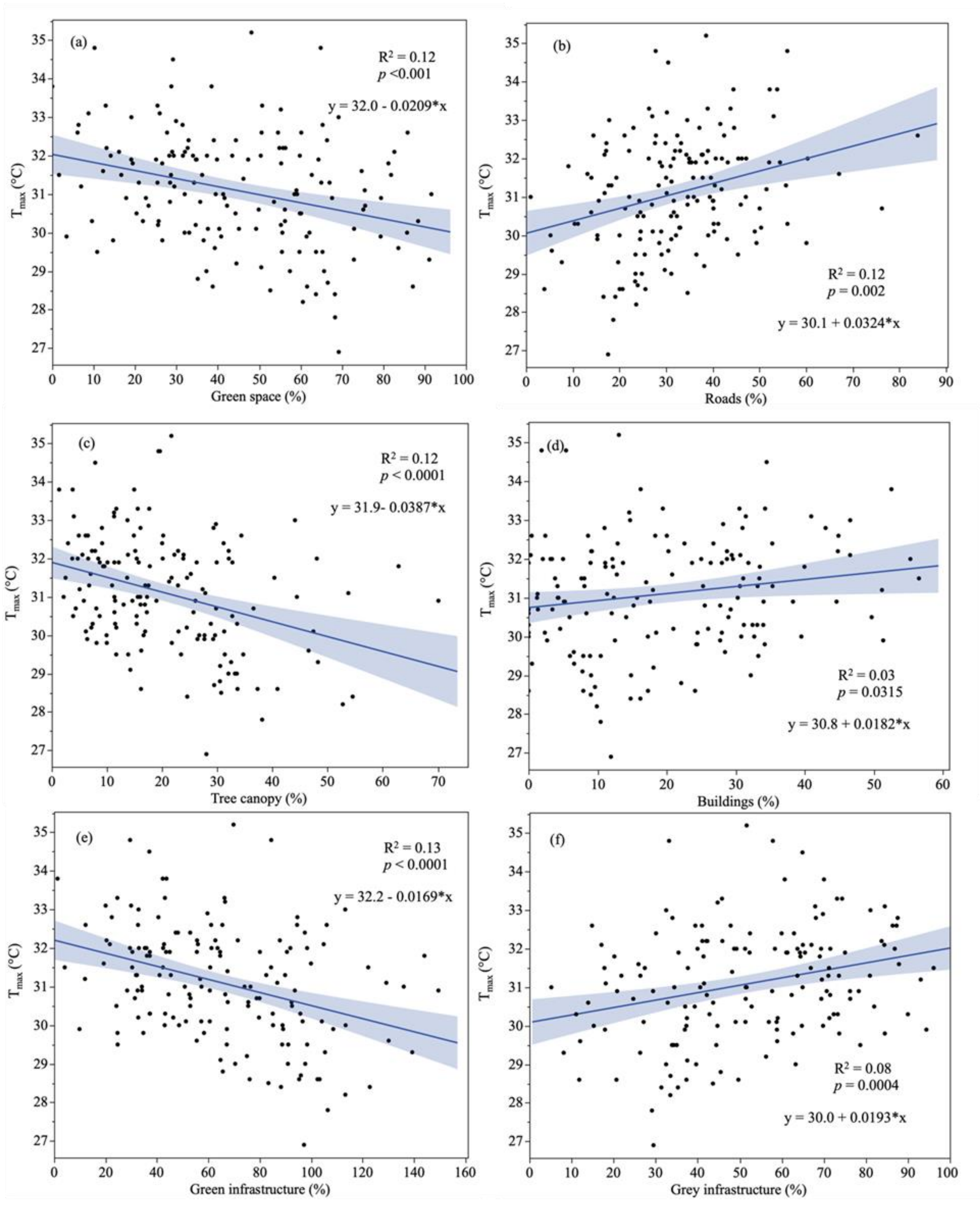


Figure 3.13: Scatterplot with fitted-line linear regression between mean temperature (T_{max}) and surface category (a-f) of all locations (n= 156). Coefficients of determination (R^2) and corresponding p-values and regression equations are given for each relationship. Areas shaded in blue display 95% confidence intervals.

Table 3.5: Standard Error and probability values of the multiple regression model of Mean maximum temperature (T_{max}) and surface categories. Standard error of 0 indicates that the statistic is error-free. The absence of a p value indicates that the data is insufficient to estimate the model.

Surface category	Standard Error	p value
Green Space	0.0231	0.71
Roads	0.0242	0.25
Buildings	0.0243	0.95
Tree Canopy	0.0131	0.01
Green Infrastructure	0	-
Grey Infrastructure	0	-
Green Infrastructure*Buildings	0.0010	0.26
Green Infrastructure*Roads	0.0017	0.81
Grey Infrastructure*Green Space	0.0014	0.46
Grey Infrastructure*Tree Canopy	0	0.00
Tree Canopy*Roads	0.0021	0.89
Tree Canopy*Building	0	-
Green Space*Roads	0	-
Green Space*Buildings	0	-

Figure 3.14 shows the linear relationships between the surface categories and the absolute highest recorded air temperature (T_{Abs}). Green space, Tree canopy and Green infrastructure displayed highly significant negative ($p < 0.0001$) relationships with T_{Abs} while Roads, Buildings and Grey infrastructure showed highly significant positive ($p < 0.0001$) trajectories. However, of all the surface categories, Green infrastructure explained most of the variation in measurements of peak heat (17%). All other independent variables helped to explain less than 15% of variation in T_{Abs}. The relationships showed that potentially an increase of Tree canopy from 0 to 60% could result in 1 °C cooling of T_{Abs}. The same degree of cooling could potentially be achieved by increasing Green space from 0 to 50% and Green infrastructure from 0 to 80% in each case. On the other hand, when the surface area covered by Grey space and Roads would be increased from 0 to 60%, and that covered by Buildings from 0 to 40%, T_{Abs} could potentially be warmed by 1°C.

The multiple regression model with all surface categories produced $R^2 = 0.15$ and $p < 0.05$ (Table 3.6). Tree Canopy had significant negative relationship with the absolute maximum air temperature ($p < 0.05$) indicating that increasing the Tree Canopy can reduce T_{Abs} after controlling for the other variables in the model. However, other surface categories did not contribute to either warming or cooling effects in the multiple regression model.

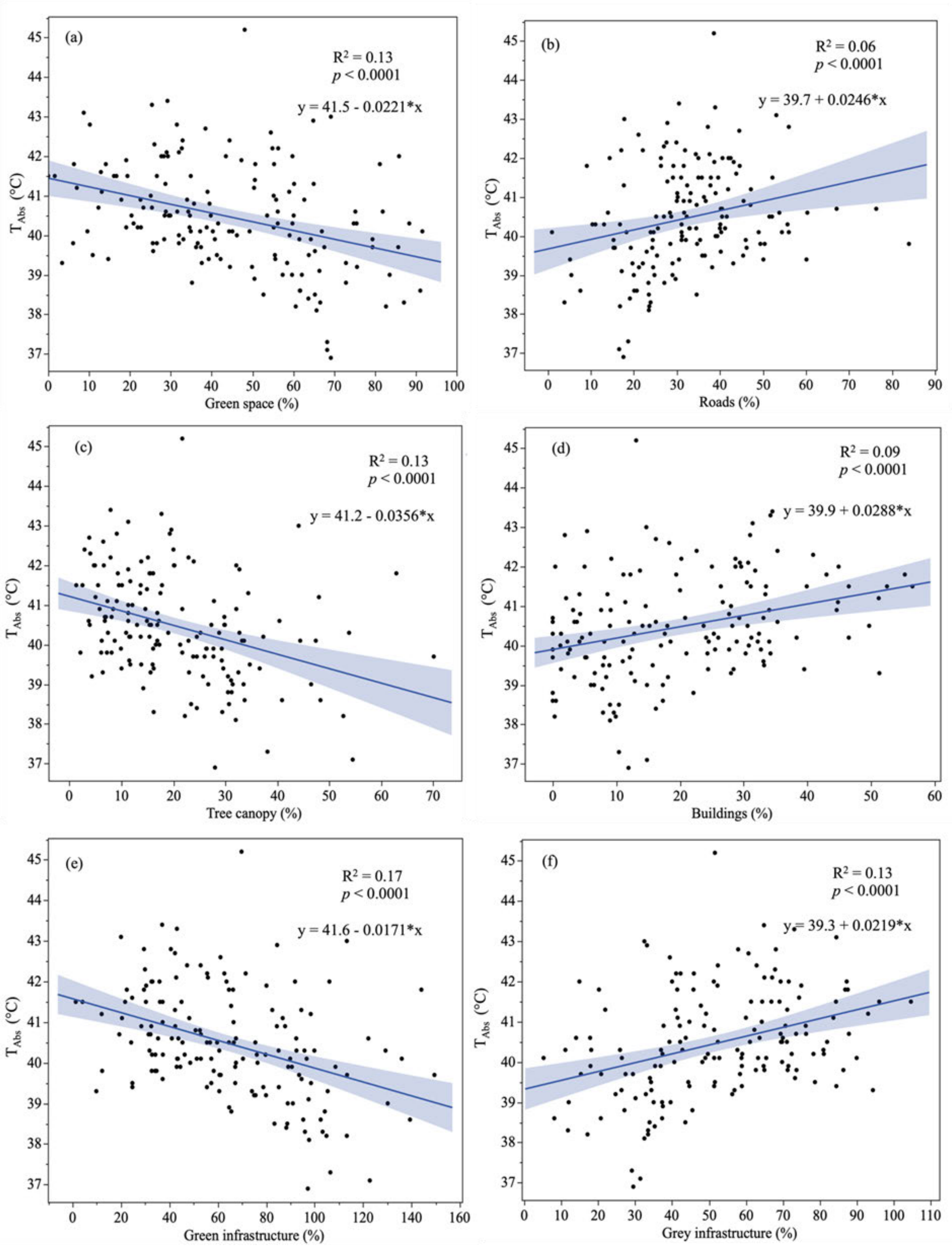


Figure 3.14: Scatterplot with fitted-line linear regression between the absolute maximum temperature (T_{Abs}) recorded on 31st January 2019 at each location within the Parramatta and Cumberland LGAs and different surface categories (a–f) (n = 156). Coefficient of determination (R^2) and corresponding p-values and regression equations are given for each relationship. Areas shaded in blue display 95% confidence intervals.

Table 3.6: Standard Error and probability values of the multiple regression model of Absolute maximum temperature (T_{Abes}) and surface categories. Standard error of 0 indicates that the statistic is error-free. The absence of a p value indicates that the data is insufficient to estimate the model.

Surface category	**Standard Error**	**p value**
Green Space	0.0679	0.82
Roads	0.0465	0.67
Buildings	0.0243	0.95
Tree Canopy	0.0258	0.01
Green Infrastructure	0	-
Grey Infrastructure	0	-
Green Infrastructure*Buildings	0.0091	0.34
Green Infrastructure*Roads	0.0045	0.99
Grey Infrastructure*Buildings	0.0038	0.57
Grey Infrastructure*Tree Canopy	0	0.00
Tree Canopy*Roads	0.0031	0.87
Tree Canopy*Building	0	-
Green Space*Roads	0	-
Green Space*Buildings	0.0000	0

3.4.4 Effect of surface category extent on daytime and night-time air temperatures

Figure 3.15 shows the relationships of the average air temperature at night (T_{Nmean}) and during the daytime (T_{Dmean}) with the relative extent in cover of several different urban surface categories. Both the Green space (R^2 = 0.07, p <0.001) and Green infrastructure (R^2 = 0.07, p <0.001) showed significant negative trajectories with the T_{Nmean}. However, the cooling effect of Tree canopy was limited at night and did not show a significant relationship (p >0.05) with the T_{Nmean}. Plotting T_{Nmean} data against the site-specific cover of Roads (R^2 = 0.05, p <0.05), Buildings (R^2 = 0.04, p <0.05) and Grey infrastructure (R^2 = 0.08, p <0.001) resulted in significant positive relationships that indicated warming effects. Increasing the area covered by Green space from 0 to 100% corresponded to 0.7 °C cooling at night. A 0.5 °C cooling was indicated by increasing the surface area covered by Green infrastructure from 0 to 100%. Increasing the area covered by both Roads and Grey infrastructure from 0 to 100% would have produced a warming effect of 0.7 °C at night. For the category of Buildings, this degree of increasing surface cover would reach 0.8 °C warming.

Increasing Green space ($R^2 = 0.11$, $p < 0.0001$), Tree canopy ($R^2 = 0.11$, $p < 0.0001$), and Green infrastructure ($R^2 = 0.13$, $p < 0.0001$) would lead to general cooling of T_{Dmean}, while increasing the area covered by Roads ($R^2 = 0.08$, $p < 0.001$), Buildings ($R^2 = 0.05$, $p < 0.05$) and Grey infrastructure ($R^2 = 0.11$, $p < 0.0001$) would lead to warming of T_{Dmean}.

The multiple regression model with all surface categories and T_{Dmean} produced $R^2 = 0.17$ and $p < 0.05$ (Table 3.7). Tree Canopy had significant negative regression ($p < 0.05$) indicating that increasing Tree canopy can reduce T_{Dmean}, after controlling for the other variables in the model. , multiple linear regression model with T_{Nmean} and surface categories ($R^2 = 0.15$ and $p < 0.05$) indicated that Green Infrastructures*Roads had a significant positive ($p < 0.05$) relationship. However, other surface categories did not contribute to either warming or cooling effects in the multiple regression model.

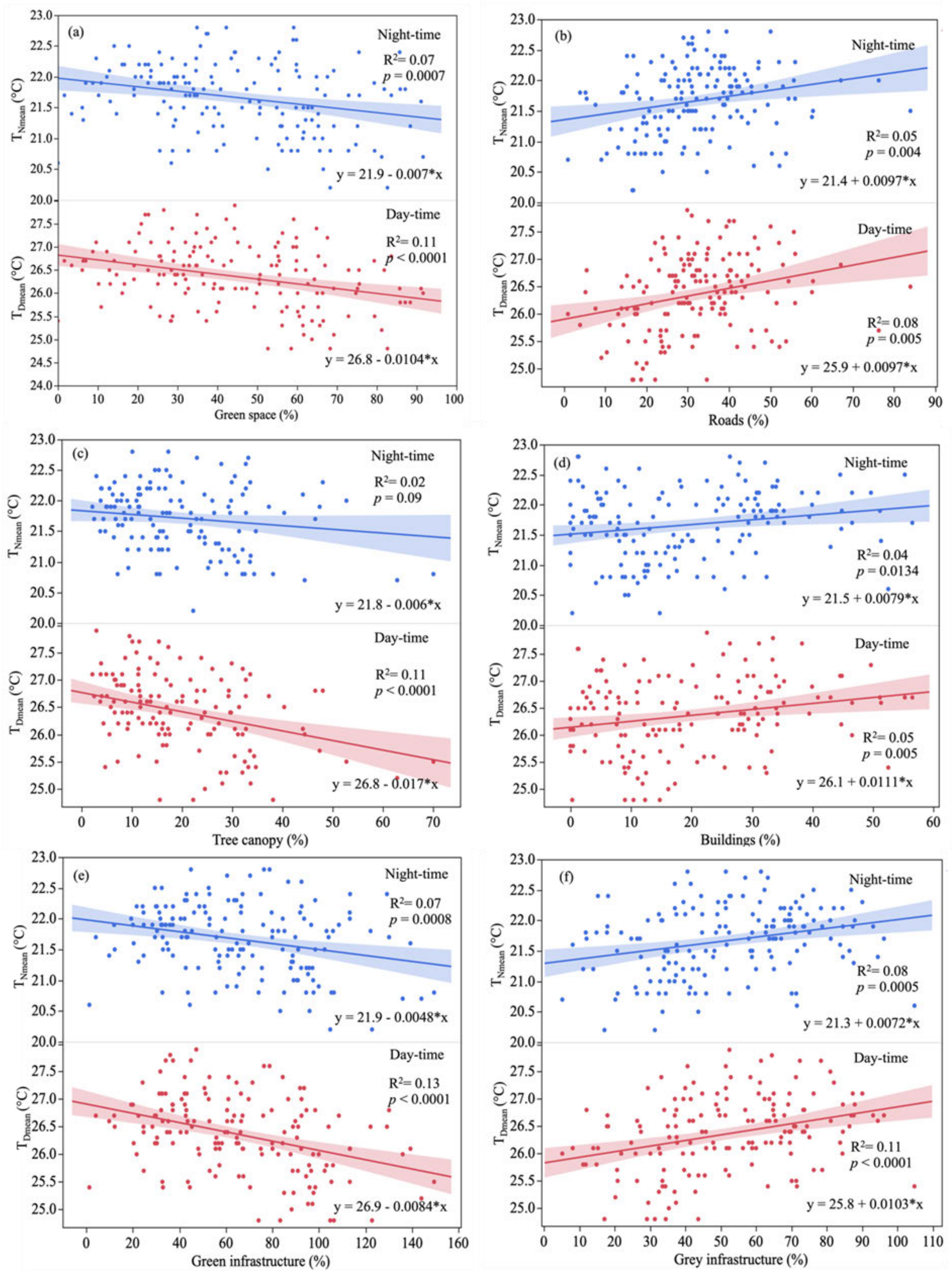


Figure 3.15: Scatterplot with fitted-line linear regression between mean daytime temperature (T_{Dmean}) and surface category and mean night-time temperature (T_{Nmean}) and surface categories (a-f) of all locations (n = 156). Coefficient of determination (R^2), corresponding p-values and regression equations are given for each relationship. Areas shaded either blue or red display 95% confidence intervals.

Table 3.7: Standard Error and probability values of the multiple regression model of Day-time mean temperature (T_{Dmean}) and Night-time mean temperature (T_{Nmean}) and surface categories. Standard error of 0 indicates that the statistic is error-free. The absence of a p value indicates that the data is insufficient to estimate the model.

	T_{Dmean}		T_{Nmean}	
Surface category	**Standard Error**	**p value**	**Standard Error**	**p value**
Green Space	0.0110	0.45	0.0089	0.82
Roads	0.0115	1.00	0.0093	0.54
Buildings	0.0116	0.38	0.0094	0.77
Tree Canopy	0.0062	0.02	0.0050	0.06
Green Infrastructure	0	-	0	-
Grey Infrastructure	0	-	0	-
Green Infrastructure*Buildings	0.0005	0.25	0.000	0.92
Green Infrastructure*Roads	0.0008	0.80	0.001	0.04
Grey Infrastructure*Green Space	0.0007	0.44	0.001	0.83
Grey Infrastructure*Tree Canopy	0	0	0	0.00
Tree Canopy*Roads	0.0010	0.74	0.001	0.79
Tree Canopy*Building	0	-	0	-
Green Space*Roads	0	-	0	-
Green Space*Buildings	0	-	0	-

3.4.5 Air temperature variation among LCZs

The majority of the measurement locations in this study belonged to the LCZ 6 (Open low rise) (n = 51), followed by LCZ 3 (Compact low rise) (n = 26). Only 6 locations were classified as LCZ 8 (Large low-rise) (Table 3.3). The LCZ B (Scattered trees) showed the lowest T_{mean} (23.4 °C ± 0.4) while LCZ 2 (Compact midrise) showed the highest T_{mean} (24.8 °C ± 0.6) (Table 3.3). The highest T_{Dmean} was recorded in LCZ 2 (Compact midrise) (26.8 °C ± 0.8) followed by LCZ 6 (Open low rise) (26.7 °C ± 0.6) whereas LCZ B (Scattered trees) exhibited the lowest (25.8 °C ± 0.6). The LCZ 2 (Compact midrise) showed the highest T_{Nmean} (21.9 °C ± 0.4) and the lowest was recorded in LCZ D (Low plants) (21.2 °C ± 0.4). The Tukey HSD test revealed that T_{mean}, T_{Dmean} and T_{Nmean} were significantly different among the LCZs classes. The T_{mean} and T_{Dmean} of LCZ B (Scattered trees) was significantly different from other

LCZ classes. The differences in air temperature between the LCZs were more likely to be significant during the day compared to the night.

Table 3.8: Mean (T_{mean}), mean daytime (T_{Dmean}) and mean night-time (T_{Nmean}) air temperatures during summer in each Local Climate Zone (LCZ). Levels not connected by same letter are significantly different. (LCZ 2 – Compact midrise, LCZ 3 – Compact low rise, LCZ 5 – Open midrise, LCZ 6 – Open low rise, LCZ 8 – Large low rise, LCZ 9 – Sparsely built, LCZ B – Scattered trees, LCZ D – Low plants).

LCZ	n	T_{mean} ± SD (°C)	T_{Dmean} ± SD (°C)	T_{Nmean} ± SD (°C)
LCZ 2	16	24.8 ± 0.6 (A)	26.8 ± 0.8 (A, B, C)	21.9 ± 0.4 (A, B)
LCZ 3	26	24.7 ± 0.5 (A)	26.5 ± 0.6 (A)	21.6 ± 0.6 (A)
LCZ 5	15	24.2 ± 0.6 (B, C)	26.4 ± 0.6 (A, B)	21.7 ± 0.3 (A)
LCZ 6	51	24.1 ± 0.7 (C)	26.7 ± 0.6 (B)	21.7 ± 0.5 (A)
LCZ 8	6	24.6 ± 0.9 (B. C)	26.3 ± 0.5 (A, B, C)	21.6 ± 0.6 (A, B)
LCZ 9	11	24.1 ± 0.4 (C)	26.3 ± 0.5 (C)	21.5 ± 0.5 (B)
LCZ B	21	23.4 ± 0.4 (D)	25.8 ± 0.6 (D)	21.7 ± 0.7 (A)
LCZ D	10	24.6 ± 0.6 (A)	26.6 ± 0.6 (B)	21.2 ± 0.4 (A)

3.5 Discussion

This study analysed the effects of common urban surface categories (Green space, Tree canopy, Roads, Buildings) on air temperature variations at micro-scale (50-m radius) in western Sydney. Among the temperature metrics examined, Tree canopy had a significant cooling effect on mean summer temperature (T_{mean}) and mean summer daytime temperature (T_{Dmean}). Results showed that 1 °C cooling of T_{mean} and T_{Dmean} can be attained if Tree canopy cover increases by 40% and 50%, respectively. Moreover, the analyses also revealed that trees can effectively counterbalance the warming caused by Roads, Buildings and Grey infrastructure during the daytime. The analyses of LCZs indicated that compact LCZ classes generally had warmer microclimates compared to classes that contained greater amounts of open space and pervious surface cover.

3.5.1 Effect of surface category on air temperature

Results of this study indicated that Tree canopy had the greatest effect on reducing T_{mean} compared to the other surface 'green' categories (Green space and Green infrastructure). The indication that an increase of Tree canopy by 40% could potentially lead to 1 °C cooling of T_{mean} is primarily because of combined effects of transpiration (Alavipanah et al., 2015; Meili et al., 2021) and shade (Wang et al., 2016b; Upreti et al., 2017). Moreover, tree canopies obstruct mixing (Nowak, 2002). Results also demonstrated that a 10% increase of surface area covered by Roads, Buildings and Grey infrastructure could increase T_{mean} by 0.2 °C whereas a 10% increase in Tree canopy cover would reduce T_{mean} by 0.3 °C. Thus, there is clear evidence that Tree canopy may effectively counterbalance the warming caused by Roads, Buildings and Grey infrastructure at microscale (50 m radius).

However, a weaker relationship was observed between T_{max} and T_{Abs} with the relative area of Tree canopy. This result could imply that the cooling capacity of trees during heatwaves is diminished or even absent. However, recent evidence suggests that transpiration in trees may be sustained during heatwaves (Drake et al., 2018). Nonetheless, transpiration rates vary among tree species under extremely high air temperatures (Konarska et al., 2016b; Ewers et al., 2005). Species with low heat tolerance generally exhibit reduced stomatal conductance and induce stomatal closure which results in low transpiration rates and thus lower air-cooling capacity (Zhao et al., 2013; Hatfield & Prueger, 2015). It was also found that areas dominated by trees with low heat tolerance can have slightly lower surface cooling rates (negative ratio of land surface temperature (LST) changes to fractional tree cover (FTC) changes) compared to areas dominated by heat-adapted plants during extreme heatwaves (Wang et al., 2019). However, one study of eucalypt trees in western Sydney indicated that trees can tolerate extreme heat via sustained transpirational cooling and increased leaf thermal tolerance (Drake et al., 2018). Meanwhile, T_{min} also showed a very weak and insignificant relationship with the relative area covered by Tree canopy. This is because transpirational cooling substantially diminishes at night as air temperatures decline and relative humidity of near surface air increases leading to very low rates of vaporisation of water (Wang et al., 2019; David et al., 2004).

Surprisingly, the area needed to be covered by Grey infrastructure was greater than Roads and Buildings to achieve 1 °C warming of T_{mean}, T_{max}, T_{min} and T_{Abs}. A similar observation was made between the temperature derivatives and Green infrastructure for cooling. This can be due to inherent limitations of the study that cannot be avoided. For example, surface categories do not act entirely independently in the environment. These surfaces interact with each other (e.g., Tree shade on buildings and roads). Furthermore, there is an autocorrelation between the individual ground surface categories (e.g., when the relative area of one goes up the other goes down). However, the results are based on more than 1.5 million individual temperature measurements taken in 156 locations in a complex urban environment, providing a robust empirical basis for the examined relationships. So, there is a strong indication that Green infrastructure cool the air while Grey infrastructure contribute to warming the air.

3.5.2 Effect of surface category on daytime and night-time air temperatures

Linear regression analyses revealed that urban trees were most effective in mitigating day-time air temperatures at micro-scale (50 m radius). The effect of surface cooling seems to increase in parallel with tree canopy area, as larger canopies will cool the air by reducing heat transfer from the ground over a larger ground area (Brandani et al., 2016). Similar observations were made in other studies where trees were found to be the most effective structures to mitigate urban heat during the day. For example, 50% tree cover in high density built-up areas would decrease daytime air temperature by 1 °C in Cairo (Aboelata & Sodoudi, 2019). In Hong Kong, increasing tree canopy cover from 0 to 33% in urban areas would also produce 1 °C cooler day time air temperatures (Ng et al., 2012). Increasing tree canopy from 0% to 100% within a 60–90 m radius corresponded to a mean decrease of 1.5 °C in daytime air temperature (Ziter et al., 2019). It seems clear that urban trees have great potential to cool daytime air temperature (Hiemstra et al., 2017; Adams & Smith, 2014; Lobaccaro & Acero, 2015), which is increasingly important in cities worldwide as urban climates continues to warm.

However, while tree canopy cover can reduce daytime air temperatures in cities, trees with dense crowns can also lead to higher air temperatures at night. While trees do not have large transpiration rates at night and thus do not provide much transpirative cooling during this time (Konarska et al.2016), they can also trap near-surface heat underneath their crowns, slowing warm air dissipation into the atmosphere (Zölch et al., 2019; Wujeska-Klause & Pfautsch, 2020). Similar observations were made in Madison (Ziter at al., 2019), Munich (Zölch et al., 2019) and Cairo (Aboelata & Sodoudi, 2019), documenting slightly warmer air temperature under tree canopies compared to air temperatures in adjacent open spaces at night. More broadly, it has been documented that tree can trap radiant heat emitted by pavements and buildings (Mallick et al., 2009), leading to reduced air infiltration and advection (Bartesaghi-Koc et al., 2020), and trap heat by reducing the sky view factor (SVF) (Bourbia & Boucheriba, 2010).

The arrangement of tree canopy can also influence the microclimatic variability. While tree clusters can mitigate high temperatures to a greater extent than individual trees because the former will reduce solar radiation loads over a much larger surface area and collectively provide greater evaporative cooling during the day (Konarska et al., 2016), the same cluster of trees would be likely to trap warmed air for longer during the night. This situation can be prolonged when air is trapped underneath the cluster of trees during warm days with low windspeeds, leaving warmed air trapped throughout the night where the air in urban space is generally more stable (Oke, 1987). Warm air masses being trapped under clusters of trees was observed during warm nights in Dallas and Phoenix (Wang et al., 2019). Observations in the present study and in the published literature indicate that having plenty of open spaces in cities is very important for night-time cooling. It was shown here that increasing the Green space from 0% to 85% could lead to 1 °C cooling at night. It thus seems possible to increase night-time cooling if open urban space covered by non-tree vegetation is extended (Lobaccaro & Acero, 2015). Besides, results presented here also indicated that air temperatures at night were predominantly influenced by Grey infrastructure. Therefore, reducing Grey infrastructure and replacing it with Green infrastructure is equally important.

Thus, the most effective means to enable fast heat exchange and cooling air temperatures both during daytime and night-time is to expand the area of trees and green spaces in our cities strategically. Review and revision of existing urban planning policies like LEPs and DCPs may be needed to expand green space strategically. In addition, local stakeholders, such as town planners, policy makers, scientists, and residents, should be included in the planning process to create multipurpose urban green spaces that cater to the needs of each. Previous studies suggested that open vegetated spaces in cities cool more effectively if they contain scattered trees and receive irrigation (Spronken-Smith & Oke, 1999). However, since space and water in cities is limited, providing many smaller, and evenly distributed green open spaces could deliver greater cooling benefits to a larger number of neighbourhoods (Coutts et al., 2013; Norton et al., 2015). Furthermore, columnar trees with narrow crowns (e.g., *Cupressus sempervirens*) would be a better option rather than planting trees with spreading canopies. The columnar trees can provide a high level of surface cooling (Speak et al., 2020) due to high foliage density and at the same time since the crown width is small, permitting fast mixing of air. Another approach could be to strategically mix open canopy trees (e.g., *Eucalyptus spp.)* with trees that develop a dense and spreading canopy (e.g., *Ficus spp.*).

Urban parks are regularly identified as “cool islands” within cites (Shahidan et al., 2012, Shahidan, 2015). The present study showed that 40% of the area covered with trees within 50 m radius area resulted in a 1 °C decrease in temperature (T_{mean}). This finding can be used to design urban parks within the LGAs to promote cooling in Parramatta and Cumberland. The urban parks should have at least 40% tree cover and the least number of paved areas. Similarly, designing parks and open spaces with at least 30% tree cover and less than 50% paved areas was recommended for Taipei City (Taiwan) (Chang & Li, 2014). Apart from public green spaces, it will be crucial for effective urban cooling to encourage private landowners to plant trees in their home gardens. Over 50% of Australia's urban forest canopy is located on private property (Shanahan et al., 2015; Lin et al., 2017). This recommendation is based on the observation that many small patches of (irrigated) vegetation can potentially provide greater cooling benefits than council-driven tree canopy cover strategies at suburb of LGA scale (Ossola et al., 2021). Figure 3.16 illustrates the urban heat mitigation methods proposed in this study.

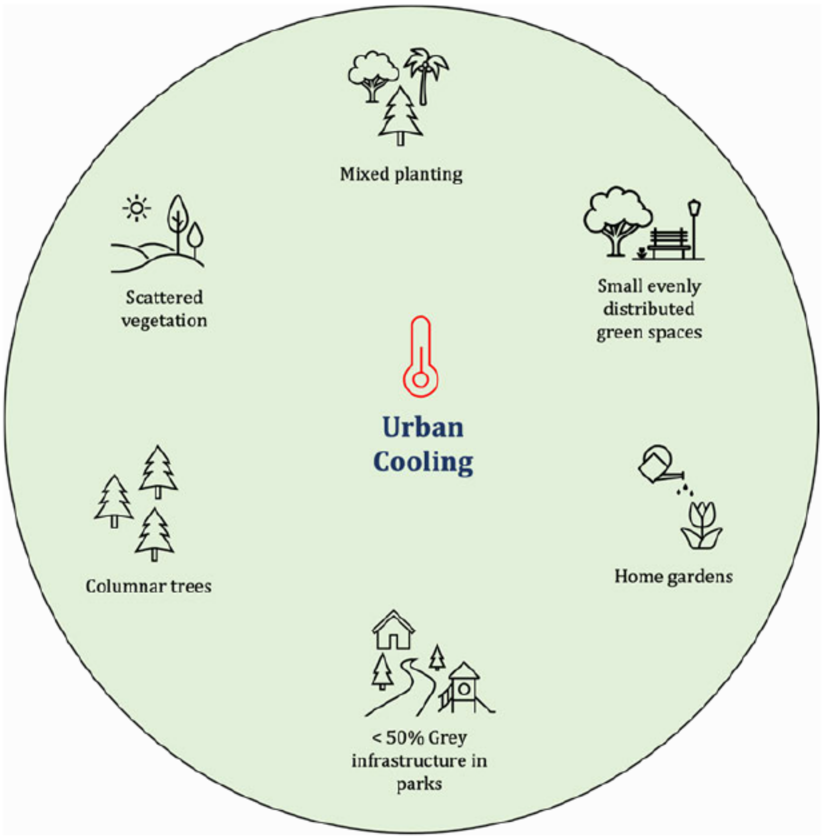


Figure 3.16: Proposed urban cooling strategies

3.5.3 Local Climate Zones and air temperature variations

Results indicated that T_{Nmean} of LCZ 2 (Compact midrise) was warmer (0.2–0.7 °C) than the T_{Nmean} of other LCZs. This coincided with a high proportion of grey space (dense mix of mid-rising buildings and paved concrete materials) and low representation of trees in this particular class of climate zone (Stewart & Oke, 2012). Moreover, building heights were generally higher in this LCZ class, resulting in a large amount of heat stored in the building bulk (Lau et al., 2019) during the day and its slow release at night. These results from western Sydney are similar to findings of Lelovics et al. (2014) in Szeged (Hungary) and Lehnert et al. (2015) in Olomouc (Czech Republic) where night-time temperatures recorded in LCZ 2 were comparatively higher than the other LCZs. The LCZ 2 also had higher T_{mean} and T_{max} compared to the other LCZs. In accordance with results presented here, higher summer mean and summer maximum temperatures were also observed in LCZ 2 in comparison to the other LCZs by Skarbit et al. (2017) in Szeged (Hungary). The LCZs analysed in the above-mentioned studies are at a larger compared to the present study (e.g., 250 m radius (Lelovics et al., 2014) & 200 m radius (Lehnert et al., 2015). This implies that concept of LCZs works well at both micro-scale (50-m radius) and meso-scale (250-m radius). The T_{mean} and T_{Dmean} of LCZ B (Scattered trees) was significantly different from other LCZ classes and recorded the lowest temperature on both occasions. This observation confirms the previous findings that trees are highly effective in cooling the air during the day (Hiemstra et al., 2017; Adams & Smith, 2014).

Compact climate zone classes (LCZ 2 & LCZ 3) showed higher temperatures (0.2–1.4 °C) (average, day & night) compared to open classes (LCZ 5, LCZ 6, LCZ 8, LCZ 9, LCZ B, LCZ D) in the study. Similar observations were made in several other studies done in Nanjing (China; Yang et al., 2018), Nagpur (India; Kotharkar & Bagade, 2018), Dublin (Ireland; Alexander & Mills, 2014), Kochi (India; Thomas et al., 2014), Nancy (France; Leconte et al., 2015) and Uppsala (Sweden; Oke, 2010) where open climate zone classes displayed lower air temperatures compared to compact classes. These warmer air temperatures in compact classes can be attributed to the limited SVF, higher cover of impervious and lower cover of pervious surfaces (Stewart & Oke, 2012).

Promoting climate zone classes which are conducive to lowering urban air temperatures and reducing the number of compact climate zone classes dominated by high building density will help combat urban heat and improve liveability for resident populations. The present analysis assists in advancing urban heat mitigation strategies at microscale for highly developed, existing urban space in western Sydney and elsewhere. It was demonstrated here that the concept of LCZs can be applied to this fast-urbanising region to identify priority areas for heat mitigation, focussing on sites where compact built forms dominate.

3.6 Conclusion

Rising urban heat as consequence of climate change and rapid urbanization requires effective cooling strategies to improve resilience of urban populations. The present study quantified the effect of surface cover on air temperature variation at microscale (50-m radius footprints) in Parramatta and Cumberland, two rapidly densifying LGAs in western Sydney, Australia. The large amount of data used to identify the observed trends pointed in a direction for cooling and warming, as supported by numerous studies. Results of this work highlight the importance of urban parks and other open vegetated areas to lower diurnal and nocturnal air temperature. At the same time, minimizing areas covered by grey infrastructure is a key to allow for even more urban cooling.

The method used in this study can be further improved by collecting other climate data such as relative humidity and windspeed as they may also influence the air temperature. Furthermore, factors like SVF can be incorporated in future research. This is because even if the relative areas of buildings or tree canopy are same at two locations, their spatial arrangement could be different (e.g., sparse arrangement vs concentrated at one location). In cities, there is a limited capacity of vegetation to cool urban space; therefore, measures such as rooftop gardening and vertical gardening should be encouraged. This study also reported elevated air temperatures in compact climate zone classes in comparison to open climate zone classes. Local authorities can use local climate zone classification methods and map the areas to identify locations with high heat exposure. By identifying such areas, site-specific mitigation strategies can be developed that address heat-related issues. Mitigation strategies could include a combination of green infrastructure types such as trees, grass, green roofs, green walls, and blue infrastructure like, fountains, creeks and other water bodies.

Chapter 4: Policy analysis of the Role of Trees in Heat Mitigation

4.1 Abstract

Urban heat has become one of the biggest concerns in Australian cities despite the efforts taken by local governments to increase tree canopy cover. Canopy cover in a city is primarily controlled by planning policies, tree ordinances and tree strategies. Although, a few studies have investigated the relationship between policies and strategies around trees and their contribution on urban heat mitigation in other parts of the world, no such work has been done in Australia. Responding to this, a thematic policy analysis was conducted on selected planning and environmental strategies related to urban trees from four councils (Parramatta City, Cumberland, City of Unley and City of Mitcham) in Australia. While the Cities of Unley and Mitcham were awarded the status of Tree City of the World in 2020, which requires implementation of a range of policy provisions in local governments to protect and promote urban trees, Parramatta City and Cumberland had not been awarded such a status.

Results indicated that all councils acknowledged trees as a highly effective countermeasure for urban heat. However, the thematic analysis showed that provisions in the statutory planning documents (Local Environmental Plans) of Parramatta and Cumberland councils did not reflect the goal of urban cooling and contained limited provisions linking urban trees with heat mitigation. On the contrary, Development Plans of Unley and Mitcham had effectively integrated urban trees as green infrastructure tool to alleviate urban heat. The non-statutory documents related to trees in all councils contained numerous approaches to achieve cooling with trees. The City of Unley had exceptionally well-designed strategies which brought private landowners and councils together to combat urban heat. However, most of these strategies and the latest scientific evidence around urban heat were not sufficiently incorporated into the statutory documents of councils investigated here. Based on these observations, several

recommendations were developed to improve the policies around trees that promote urban cooling.

4.2 Introduction

4.2.1 Heat mitigation in cities

Increasing population density and impervious surfaces coupled with reduced tree cover and green space in cities cause the Urban Heat Island Effect (UHIE) (Guo et al., 2020). The UHIE phenomenon makes urban areas warmer than the surrounding non-urban areas (Zhou et al., 2017). Recent studies have provided the evidence that UHIE prevails in more than 400 cities around the world (Santamouris, 2018; Manoli et al., 2019). The UHIE can lead to increased water consumption and energy use (Santamouris et al., 2015b), increased production of ground level ozone (Lo & Quattrochi, 2003), and alter the distribution and composition of flora and fauna (White et al., 2002; Niemelä, 1999). Furthermore, it can impose a greater health risk associated with excess heat which can ultimately lead to increased mortality and morbidity in cities (Arifwidodo & Chandrasiri, 2020; Venter, 2020).

Mitigation strategies are often used to counterbalance the impacts of urban heat. Three major clusters of mitigation applications have been identified in the literature. These are (1) increasing solar reflectance, (2) shading and (3) increasing evapotranspiration (Santamouris, 2014). Increasing solar reflectance is generally achieved through incorporating materials with high albedo (Akbari & Kolokotsa, 2016), for example, when used in roofs, pavements and building façades. Trees provide surface cooling through casting shade (Alavipanah et al., 2015; Kaluarachchi et al., 2020) and by absorbing some solar radiation to generate transpirative cooling of the air. Among all the UHIE mitigation approaches trees are found to be the most effective and economic way to improve the urban thermal environment (Rizwan, 2008; Qiu et al., 2017). Experimental research conducted in many cities in the world provide evidence for the cooling capacity of trees. For example, a study conducted in Hong Kong (China) compared five scenarios of urban tree cover (0%, 8%, 16%, 34% and 56%) and found out that every scenario above 0% had a significant cooling effect, while the 56% tree scenario had the greatest effect (Ng et al., 2012). A nonlinear decrease of air temperature with increasing canopy cover from 0 to 100% was observed and greatest cooling was attributed to canopy cover exceeding 40% in Wisconsin (United States) (Ziter et al., 2019). Similarly, Chapter 3 of the thesis revealed 1 °C air temperature cooling can be achieved by increasing the canopy cover from 0 to 40% in western Sydney. Further, tree shade was found to lower air temperature by up to 2 °C in the eastern suburbs of Sydney, Australia (Gao et al., 2020). Shade cast by street trees can reduce the surface temperature of streets and pavements by 10 °C (Armson et al., 2012; Lin et al., 2016) and other surfaces (grass, bark mulch and bare soil) by up to 20 °C (Kaluarachchi et al., 2020) compared to unshaded conditions.

4.2.2 Urban trees and policies

Urban development and planning policies are designed to influence the land use patterns in the built environment and thus have a strong influence on the presence of urban trees (Phelan et al., 2018). Factors like building geometry and urban density (Razzaghmanesh et al., 2016; Rajagopalan et al., 2014), tree canopy cover and green space (Wang & Akbari, 2016), sky view factor and canyon aspect ratio (Rizwan et al., 2008), open space and paved areas (Luo & Asproudi, 2015, Zhou et al., 2011), building material (Gago et al., 2013), usage of building or space (residential, commercial) and transportation system (Li et al., 2013) in a city are primarily controlled by these policies (Rajagopanan et al., 2014). In addition, other management instruments like local tree policies (Daniel et al., 2016), urban tree strategies and management plans (Gibbons & Ryan, 2015) are in place to govern the urban tree cover.

Cities across the world have developed various policies to retain or increase tree cover especially in their UHIE hotspots (Klemm et al., 2015). For example, The City of Toronto (Canada) has introduced several policies addressing the UHIE that incorporate trees (Wang et al., 2016b). Additionally, the Toronto Green Development Standard recommends that 30% of the surface of car parking areas and other grey surfaces be shaded by trees (City of Toronto, 2006). “Cool Neighbourhoods NYC” is a climate change resiliency programme which aims at alleviating the UHIE in New York City (New York, United States). This programme announced an $82 million (USD) commitment to fund street tree plantings in heat-vulnerable neighbourhoods (City of New York, 2021). The City of Boston (Massachusetts, United States) has pledged to increase its tree canopy cover from 27% to 35% by the year 2030 as a response to UHIE (City of Boston, 2021). Priority regions for tree planting in Boston are identified based on the Heat Vulnerability Index (HVI) which considers adaptive capacity, social vulnerability, and physical vulnerability (Werbin et al., 2020; Chuang & Gober, 2015). In 2020, the City of Phoenix (Arizona, United States) has set a 20-year goal to achieve a 25% tree canopy cover with drought-tolerant native trees which is expected to reduce air temperature by nearly 8 °C (City of Phoenix, 2021). Moreover, cities like Ontario (California) and Philadelphia (Pennsylvania) in the United States and London (United Kingdom) have already implemented strategies to plant more trees in streets, urban parks, and other municipal lands (Han et al., 2021).

In this context, where municipalities strive to expand their tree cover, it is important to briefly highlight ‘values’ of trees for cities. Trees are an integral part of the ecosystem and provide a number of services other than urban heat mitigation. These can have a direct or indirect benefits for human well-being (Haines-Young & Potschin, 2010). Urban trees also can trigger allergic responses (e.g., asthma) and may present hazards, so there is uncertainty regarding the extent of tree benefits and services. Roy et al. (2012) evaluated the benefits and costs of urban trees across different cities, geographies, and climates. They found that trees provide economic, social, health, aesthetic, and visual benefits, along with ecosystem services such as carbon sequestration and air quality improvement. Energy savings, improved biodiversity, aesthetics, and storm water mitigation are some additional values of urban trees, which collectively can be reflected in higher real estate value (Staats & Swain, 2020; Wang et al., 2018; Zhang & Dong, 2018), lower energy consumption (Wang et al., 2018; Aboelata & Sodoudi, 2020) and water bills (Shickman & Rogers, 2019), and even increased visitation by tourists (Terkenli et al., 2020). Among the disservices are maintenance costs, light attenuation, infrastructure damage, and health problems.

Benefits and values of urban trees are increasingly recognised by the local governments and incorporated into their key planning policies. Ecosystem services of trees are becoming increasingly important in policymaking, as decision makers must deal with explicit demands for ecosystem services from a broad range of stakeholders (Hein et al., 2006). The current landscape models are primarily based on land cover patterns or are strongly sector oriented (Vejre et al., 2007). Most policy support tools do not include ecosystem services (De Groot et al., 2010). Even though there is a growing body of literature on ecosystem services, it remains challenging to structurally integrate ecosystem services into landscape planning, management, and design (De Groot et al., 2010).

In Australia, protecting and increasing urban canopy cover is generally attempted through state government or local government (also known as councils) policies, strategies, and programmes. Victoria Planning Provisions (Victoria), State Environmental Protection Plans (New South Wales), State Planning Policy (Queensland) and the Northern Territory planning Schemes (Northern Territory) are some examples of state government planning policies that affect urban green infrastructure in Australia. Local governments in Australia have been producing urban tree strategies over the last 10 years. They predominately aim at improving the liveability and enabling better management of trees in cities (Phelan et al., 2018), including setting targets for canopy cover and tree management. For example, the urban tree strategy in the City of Melbourne (VIC), sets out to achieve a 40% tree canopy cover by 2050 (City of Melbourne, 2012). Similarly, Parramatta Council (NSW) plans to plant around 1,000 street trees every year along cycleways and the Parramatta Ways walking network through their City of Trees programme (City of Parramatta, 2017a). They aim to achieve 40% tree canopy cover by the year 2050. Further, Cumberland Council (NSW) has proposed to plant trees in town centres, schoolgrounds, along road verges, nature strips, rail corridors and open spaces to increase its canopy cover (Cumberland Council, 2020).

In Australia, local government tree strategies typically address tree canopy cover on both public and private lands through improved planning frameworks and decision-making processes (Kirkpatrick et al., 2013). This is important, because in Australian cities the majority of vegetation cover (trees, shrubs and grasses) is located on private properties (Daniel et al., 2016). However, local governments find it difficult to retain and promote trees on private lands (Cooper, 1996) due to the ambivalent relationship residents have with trees (Pincetl, 2013). Recent surveys observed a rapid decline of tree cover in cities in Australia with some showing losses concentrated on private land (Hurley et al., 2019; Phelan et al., 2018). Although local governments have some control over trees on private land through laws that prohibit tree removal without a permit (Sung, 2012; Landry & Pu, 2012), conflicts may sometimes arise with private property rights recognized by the common law (Watson, 2015). Therefore, some local governments have introduced financial incentives to encourage public participation and compliance in protecting trees on private land (Watson, 2015). For example, Victoria Park Council (Western Australia) has trialled an incentives programme to protect trees on private land. Under this programme private landowners will be funded to maintain registered significant trees (Victoria Park Council, 2021). Local governments have also arguably failed to address the reduced area available for tree planting on private land associated with small lot housing and apartment infill development (Pearce et al., 2015; Daniel et al., 2016), development forms that are becoming more widespread in Australian cities.

4.2.3 Research gaps and objectives

Local governments in Australia play an important role in urban heat mitigation through their planning policies and tree strategies. However, UHIE is still a prominent issue in many cities in Australia (Santamouris et al., 2017a; Santamouris et al., 2020; Sidiqui et al., 2016). Addressing UHIE mitigation in a city requires long-term and fundamental changes in urban planning policies (Parsaee et al., 2019). It was found in chapter 2 of this thesis that shade cast by trees can reduce pavement and street temperatures by up to 20 °C compared to unshaded conditions. Further, surface material has a greater influence on surface temperature than tree morphological traits. Additionally, Chapter 3 shows that cooling the air temperature by 1 °C in western Sydney can be achieved by increasing canopy cover from 0 to 40% and limiting the relative area covered by grey infrastructure below 50%. Moreover, trees did not contribute to urban cooling at night. The key findings from this study and published literature indicate that urban greening regulates surface temperature and air temperature. Consequently, it's interesting to see how urban and land use strategies capture the inherent value of trees and green space within their current policies and strategies.

However, no published studies have been conducted in Australia to critically analyse the policy in relation to research and best use of urban trees in mitigating UHIE. Even globally, a limited number of studies have assessed the relationship between land use policies and urban heat mitigation (Heris et al., 2019; Dare, 2019; Bosomworth et al., 2013). It is thus not surprising that studies investigating provisions related to urban trees in key planning polices and their implications in counterbalancing urban heat are lacking. Responding to this, this chapter investigates the planning policies and environmental strategies of two councils from NSW (Parramatta and Cumberland) and two councils from South Australia (SA) (Unley and Mitcham) to determine if and how they identify microclimate benefits of trees within the context of urban planning.

The former two councils were selected to build on detailed heat assessments provided in Chapters 2 and 3 of this thesis. Results of these analyses clearly demonstrated the capacity of tree canopy cover to reduce surface and air temperatures across numerous types of urban typologies. The latter two councils were selected due to their status as Tree Cities of the World (see Chapter 4.2.1 of this thesis for further details), which requires developing strong policies and management around urban tree canopy.

This chapter further investigates whether the microclimate benefits, science-based evidence of cooling and its limitations are incorporated into the documents. The following research questions are addressed in this chapter:

1. What are the values of trees described and embedded in urban planning policies and strategies?
2. Do the provisions related to trees in urban planning policies and strategies directly address the UHIE mitigation?
3. What are the strengths and weaknesses related to trees and urban heat mitigation in planning policies and strategies of councils?

4.3 Materials and methods

4.3.1 Rationale of the Study

Despite significant actions taken to increase urban tree canopy cover to mitigate UHIE, western Sydney continues to experience very high UHIE in summer where it can vary between 6–10 °C (Santamouris et al., 2020). Results of the Chapter 3 showed that air temperature in 123 locations out of 156 exceeded 40 °C across the local government areas (LGA) of Cumberland and Parramatta City in the summer 2018/2019, indicating that there is intensive urban heat across the region. Yet at the same, the data also showed that local temperatures at 33 locations remained below 40 °C, indicating the capacity to effectively cool urban microclimates.

In the next decades, the Sydney Basin is highly likely to experience an increase in the number of extreme heat (>40 °C) due to the replacement of forest and existing vegetation by new urban developments (Office of Environment & Heritage, 2014). Addressing rising urban heat in western Sydney will require careful planning. Here, the planning and strategy documents of Parramatta City and Cumberland councils were examined to better understand how these local governments understand and frame the capacity of trees to cool built environments.

Unley and Mitcham councils were selected as they are recognized by the "Tree Cities of the World" program. In 2021, five cities in Australia namely, Unley (SA), Mitcham (SA), Burnside (SA), Victoria Park (WA) and Lake Macquarie City (NSW) gained the recognition through the "Tree Cities of the World" program. This program is developed by the Food and Agriculture Organization (FAO) of the United Nations (UN) and the Arbor Day Foundation to celebrate greener cities and towns worldwide. Cities must meet five core criteria to be recognized by the Tree Cities of the World Program:

1. *Establish Responsibility* – A written statement should be made delegating responsibilities of trees to a department and/or a staff member of the local planning authority.
2. *Set the Rules* – Tree policies and strategies that govern the management of urban trees in the city should describe the best practices and how work is performed to protect trees. Further, penalties for noncompliance should be detailed.
3. *Know What You Have* – The city should have an updated tree inventory or assessment and should address the long-term plans for promoting, protecting and regulating removal of trees in the city.
4. *Allocate Resources* – An annual budget should be allocated for regular maintenance and implementation of management strategies.
5. *Celebrate Achievements* – Annual celebrations are hosted by a city to raise awareness among the public and acknowledge the efforts of staff and residents for successfully carrying out tree management.

Hence, it can be expected that this voluntary program significantly impacts the way a local government deals with its tree canopy. Policies and strategies related to urban trees in Unley and Mitcham should reflect this, being highly supportive of efforts to mitigate urban heat. Furthermore, UHIE in Adelaide is as intense as in western Sydney. The rural-urban temperature difference in Adelaide varies between 3–8 °C (Sharifi & Soltani, 2017; Rogers et al., 2019).

According to my findings, surface material had a greater influence on surface and globe temperatures than tree morphological characteristics. Since the increase in tree canopy coverage is widely considered an important method of reducing urban heat, this finding raises issues regarding the role of urban greening. This issue is addressed in the third chapter by examining how the spatial heterogeneity of urban surfaces, including trees, alters the air temperature at a micro-scale. It should be noted, however, that urban greening is controlled by land-use planning policies and urban governance. Hence, a policy analysis would provide a means of identifying any existing gaps in existing policy documents in relation to the urban heat that need to be addressed to achieve urban cooling.

This chapter investigates urban heat mitigation and other values of trees through analysing publicly available policy documents related to urban planning and urban trees from each local government area. This study takes a thematic policy analysis approach, and a similar approach has been used elsewhere in the world to investigate the extent of ecosystem services integration into planning policies. An analysis of how ecosystem services are incorporated in Scottish policy both conceptually and operationally was presented by Claret et al. (2018). The aim of this study was to demonstrate how Scotland has undervalued the ecosystem services through the analysis of 224 policy documents, strategies, and other policy-relevant documents. Similarly, policy analysis of strategic environmental assessment reports in Chile has been conducted to investigate how ecosystem services have been incorporated into spatial planning at different scales (Rozas-Vásquez et al., 2018). The study concluded that ecosystem services were present at every strategic environmental assessment stage and planning level.

Three principles were followed to choose the documents for the study.

1. This study only chose documents listed on official websites of the Parramatta Council, Cumberland Council, City of Unley and City of Mitcham.
2. The forms of documents that were used in the study were plans (statutory and non-statutory) and strategies that directly reflect the local governments' attitude towards land use, urban trees and urban heat.

3. Documents were eliminated if trees were not an integral part of the document or trees were not directly related to the contents of the document.

4.3.2 Parramatta and Cumberland councils

The LGA of Parramatta City covers an area of 84 km^2 in the geographic centre of the Sydney Basin. Parramatta has a population of 260,296 as of 30th June 2020 (ABS, 2021). The tree canopy cover of Parramatta is 33% (City of Parramatta, 2021). The Cumberland LGA extends over an area of 72 km^2 and has a population of 242,674 as of 30th June 2020 (ABS, 2021). Currently, the Cumberland LGA has 15% tree canopy cover (Cumberland Council, 2020).

In NSW, every council has a Local Environmental Plan (LEP). It is a legal document prepared by the council and approved by the NSW Government to regulate land use and development within the council area. The LEP guides planning decisions for local governments. The plan allows councils to regulate the ways in which all land both private and public may be used and protected through zoning and development controls. In addition, some councils in NSW own Development Control Plans (DCPs). The DCP is a non-statutory planning document which provides detailed guidelines to assist a person in developing a formal development application. A DCP must be in consistent with the provisions and objectives of the respective LEP. More details about these and other plans were provided in the Introduction of this thesis.

In Parramatta City, the primary planning documents are the Parramatta Local Environment Plan (2011), the Parramatta Development Control Plan (2011) and the Parramatta Public Domain Guidelines (2017). Therefore, these three documents were analysed in the study. In addition, the Parramatta Environmental Sustainability Strategy (2017) and Newington

Street Tree plan (2017) were selected for Parramatta Council due to their topical relevance (Fig. 4.1).

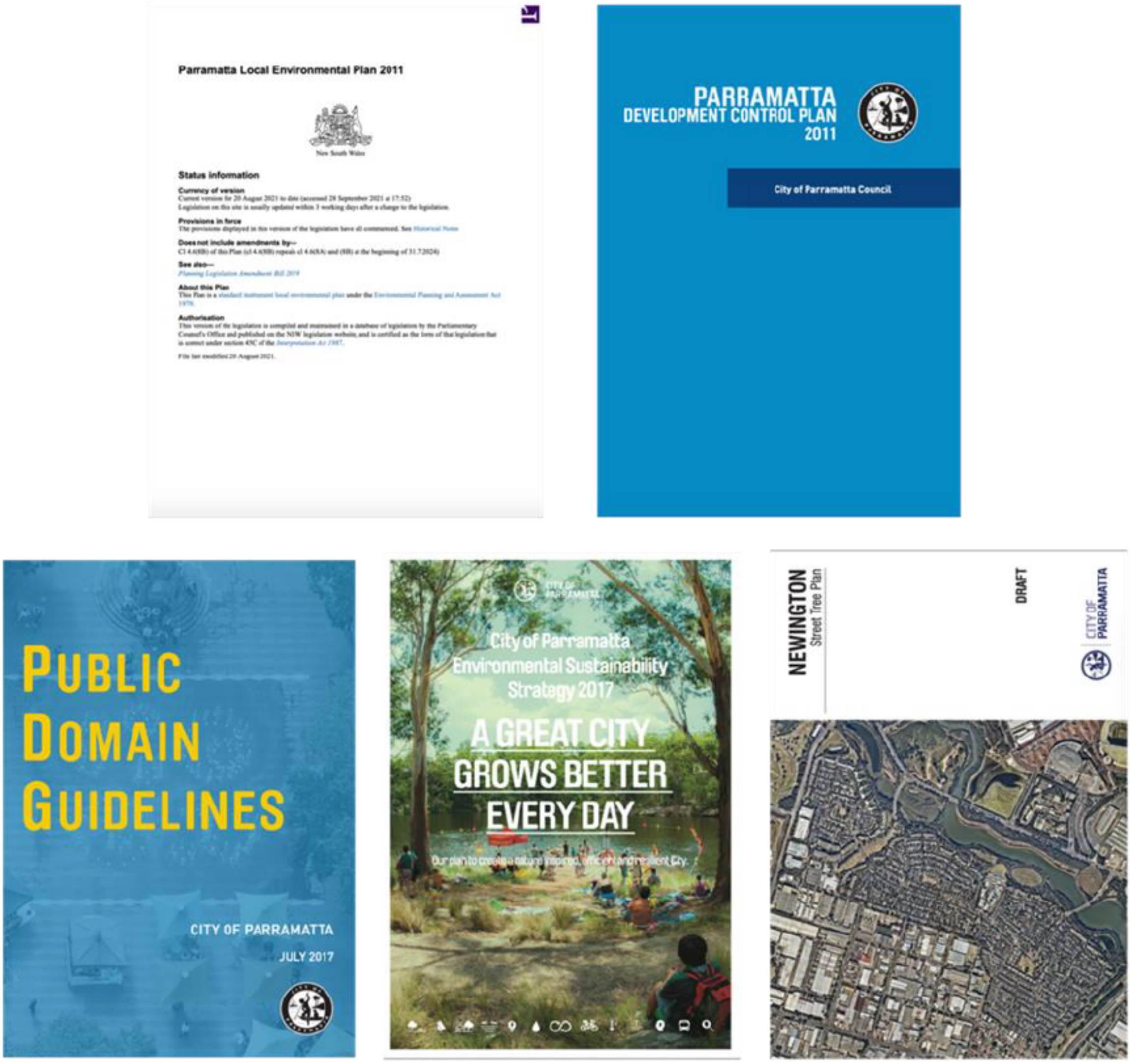


Figure 4.1: Urban planning and environmental strategy documents analysed for Parramatta Council.

Similar to Parramatta Council, the main planning documents for Cumberland Council were their LEP and DCP. The Cumberland Council has proposed a new LEP which will be finalised and gazetted during the 20/21 financial year (Cumberland Council, 2021). Until the new LEP becomes effective, Cumberland Council relies on LEPs from Parramatta (2011), Auburn (2010) and Holroyd (2013). Similarly, Cumberland Council does not have an approved

DCP, however it has a draft DCP publicly available on the council's website. Therefore, the Cumberland draft DCP was analysed here. Nevertheless, the website states that until the draft DCP is finalised by council, the existing DCPs from the three former LGAs of which sections were amalgamated in 2016 to form the new LGA of Cumberland (Parramatta, Holroyd, Auburn) remain in place. Therefore, DCPs of Parramatta, Holroyd and Auburn were examined as well. In addition, and similar to the documents selected for Parramatta Council, the Urban Tree Strategy (2020), Biodiversity Strategy (2019), Community Strategic Plan – 2017–2027 (2017) and Open Space and Recreational Strategy 2019–2029 (2019) were analysed for Cumberland Council (Fig. 4.2).

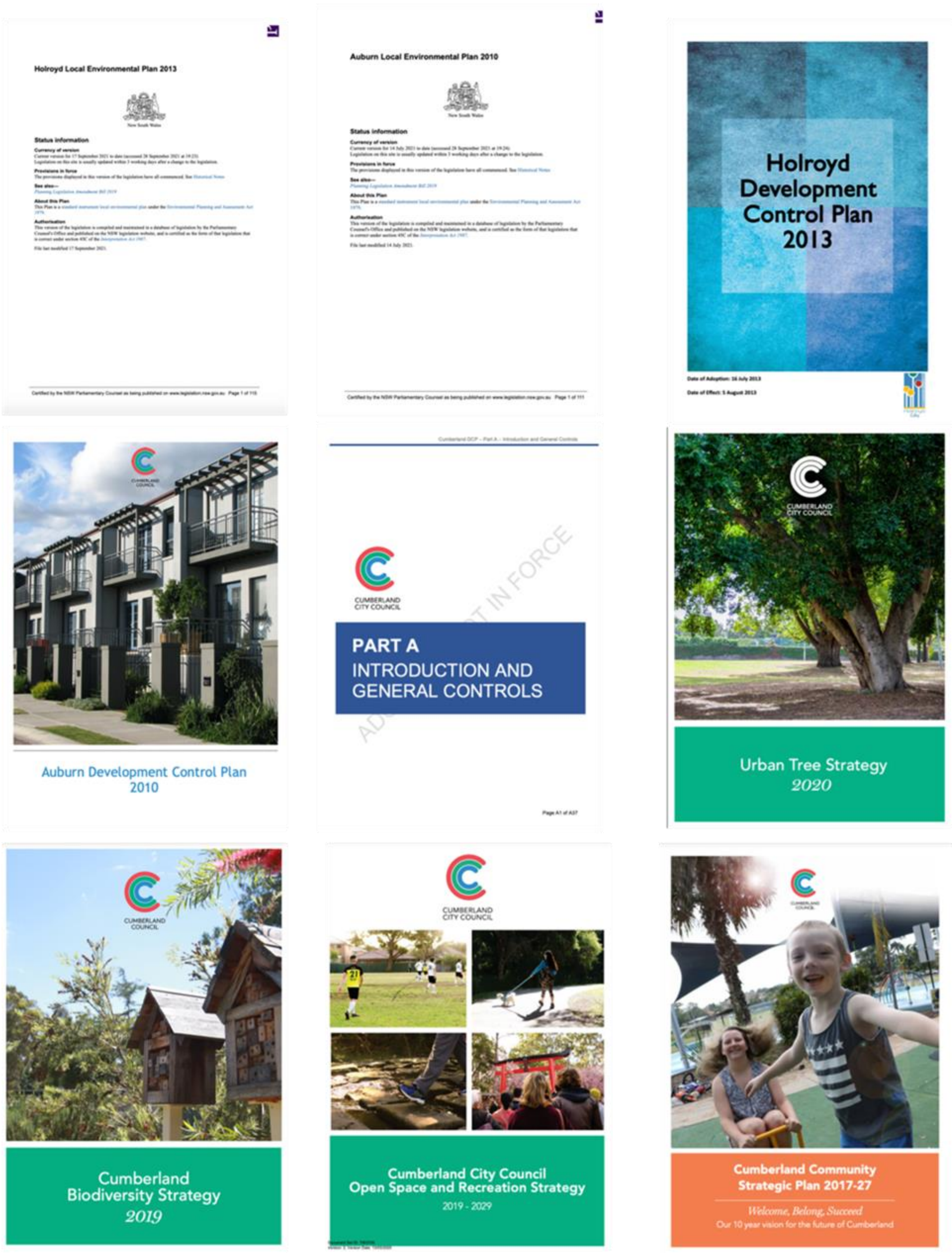


Figure 4.2: Urban planning and environmental strategy documents analysed for Cumberland Council.

4.3.3 Unley and Mitcham Councils

The City of Unley covers an area of 14 km^2 and is located directly south of Adelaide's city centre. The City of Mitcham is located further south of the Adelaide CBD and covers an area of 75 km^2. The Cities of Unley and Mitcham have populations of 39,416 and 67,907 respectively as of 30th June 2020 (ABS, 2021). At the time of this study, Unley had 27% (City of Unley, 2020) and Mitcham had 49% (City of Mitcham, 2021) tree canopy cover.

Unlike in NSW, councils in SA do not produce separate LEPs and DCPs for the purpose of planning. Instead, Development Plans represent the only statutory documents which give power to the local governments to undertake development within their area under the specified guidelines. Therefore, Development Plans of Unley and Mitcham were reviewed. Tree strategies of Unley and Mitcham were selected as they outline current and emerging issues, opportunities and trends in the community relating to trees. Therefore, the Development Plan (2020) and Tree Strategy (2020) for Unley City Council and the Development Plan (2020) and Tree Strategy (2020) for Mitcham City Council were analysed (Fig. 4.3).

Figure 4.3: Urban planning and environmental strategy documents reviewed for Unley and Mitcham councils.

4.3.4 Data analysis

Council documents were imported into NVivo 12 (QRS International, Australia) to conduct a thematic and systematic analysis of their texts following recommendations of

Castleberry & Nolen (2018). A thematic analysis is generally used to analyse classifications and present themes (patterns) that exist in a text (Alhojailan, 2012). In the research, Nvivo software was used because it was easy to organize text into themes to facilitate data retrieval. Moreover, it was easy to identify key themes in the policy documents by analysing multiple codes. This is the most widely used approach to analyse qualitative interviews or textual data (Castleberry & Nolen, 2018). Moreover, it is the most widely used method of analysing qualitative policy data (Herzog et al., 2017; Herzog et al., 2019; Kamali, 2018). For example, a thematic policy analysis was conducted to explore the evolution of information and communication technology policies of Zimbabwe (Ruhode, 2016). Similarly, Aikens et al. (2016) conducted a thematic analysis in the area of environmental and sustainability education by analysing policy research articles.

The necessary coding process was initially inspired by values of trees identified in past studies (Turner-Skoff & Cavender, 2019; Song et al., 2018; Song et al., 2017; Reid et al., 2017; Coder, 2011). These preliminary data driven codes aligned well with the research objectives of the study. While working through the documents, more codes were generated which supported the objectives of the study which were as follows:

Objective 1: What are the values of trees described and embedded in urban planning policies and strategies?

Values of trees are generally divided into three categories in the literature: environmental values, economic values, and socio-cultural/aesthetic values. These categories were used as top-level codes (also known as *themes*) in the analysis.

Environmental values theme: This theme included values of trees related to air quality improvement, storm water mitigation, enhancement of biodiversity and carbon sequestration.

Economic values theme: This theme included all aspects related to increase property value, tourism, recreation, energy conservation, provision of food, timber and medicine. Economic disservices of trees such as infrastructure damage and cost of maintenance were also included in this theme.

Socio-cultural/aesthetic values theme: This theme included health benefits of trees (physical and mental wellbeing), improving liveability, enhancing safety and privacy and heritage values.

Objective 2: Do the provisions in urban planning policies and strategies related to trees directly address mitigation of the UHIE?

More child codes (also known as *sub-themes*) were added to the Environmental values theme.

Environmental values theme: In addition to those attributes listed in Objective 1, microclimatic benefits, tree shade and overall UHIE mitigation in relation trees were added to this theme.

Objective 3: What are the strengths and weaknesses related to trees and urban heat mitigation in planning policies and strategies of councils?

A new theme was created which comprised of different aspects related urban canopy and heat management.

Canopy cover theme: This theme contained canopy cover targets, programmes/action plans to retain and increase the tree cover, legislations and guidelines directly related urban heat mitigation, tree removal and tree replacement, and challenges associated with improving tree cover and open space.

Altogether, four themes (top-level codes) and 27 sub- themes (child-codes) were developed to analyse the content of the selected documents (Fig. 4.4).

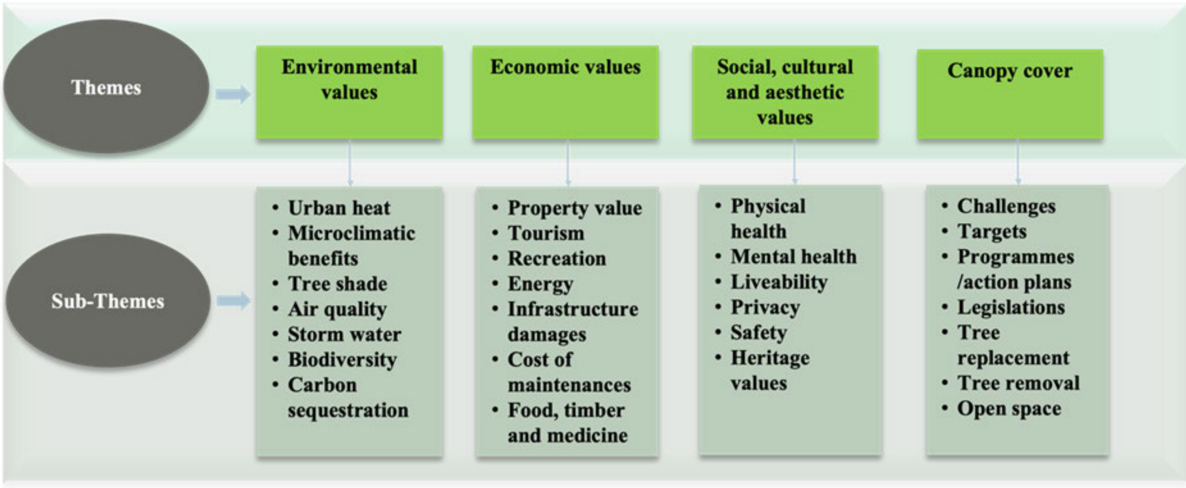


Figure 4.4: Hierarchy diagram of Themes (top-level codes) and Sub-Themes (child codes) used in the policy document analysis.

4.4 Results

4.4.1 Parramatta Council

Five documents were analysed for Parramatta Council. This includes one statutory document (Parramatta Local Environmental Plan) and four non-statutory documents. The Parramatta Local Environmental Plan primarily recognizes the biodiversity and landscape values of trees. The Development Control Plan of Parramatta emphasises the importance of incorporating trees in precinct specific plans to mitigate heat. The Environmental Sustainability Strategy is consisted of environmental, economic, social cultural and aesthetic values of trees. It is noted that this document specified tree canopy cover targets and mentioned the negative consequences of urban heat and action plans to mitigate UHIE. Similarly, the Parramatta Public Domain Guidelines recognizes the environmental, economic, social cultural and aesthetic values of trees and actions that could be taken to alleviate urban heat (e.g., creating green corridors, increase tree planting). The Newington Street Tree Plan is dedicated to the practical management of street trees in Newington. It acknowledges the microclimatic benefits and other values of trees.

Overall, all the non-statutory documents of Parramatta Council recognize the role of trees in mitigating urban heat whereas the Local Environmental Plan does not contain provisions for urban heat mitigation.

4.4.1.1 Local Environmental Plan (2011)

The Parramatta LEP provides the framework for planning work across the City of Parramatta. Urban trees are predominantly described as elements of the landscaped area. The LEP defines the landscaped area as “a part of a site used for growing plants, grasses and trees, but does not include any building, structure or hard paved area” (page 149). It identifies the importance of urban trees in terms of biodiversity protection. The LEP states the objective of the biodiversity protection is to "maintain terrestrial and aquatic biodiversity, including the following— (a) protecting native fauna and flora, (b) protecting the ecological processes necessary for their continued existence, (c) encouraging the recovery of native fauna and flora and their habitats" (page 48). Before determining a development application for any development, it is specified that the consent authority must consider any adverse impacts on "native ecological communities, habitat of any threatened species, populations or ecological community, regionally significant species of fauna and flora or habitat and habitat elements providing connectivity" (page 48). However, despite recognising biodiversity and landscape features including trees, the Parramatta LEP does not reference any connection between urban trees and heat.

4.4.1.2 Development Control Plan (2011)

The Parramatta DCP provides detailed controls and standards for various development types across the LGA, including residential, commercial, and industrial. Urban heat is mentioned as an important concern in the DCP. Objective 2 within Section 5.3 on Preservation of Trees or Vegetation in the DCP is "to retain Parramatta local government Area's urban forest cover particularly its street tree and parkland tree population to alleviate urban heat impacts" (Section 5, page 48). Further, the DCP states that "Trees make our surroundings pleasant, provide relief from summer heat and reduce glare from the pavement" (Section 5, page 48). To mitigate urban heat, the DCP recommends appropriate species selection of street trees, maintaining existing street trees and addition of street trees where they are absent. Further, the importance of using a variety of trees not only to create visual interest but also to provide shade and cooling in summer is extensively mentioned.

Trees are also connected with urban heat management in precinct specific plans. For example, the DCP states that the City of Parramatta had a long-term vision to create the "Civic Link Precinct". The objective of the Civic Link is to support "development that positively and innovatively impacts on environmental outcomes, including flood, urban heat, energy use and the City's long-term strategy to improve water quality and public engagement with the Parramatta River" (Section 4.3, page 166) and "pedestrian amenity within the Civic Link by maximising solar access during lunch hours, mitigating the urban heat island effect and ameliorating wind" (Section 4.3, page 166). Other urban heat mitigation methods acknowledge in the DCP were "use of green roofs to assist with reduction of energy use, improve stormwater management, enhance environmental biodiversity and reduce urban heat island effects" (Section 4.3, page 89).

Other notable benefits of trees mention in the DCP include improving local biodiversity, reducing surface runoff, improving air quality, increasing the value of real estate, and improving visual screening. The DCP encourages planting and conserving native trees with low water consumption and retaining large and medium sized trees to increase tree canopy cover. It recommends that development activities are to be carried out causing a minimal impact on trees; it also supports planting indigenous trees.

4.4.1.3 Environmental Sustainability Strategy (2017)

The stated aim of the Environmental Sustainability Strategy is to create a nature-inspired, efficient and resilient environment in the City of Parramatta. The Environmental Sustainability Strategy identifies urban heat as one of the greatest challenges to local communities and recognises the important role of trees in mitigating that impact. The Environmental Sustainability Strategy focuses on four key themes.

1. *A City in Nature*
2. *Built for the Future*
3. *Connected and Resilient Communities*
4. *Leading by Example*

Each theme covers key environmental priorities and urban heat falls under the theme of "Connected and Resilient Communities". Furthermore, the Environmental Sustainability Strategy states "more trees mean more shade and trees help us tackle the rising issue of urban heat by cooling down our city" (page 12) and "planting more trees will help cool down our buildings and streets" (page 9). The document quantifies council goals, identifying an aim to increase the tree canopy cover to 40% by 2050 (based on 2016 level).

The Environmental Sustainability Strategy identifies a series of negative effects of urban heat including increased health risks, particularly with young and elderly people, low productivity, high energy and water consumption, reduced visitation/tourism and reduced social interaction. The Environmental Sustainability Strategy describes urban heat as concern within the community. It mentions that "heat affects our health, productivity and our economy" (page 10). It further mentions that heat will cause some people to take time off work. Generally, this strategy positions itself as responding to community concerns. It states that a recent urban heat survey undertaken by Parramatta Council found that 85% of community respondents would like more shade in their local area to provide cover on hot days. It also reveals that the Parramatta Ways Walking Strategy was developed by the council to improve the walkability in Parramatta through a network of green streets, open spaces and connections to local centres (page 10).

The Environmental Sustainability Strategy states that Parramatta Council aims to improve liveability by cooling the city and protecting people and communities from heat stress (page 8). In order to do so, the council pledges to protect and increase green space and continues to deliver tangible outcomes on the Cool Parramatta initiative. Cool Parramatta is an initiative designed to guide residents to prepare and respond to urban heat by taking initiatives like planting trees annually through the City of Trees program. Under this initiative the council would continue to develop community resilience programmes, promote urban green infrastructure (GI) (page 39) and plant trees along cycleways. Furthermore, the council aims to plant more diverse street tree species to withstand pests, disease and the changing climate. Under this initiative, the council wants to regulate planting in new growth precincts to ensure canopy trees were planted in streets and on private properties (page 23).

4.4.1.4 Public Domain Guidelines (2017)

The Parramatta Public Domain Guidelines provides the blueprint for all public domain improvements in the City of Parramatta. Improving the appearance and amenity of streets (page 166), improving health and well-being of people (page 166), increased property value (page 166) and mitigating UHIE (page 166) are the benefits of trees outlined in this document. The document states that "Street trees are an effective way to increase shade and mitigate the urban heat island effect" (page 166). Planting medium to large trees in major urban centres (page 166), creating green corridors with increased tree planting (page 166) and increasing tree canopy in the public domain (page 166) are the proposed measures to mitigate UHIE in this document.

4.4.1.5 Newington Street Tree Plan (2017)

This plan is a precinct-specific plan that provides a strategic framework and plan for future management of street trees in the former Olympic athlete's village of Newington. Urban trees are highly valued in the street tree plan. Mitigation of UHIE by providing continued tree canopy cover is acknowledged in the document. "Minimise the heat island effect by providing continued tree canopy cover for shade and cooling of hard surfaces" (page 6) is one of the core objectives of the plan. Street tree selection criteria mentioned in the document include tolerance of seasonal temperature variation and adverse climate, acceptable leaf and fruit fall characteristics, being not prone to dropping green limbs, low maintenance and low risk of becoming an environmental weed.

Beyond urban heat, the document identifies a series of further benefits of urban trees. These include improving physical and mental well-being of the people, improving walkability, carbon sequestration, enhancing biodiversity, energy conservation, extend life of infrastructure, soften the contours of the built environment, calming and slowing traffic, providing a buffer between pedestrians and cars and increasing property value (page 7). It also outlines the disadvantages like damage to pavement, interference with powerlines and the potential to create slippery pedestrian pavements (trees with heavy fruits) (page 8). Residents are encouraged to submit a request to council should they feel the front of their property is suitable for additional tree planting (page 8).

4.4.2 Cumberland Council

Nine documents were examined for Cumberland Council. This included two statutory documents (Auburn and Holroyd Local Environmental Plans) and seven non- statutory documents. Urban heat is not a primary concern within the provisions of Auburn and Holroyd Environmental Plans. These Development Control Plans list other environmental and social, cultural and aesthetic values of trees. Urban heat management is a primary area of focus in the Cumberland Draft Development Control Plan. Mitigation methods such as planting trees, Water Sensitive Urban Designs (WSUD) and material with high albedo are mentioned in the document. One of the key focus areas of Cumberland Tree Strategy is to “Maintain, protect and increase existing tree canopy”. It identifies the relationship between trees and urban heat. Trees and their role in mitigating urban heat is not specified in the Biodiversity Strategy. However, trees are recognized as part of GI to improve microclimate. Both the Community Strategy Plan and the Open Space and Recreation Plan of Cumberland address the growing need for “cool spaces” and “green areas” to reduce the severity of urban heat. Trees are identified as a type of urban GI in these documents. Notably, all none-statutory documents of Cumberland Council analysed here identify trees as beneficial to urban microclimates.

4.4.2.1 Auburn Local Environment Plan (2010)

Urban trees are represented as elements of landscape and biodiversity in the LEP. It defines landscaped area as "a part of a site used for growing plants, grasses and trees, but does not include any building, structure or hard paved area" (page 89). The Auburn LEP does not reference any connection between urban trees and heat.

4.4.2.2 Auburn Development Control Plan (2010)

The DCP acknowledges the important role of trees in cooling ambient temperature. It stated that "vegetation shall be used to cool the ambient temperature within the development" (page 42). It recommends planting deciduous trees to provide summer shading and winter sunlight. According to the plan, improved landscape amenity enhances ecological and aesthetic values and increased visual privacy (page 57). The DCP outlines that it was vital to preserve existing significant trees on development sites where appropriate and "Suitable replacement trees are to be provided if existing trees cannot be retained" (page 13).

4.4.2.3 Holroyd Local Environment Plan (2013)

Landscape value, heritage values and improving biodiversity are the identified benefits of urban trees in the Holroyd LEP. The definition of landscaped areas is identical to that given in the Auburn LEP and the use of trees to enhance the landscape value was emphasised throughout the document. The LEP states that a tree must be dead to remove it (page 81), yet indicators for tree death are not provided. Nevertheless, no significance is given to other benefits of trees, especially mitigating urban heat.

4.4.2.4 Holroyd Development Control Plan (2013)

The Holroyd DCP identifies trees as part of the urban landscape. The DCP states that preservation of trees was important to "promote the many benefits of trees such as provision of shade, cooling of hard surfaces and increase privacy" (page 48). Further, incorporating deciduous trees in summer and use of tree species with varying heights to shade walls and windows of buildings is acknowledged in the document (page 164).

Habitat for native wildlife, improved air and water quality, reduced noise pollution and energy conservation are the other environmental values of trees identified in the DCP. "To conserve and retain trees and vegetation within the City of Holroyd and to promote the retention and planting of trees" (page 45) are the objectives mentioned in the DCP which address the conservation of trees in the city. The DCP states that when a tree is removed for development, a replacement tree, preferably a native species, should be planted (page 11).

4.4.2.5 Cumberland Draft Development Control Plan (2020)

The Cumberland Draft DCP provides a unified set of planning controls to support the future needs of Cumberland City. "Urban Heat Management" (Section G, page 88) is a major theme in the Cumberland draft DCP which fell under "Sustainability and Environmental Management" (Section G page 78). The objectives outline in the Urban Heat Management section are "to encourage residential development that is designed to reduce the heat island effect and to encourage developments to incorporate GI, water and cool materials to reduce urban heat" (Section G, page 88). To achieve these objectives, the DCP proposes to include at least one element that helps reduce heat in residential development, even better a combination of these elements which includes vegetation, green roofs, green walls and WSUD (Section G, page 75). Additionally, "improvements to local GI (such as the urban tree canopy) on public or private land" (Section G, page 89) are also encouraged. In addition to GI and WSUD, incorporating permeable pavements with light-colours and the construction of roofs from high albedo, low solar absorbance or high solar reflectance materials are also suggested (Section G, page 89). Furthermore, the draft DP states that "a development application for new low-density development is to include evidence to demonstrate how the above urban heat management will be addressed" (Section G, page 88). Most importantly, the draft DCP adopts guidelines developed by the Green Building Council of Australia and WSROC into consideration to set objectives and encourage developers to incorporate GI in their projects to reduce urban heat (Section G, page 89).

Other environmental, economic and social and aesthetic benefits of urban trees highlighted in the DCP include adding character to the neighbourhood (Section G, page 39), improving visual quality and amenity (Section G, page 103), protecting privacy (page G28), improving water infiltration (Section G, page 81), enhancing biodiversity (Section G, page 78), reducing noise and light pollution (Section G, page 78) and conserving energy (Section G, page 78). It recommended retaining and enhancing continuous canopy and hollow-bearing trees to support and improve biodiversity (Section G, page 81). The draft DCP gives the utmost priority to preserving trees. Existing mature trees, significant trees (see below for definition), trees with cultural and heritage values, endemic and native trees should be preserved (Section G, page 103). The draft DCP states that significant street trees shall be conserved and "where there is an absence of existing street trees, additional trees shall be planted to ensure that the existing streetscape is maintained and enhanced" (Section G, page 8). The DCP advises on using locally indigenous plant species, including threatened and regionally significant species for this purpose (Section G, page 102). It mentions that when selecting tree species, species habit, mature size, resilience to storm damage and requirements for evergreen or deciduous trees should be considered (Section G, page 101).

The DCP points to the council's Tree Management Plan (TMP) which protects nominated trees on a site during construction (Section G, page 84). Council retains the right to refuse an application for the removal of a tree if it is a "prominent part of the streetscape; stands alone and is thus of more significance than if it is part of a group of trees; is of historic or cultural significance or is/are registered on any council register of significant trees; is prominent due to its height, size, position or age; is a locally indigenous, rare or endangered species; provides a significant visual screen; is part of an important habitat for wildlife; and is part of remnant or riparian vegetation" (Section F1, page 309). Consequently, when an existing mature tree is approved to be removed by the council a replacement tree should be planted (Section G, page 103).

4.4.2.6 Urban Tree Strategy (2020)

The Urban Tree Strategy provides guidelines to manage the tree population in Cumberland over a 10-year period (2020-2030). Urban tree canopy cover is recognized as part of the City of Cumberland's GI network in this strategy (page 11). It identifies mitigation of UHIE as one of the benefits of urban trees (page 12). Further, it states that urban heat "is made worse as our cities grow and replace natural green spaces with hard surfaces" (page 12). The Urban Tree Strategy suggests that "increasing tree plantings and species diversity are ways we can address climate change and urban heat effects" (page.22). It highlights the importance of planting the right tree in the right location to gain maximum benefits (page 22). The tree strategy also outlines the health impacts of urban heat on vulnerable parts of the population. It states, "periods of extreme hot weather affect the health and wellbeing of the very young, senior citizens and outdoor workers in our community" (page 13).

Three Key Focus areas have been developed in the strategy to manage the council's tree population over a 10-year period. "Maintain, protect and increase existing tree canopy" (page 50) is one of the focus areas. "Identify and progress planting opportunities to increase tree canopy, continue to maintain, monitor and protect publicly owned trees, increase species diversity to ensure urban canopy is resilient and collaborate with external agencies to protect and enhance tree canopy" (page 50) are the objectives to be achieved under this focus area.

Habitat for native wildlife, air purification, carbon sequestration, stormwater management, improved liveability and outdoor activity, increased property value and conservation of energy are the other benefits of urban trees recognized in the strategy (page 29). However, the strategy also outlines the disservices of trees such as damage to pavement and interference with powerlines (page 22). The document states that when it comes to removing a tree, council would work with residents to select and replant the tree with a suitable species appropriate for the site (page 51). Moreover, it highlights that the council had identified a strategic program to focus efforts on tree planting for council assets and public areas (page 51).

4.4.2.7 Cumberland Biodiversity Strategy (2019)

The Biodiversity Strategy presents a strategic and coordinated approach that has been developed by council in consultation with the community to attract and effectively manage resources for biodiversity protection and enhancement in the Cumberland LGA. It identified trees as a part of GI (page 8). It also identifies residential gardens, local parks, streetscapes and service corridors as elements of GI. It states that the "benefits of green infrastructure include increased biodiversity, improved microclimate, and improved amenity and community wellbeing" (page 8). However, the Biodiversity Strategy does not specify the importance of trees in mitigating urban heat.

4.4.2.8 Cumberland Community Strategic Plan 2017–2027 (2017)

The Community Strategic Plan sets six strategic goals to achieve its vision for "A clean and green community", with one goal addressing the UHIE. It stated that "green and open spaces suit a variety of uses and help to mitigate heat island effects" (page 8). The strategic plan recognises the importance of having high-quality green space and it focused on providing the community with abundant green space (page 8). It states that green space is protected through policies (page 8).

4.4.2.9 Cumberland Open Space and Recreation Plan 2019–2029 (2019)

The Open Space and Recreation Plan provides council with a 10–year direction for open space, sport and recreation facilities. Mitigation of urban heat with trees and green space is mentioned in this document. It states that the council had a focus on supporting clean and green community with high quality and abundant green space and open areas (page 9). The plan outlines four strategic directions and actions under each to address the open space and recreation needs of the Cumberland community at present and in the future. “Protecting our natural environment and increasing resilience” (page 32) is one of the strategic directions which set the actions needed to mitigate the UHIE. Some notable actions highlighted in the document to cool the environment are “identify, develop and promote “cool spaces” such as well shaded parks, identify areas with higher urban heat impacts, tree planting, water features, shading, and incorporate recommendations from heat mapping to mitigate heat effects in play spaces and contribute to WSROC's Turn Down the Heat Strategy 2018” (page 37).

It states that findings of a collaborative study done by the University of New South Wales and Sydney Water (2017) should be included in new council-led developments. The mentioned study showed that strategic inclusion of water in public places can reduce the ambient air temperature by 2.5 °C (page 31). It further suggestes integrating WSUD and street tree plantings to reduce urban heat (page 31). It is mentioned that the council was working closely with research institutes like Western Sydney University to identify areas with higher urban heat impacts, aiming at mitigating these impacts through improved quality of open spaces and recreation facilities, as well as adding trees, water features and shading (page 31). The document highlights the five million trees programme of the NSW Government to increase canopy cover (page 8). Enhancing biodiversity and improving air quality are the other benefits of trees identified by this document (page 32).

4.4.3 City of Unley

The Unley Development Plan (statutory document) recognizes trees as a type of GI which was essential in mitigating urban heat in Unley. Other types of urban GI mentioned in the document are green roofs and green gardens. A number of other environmental, social, cultural and aesthetic values of trees are mentioned in the document. Significant and regulated trees are protected under the Unley Development Plan. The Unley Tree Strategy provides an extensive list of action plans to conserve and improve tree cover across the city. Further, it identifies the central role of trees in mitigating urban heat.

Overall, both statutory and non-statutory documents of Unley incorporate trees in development planning due to their inherent ability of cooling the environment.

4.4.3.1 Unley Development Plan (2020)

The UDD provides development controls to be used when undertaking any development in the City of Unley. It recognizes trees as an element of GI and its role in reducing UHIE by stating that “green (vegetated) places will assist UHIE” (page 163). Minimising impervious surfaces beneath the canopies of trees is one of the development controls outlined in the plan to reduce the urban heat and improve water infiltration (page 28). In addition to trees, incorporating “roof top gardens and green ‘living’ walls, particularly for multi-storey and large developments, to reduce the ‘urban heat island effect” (page 28) is also recommended.

Improved liveability, visual and aesthetic values, increased biodiversity, and energy conservation are the other benefits of trees outlined in the document. The development plan lists a number of significant[2] and regulated[3] trees and development should be designed and

[2] “Any tree in metropolitan Adelaide, Adelaide Hills Council townships and parts of the Mount Barker Council with a trunk circumference of 2.0 metres or more (measured at a point 1.0 metre above natural ground level) In the case of trees with multiple trunks, regulated trees are those with trunks having a total circumference of 2.0 metres or more and an average circumference of 625 millimetres or more”. (SA Government, 2021).

[3] “A regulated tree in metropolitan Adelaide, Adelaide Hills Council townships and parts of the Mount Barker Council with a trunk circumference of 3.0 metres or more (measured at a point 1.0 metre above natural ground level). In the case of trees with multiple trunks, significant trees are those with trunks having a total circumference of 3.0 metres or more and an average circumference of 625 millimetres or more” (SA Government, 2021).

undertaken to retain and protect these trees (page 56). Any development should be carried out in a manner where it had minimum adverse effects on regulated and significant trees (page 56). A significant or regulated tree could only be removed if the "tree is diseased and its life expectancy is short, risk to public or private safety, causing damage to a building, treatment of disease, or is in the general interests of the health of the tree" (page 56).

4.4.3.2 Unley Tree Strategy (2020)

This comprehensive document is designed to conserve, manage, and increase tree cover in the City of Unley. Mitigation of UHIE is given high importance in the strategy. It mentioned that "the use of tree planting and greening in streets, parks and private gardens in the City of Unley will help to increase the resilience" (page 18) of the city against climate change. The tree strategy identifies losing tree cover across private land as one of the biggest challenges faced by the council. It emphasises that the loss of tree cover was "of a significant concern to future neighbourhood character and urban heat impact" (page 15). Thus, there is a significant challenge in increasing the tree canopy cover to mitigate the heat impacts. "Urban forests" are identified as the most effective tool to mitigate heat in urban areas (page 8). Mitigating the cause of climate change by carbon sequestration and cooling local climate in the city are identified as the two ways that trees directly helped build resilience and reduce the impacts of climate change (page 17).

Enhanced urban biodiversity, production of food, carbon sequestration, improved air and water quality, stormwater management, improved mental and physical health provision for social interactions and recreation, increased tourism, improved liveability, and increased property value are the other benefits of trees outlined in the document (page 8). Council has a target of achieving a "green liveable city" (page 11) by increasing urban green cover by 20% in metropolitan Adelaide by 2045 (from 27% (2014) to 32.4% in 2045). Some of the initiatives stated in the document to increase canopy cover are:

a. “Review the Tree Strategy every five years to provide strategic planning” page.33),
b. “Undertake a proactive approach to cyclic pruning” (page 34),
c. “Replace trees as required based on condition audit results” (page 34),
d. “Offer a Conservation Grant to private residents to assist with the ongoing maintenance of Regulated and Significant Trees on private land” (page 35),
e. “Implement an accelerated tree planting program for additional trees on council land using Precinct Plans to prioritise planting locations” (page 36),
f. “Review and update young tree care practices in line with industry standards to ensure new trees are provided with the best development potential” (page 38),
g. “Revitalise and monitor the “adopt a tree” program to encourage residents to provide supplementary watering to new street tree” (page 38),
h. “Provide support and incentives for the community to become engaged in the planting and ownership of trees within private properties” (page 38).

4.4.4 City of Mitcham

In the Mitcham Development Plan, trees are identified as elements of the landscape as well as types of GI to provide shade and alleviate heat. Like in plan reviewed for Unley, significant and regulated trees are protected by the Mitcham Development Plan. Several action plans are mentioned in the Mitcham Tree Strategy to protect and enhance the tree canopy cover in Mitcham. Urban heat mitigation, other environmental, economic, social, cultural and aesthetic values of are mentioned in the document.

Overall, both the statutory and none-statutory documents of Mitcham identify the relationship between trees and urban heat.

4.4.4.1 Mitcham Development Plan (2020)

The DP provides guidelines for the types of construction that could take place in the City of Mitcham. It focuses on reducing urban heat load through incorporating trees and other GI elements. It states that "development will be interspersed with suitable on-site landscaping to reduce heat load in summer" (page 213). Moreover, it states that "development is designed and orientated to take advantage of natural features in climate control and energy conservation" (page 24). The Development plan highlights the importance of trees in providing shade. "Footpaths will be wide and street trees will shade the footpath and soften the built form." (page 174).

Improved visual screening and energy conservation are some other benefits of urban trees identified in the document (page 242). Additionally, the document states that "…trees are a highly valued part of Metropolitan Adelaide and are important for a number of reasons including high aesthetic value, conservation of biodiversity, provision of habitat for fauna, and conservation of original and remnant vegetation" (page 28). Developments should be undertaken with minimum adverse impact on the health of significant and regulated trees (page 28). Further, the document states that where possible, development should retain existing mature street trees that contribute positively to the landscape character of the locality (page 117).

4.4.4.2 Mitcham Tree Strategy 2016–2025 (2016)

The strategy is designed to provide greener and more resilient places for the community of Mitcham. The UHIE was widely discussed in the strategy. It is stated that "by increasing shading and cooling through tree planting and the use of 'green infrastructure' to reduce urban heat island effects" (page 20) the impacts on vulnerable members of the community could be mitigated. Furthermore, the document states that linking WSUD with GI would increase climate change adaptation benefits of urban trees and other vegetation (page 14). Aging tree populations, rapid development and climate change are identified as the main constraints faced by the council in the document (page 8). It is mentioned that the *Resilient South Regional Climate Change Adaptation Plan* (2014) (page 20) is adopted by the council to increase tree planting and greening of public areas.

Air purification, stormwater management, enhanced biodiversity, reduced energy conservation, crime and anxiety, improved physical and mental wellbeing, increased exercise and social interaction, as well as higher property value are the other benefits of trees mentioned in the document (page 12). The strategy emphasises that most of the benefits provided by trees do not generate income, but they offset expenses that would otherwise have to be paid, for example, "through their summer cooling and winter windbreak effects trees save residents money on heating and cooling, with savings of up to 30% possible" (page 12). The urban forest planting programme is a new initiative mentioned in the tree strategy which is implemented by the council to increase the canopy cover in Mitcham. It aimed to plant around 400 trees per year across the LGA (page 7). The document states that council had developed a tree asset management plan to inform the community regarding the species of trees allocated for each street (page 13), how closely they will be planted (page 14), how long they are likely to live (page 14) and how their replacement will be arranged when necessary (page 13). Tree maintenance and management guidelines and street tree audits at intervals of five years are the other tree management procedures mentioned in the document (page 13).

4.4.5 Summary

The results of the policy analysis of the research are summarized in Table 4.1. The policy and strategy documents of all councils included environmental values. However, no statutory planning documents of councils located in western Sydney addressed urban heat.

Conversely, both the statutory and non-statutory planning documents from councils in Adelaide addressed the issue of urban heat in relation to trees.

Table 4.1: A summary of themes covered in policy and strategy documents of Parramatta, Cumberland, Unley and Mitcham Councils

Council	Policy Document	Themes	Urban Heat
Parramatta	Local Environmental Plan	🟢	No
	Development Control Plan	🟢 🟠	Yes
	Environmental Sustainability Strategy	🟢 🔵 🟡 🟠	Yes
	Public Domain Guidelines	🟢 🔵 🟡 🟠	Yes
	Newington Street Tree Plan	🟢 🔵 🟡 🟠	Yes
Cumberland	Auburn Local Environmental Plan	🟢	No
	Auburn Development Control Plan	🟢 🟡	No
	Holroyd Local Environmental Plan	🟢	No
	Holroyd Development Control Plan	🟢 🟡	No
	Cumberland Draft Development Control Plan	🟢 🔵 🟡 🟠	Yes
	Urban Tree Strategy	🟢 🔵 🟡 🟠	Yes
	Cumberland Biodiversity Strategy	🟢 🟡	No
	Cumberland Community Strategic Plan	🟢 🟡	Yes
	Cumberland Open Space and Recreation Plan	🟢 🔵 🟡 🟠	Yes
Unley	Unley Development Plan	🟢 🔵 🟡 🟠	Yes
	Unley Tree Strategy	🟢 🔵 🟡 🟠	Yes
Mitcham	Mitcham Development Plan	🟢 🔵 🟡 🟠	Yes
	Mitcham Tree Strategy	🟢 🔵 🟡 🟠	Yes

🟢 Environmental values
🔵 Economic values
🟡 Social, cultural, and aesthetic values
🟠 Canopy cover

4.5 Discussion

This study investigated how urban cooling delivered by trees was represented in policy documents in four local governments in Australia. Parramatta Council and Cumberland Council display sound knowledge about tree canopy management yet provide limited action plans to increase the canopy cover. In contrast, the cities of Unley and Mitcham exhibit a high level of awareness about UHIE mitigation potential through urban tree canopy cover and list several action plans to maintain and increase tree canopy cover. Being awarded the status of a Tree City of the World seemingly had major benefits when using active tree management to mitigate urban heat.

4.5.1 What are the values of trees described and embedded in urban planning policies and strategies?

Various environmental, economic, social, cultural and aesthetic values of trees are acknowledged in the documents analysed in the study. Improving biodiversity, storm water management, air quality and carbon sequestration are the environmental values mentioned in the documents. The role of urban trees in enhancing local biodiversity is mentioned in all the documents except the Parramatta Public Domain Guidelines and the Cumberland Community Strategic Plan. A few studies (Gunnarsson et al., 2019; Roy, 2017; González et al., 2009; Young et al., 2007) have demonstrated that the abundance of trees in an urban landscape can be a major determinant of species richness. In contrast to biodiversity, improved storm water management is linked with trees in all documents assessed. This is consistent with the findings of studies that have shown how urban trees reduce the volume of stormwater by high rates of interception and infiltration (Elliot et al., 2018; Armson et al., 2013; Scharenbroch et al., 2016; Grey et al., 2018; Berland et al., 2017). Xiao & McPherson (2002) simulated rainfall interception by street and park trees in Santa Monica, California. Street and park trees intercepted 193,168 m^3 (1.6% of total precipitation) of annual rainfall. Different species and sizes of trees intercepted water differently (Xiao & McPherson, 2002). Improving air quality and carbon sequestration are attributes identified in the Parramatta DCP, Parramatta ESS, Newington Street Tree Plan, Cumberland Tree Strategy, Holroyd DCP, Unley Development Plan, Unley Tree Strategy and the Mitcham Tree Strategy. Indeed, several studies (Roy, 2017; Shirazi & Kazmi, 2016; Turner-Skoff & Cavender, 2019; Ng et al., 2015) have provided evidence that urban trees can remove the air pollutants from the atmosphere. Studies done in the United States (Domke et al., 2020) and China (Zhao et al., 2018) have illustrated that urban trees take up atmospheric CO_2.

Increased property value and energy conservation are the economic values of trees stated in the documents. These values are acknowledged in the Parramatta DCP, Parramatta ESS, Newington Street Tree Plan, Cumberland Draft DCP, Cumberland Tree Strategy, Unley Development Plan, Unley Tree Strategy, Mitcham Development Plan and the Mitcham Tree Strategy. The relationship between trees and increased value of real estate is supported by studies done in Australia (Pandit et al., 2012) and the United States (Donovan et al., 2019). Several studies reported that trees are effective at lowering air temperature and thereby reducing domestic energy usage (Roy, 2017; Soares et al., 2011; Mullaney et al., 2015).

The social, cultural and aesthetic values of trees mentioned in the documents are related to improved liveability, visual and aesthetic benefits, improved physical and mental wellbeing and improved visual screening. The Cumberland Tree Strategy, Unley Development Plan and Unley Tree Strategy outline that improved liveability was often associated with urban trees. Parker & Simpson (2018) supported this claim in their review on public green infrastructure and liveability. Visual and aesthetic benefits of urban trees are mentioned in Parramatta DCP, Newington Street Tree Plan and Unley Development Plan. It resonates with the professional and non-professional perception studies on urban trees carried out in Australia (Kirkpatrick et al., 2012), Pakistan (Sabir et al., 2021) and Portugal (Fernandes et al., 2019). The Newington Street Tree Plan and Mitcham Tree strategy highlights that having more urban trees would improve the physical and mental well-being of members of the community. Studies done in past illustrated the relationship between reduced psychological stress and increased exercise associated with the presence of more trees (Donovan, 2017; Jiang et al., 2016; Collins et al., 2019; Hami & Maruthaveeran, 2018). Improved visual screening is another social benefit related to urban trees mentioned in Parramatta DCP, Cumberland Draft DCP, Unley Development Plan and Mitcham Development Plan. Kirkpatrick et al. (2012) stated in their study that residents found tall and dense trees were useful in enhancing privacy.

There are several disservices of trees mentioned in the documents: damage to infrastructure and generation of rubbish/debris. The Newington Street Tree Plan, Cumberland Tree Strategy and Unley Tree Strategy emphasis the negative aspects of urban trees such as damage to powerlines and pavements and generation of litter and other waste. Some studies showed that trees can indeed cause significant damage to powerlines, pavements and can generate large quantities of litter (Blunt, 2008; Mullaney et al., 2015b; Kirkpatrick et al., 2013; von Döhren & Haase, 2015).

Hence it appears that most statutory and non-statutory plans analysed here were grounded in scientific facts. However, often, council policies undervalue trees by leaving their maintenance to local residents and only intervening when problems or special needs arise (Meenachi-Sunderam & Thompson, 2007). Despite the clear evidence in support of the benefits of urban trees, none of the statutory documents of western Sydney incorporate these benefits strategically into their land use and urban planning guidelines. An explanation could be the lack of communication between policy and strategy makers and the scientific community. Other possible reasons might include the cost of maintaining urban trees and the lack of land availability in western Sydney's urban areas.

This evidence-informed approach is likely to enhance their effectiveness in conserving urban trees. Although values and disservices of urban trees were mentioned in these documents, councils remain vague on their economic effects. For example, achieving a certain canopy percentage would reduce the electricity consumption by X dollars or increasing the street tree planting by a certain percentage would increase the amount of time people spend outdoors by Y hours. Outcomes linked with a discrete value and disservices of trees were missing in these documents. Since these outcomes vary from location to location, councils should consider investigating publically available cost-benefit tools and calculators for the benefits of urban trees and green infrastructure more broadly. In addition, collaborative research with universities and research institutes to better quantify the benefits of urban tree canopy cover could be highly beneficial to integrate state-of-the-art ‘green accounting tools’.

City of Parramatta and Cumberland need to fully incorporate tree ecosystem services into their statutory planning documents. The current planning tools used by these councils pose a significant obstacle to the efficient integration of ecosystem services. There is a need to gain a clearer understanding of the difficulties associated with integrating ecosystem services with statutory planning documents. Currently, the planning tools do not allow ecosystem services to be integrated effectively. Keeping ecosystem services in mind as we develop our cities and urban regions will require more science-practice collaborations between experts, practitioners, and policymakers.

4.5.2 Do the provisions related to trees in urban planning policies and strategies directly address the UHIE mitigation?

Results indicated that all investigated councils are aware of the UHIE and most of the documents address the UHIE primarily with trees. The relationship between trees and urban cooling has long been established and backed up by numerous studies from the UK (Armson et al., 2012), Germany (Rahman et al., 2017), Brazil (De Abreu-Harbich et al., 2015), and Australia (Gao et al., 2020). These studies revealed that urban trees present a feasible form of GI for heat mitigation and improving human thermal comfort. While awareness was high, statutory plans (LEPs) of Parramatta and Cumberland are devoid of provisions for urban heat management. Besides, these documents portrayed trees as elements of the landscape and an important part of biodiversity yet fail to identify their vital role in cooling the urban environment, especially at micro-scale. In contrast, Development Plans of Unley and Mitcham recognize trees as a type of cooling GI. However, the LEPs of Parramatta and Cumberland councils contain provisions to protect the trees (native, endangered species) from development activities. Such measures may indirectly help in retaining the trees and promote urban cooling.

Parramatta DCP and Cumberland draft DCP have identified trees as an integral part in development planning. Appropriate selection of street trees, maintaining existing street trees and addition of street trees where there was no tree planting are recommended in the Parramatta DCP to mitigate urban heat. Careful selection of street trees (species, age, height, canopy density, see Introduction of this thesis) is mentioned as important feature, because it had a strong impact on cooling (Zhang et al., 2020; Rahman et al., 2020; Massetti et al., 2019). The Parramatta Environmental Sustainability Strategy and Newington Street Tree Plans are in accordance with the Parramatta DCP as they also emphasis street tree selection criteria. Urban trees were identified as a type of GI in the Cumberland Draft DCP and applications for new low-density developments are required to demonstrate how urban heat was managed. A similar approach is taken by City of Melbourne where development applications must assess heat mitigation strategies prior to approval (City of Melbourne, 2020).

The present analysis showed that trees and urban heat are sufficiently integrated into non-binding, and recently dated strategies of all councils (Newington Street Tree Plan, Cumberland, Unley and Mitcham tree strategies). This reflected the growing scientific concern and public about rising urban heat (Santamouris et al., 2017a; Imran et al., 2019). On the contrary, the existing LEPs of Parramatta and Cumberland were developed nearly 10 years ago and did not mention trees in the context of heat mitigation or cooling. Both the Cumberland Community Strategic Plan and the Open Space and Recreation Plan highlight the key role of trees and urban greening to improve human thermal comfort. The Biodiversity Strategy of Cumberland was the only strategic document which displays a very limited information about UHIE and trees. This is reflected by identifying the UHIE phenomenon with some customary terms like "improve microclimate" and trees as part of "residential gardens, local parks and service corridors".

The present analysis clearly showed that councils are taking actions towards urban heat mitigation as all more recent documents reflect recommended best practices from the scientific literature. However, as mentioned in Section 4.4.1, expected outcomes of increasing tree cover with respect to urban cooling are not specifically mentioned in these documents. For example, Chapter 3 of this thesis found that increasing tree canopy cover from 0 to 40% can cool the air temperature by 1 °C. Councils could integrate such findings into their existing tree canopy cover targets. Currently, the majority of the councils have broader canopy cover targets. In the Introduction of this chapter, it was mentioned that the City of Phoenix has set a 20-year goal to achieve a 25% tree canopy cover with drought-tolerant native trees which is expected to reduce air temperature by nearly 8 °C. Similar approaches could be adopted by Australian councils to establish more comprehensive and measurable targets.

4.5.3 What are the strengths and weaknesses related to trees and urban heat mitigation in planning policies and strategies of councils?

The local governments of Unley and Mitcham have incorporated numerous measures that address urban heat in their Development Plans. They are the only statutory documents analysed in the present study that discussed mechanisms of land-use planning to reduce heat exposure through the use of GI, including trees. This is a critical indicator for potential improvements at the City of Parramatta and Cumberland because laws and legislations, strategies and standards can have a strong influence on urban greenspace (Boulton et al., 2018; Boulton et al., 2021) and thus heat resilience of cities. The LEPs of Parramatta and Cumberland (Holroyd and Auburn LEPs) could be improved by including a standalone provision related to urban heat management. For example, development consent could only be granted upon the submission of an urban heat management plan. Such a plan could be written for any land use zone (e.g., residential, business, industrial).

Urban trees are incorporated into heat management in precinct specific plans in the Parramatta DCP. For example, the proposed Civic Link, which extends through the Parramatta Central Business District (CBD) has a network of green corridors and cycle and pedestrian friendly avenues. Though the canopy cover across the LGA of Parramatta is 33%, it remains very low (9%) in its CBD (City of Parramatta, 2017a). By implementing the Civic Link, the tree canopy cover within the CBD can be improved and with it, urban cooling can be delivered. At present, all the councils that were investigated here have canopy cover targets at LGA level. Even if the set canopy cover targets are achieved in the future, tree canopy may not be uniformly distributed across the respective LGA. Highly developed areas like CBDs will have less than average tree cover. Therefore, incorporating trees into precinct specific plans that work at finer spatial scales could be a successful strategy to deliver canopy cover in areas where the value of space often does not permit GI.

The City of Unley includes measures to reduce impervious cover under tree canopies in the Urban Tree Strategy as an effective mechanism to reduce urban heat. Incorporating grass cover under tree canopies is more effective in alleviating urban heat than paving these areas. As shown in Chapter 2 of the thesis, surface types under tree canopies influence surface temperature more than tree species. Grass surface under trees had the lowest mean surface temperature (Kaluarachchi et al., 2020). Incorporating such science-based evidence in the way the City of Unley will make existing urban cooling strategies more effective. These are ‘low hanging fruit’ that could be adopted by other councils.

Importantly, the City of Unley provides incentives and conservation grants to encourage retention, maintenance and expansion of tree canopy on private land. Financial incentives are an effective method to encourage private landowners to retain trees on their properties (Jim & Chan, 2016; Li et al., 2016). Providing financial incentives and creating economic value to increase urban tree canopy cover is practiced in other cities as well. For example, Portland (VIC) offers a tax rebate for tree retention and planting (City of Portland, 2020). European cities like Helsinki (Finland) and Berlin (Germany) offer tax rebates for greening new or redeveloped sites (Juhola, 2018). It seems that the Unley Tree Strategy set a good example by implementing projects like *Living with Trees* to provide discounts towards gutter cleaning and green waste removal for private landowners. A review of the drivers for tree loss on private land identified that perceived safety concerns and increased maintenance time and costs were the main reasons against tree retention (Clark et al., 2020). These drivers for tree removal may prevent achieving set urban tree canopy targets, thus, providing financial incentives for tree maintenance may be an effective way to encourage private landowners to refrain applying for a removal permit. Although the *Cool Parramatta Initiative* (mentioned in Parramatta ESS) also offers a programme to prepare residents to respond to urban heat by planting trees, no clear guidelines are given as to how private landowners would be engaged. Based on the documents analysed for Parramatta, Cumberland and Mitcham Councils, there are no evidence for any financial incentives and conservation grants targeting private landowners to retain trees.

Mitcham Council has a *Tree Asset Management Plan* which enables local communities to achieve their desired goals through managing the city's urban forest. councils like Southern Grampians and Knox (VIC) also have adopted asset management plans to manage their street trees. A robust asset management plan can provide up-to-date information on trees for decision-making by different stakeholders, including residents, urban developers, Councils, and the National Government (Winram, 2019). Additionally, Unley and Mitcham councils conducted regular tree audits to document tree health and structural conditions which formed an integral part of their tree asset management plans. This approach can be adopted by Parramatta and Cumberland Councils to strengthen their efforts to increase the canopy cover and consequently mitigate UHIE. However, any effective tree asset management plan should be reviewed frequently to improve urban and environmental planning. Additionally, emerging technologies like the combination of high-resolution LiDAR imaging and machine learning could be used to automatically assess the dynamic changes in urban tree canopy cover, which provides up-to-date information on canopy gains and losses while at the same time reduces laborious tree inventories (Ossola & Hopton, 2018; Parmehr et al., 2016; Alonzo et al., 2014)

The documents of all councils assessed here contain goals to increase their tree canopy cover yet provide limited tree species selection criteria. However, a proper action plan should contain detailed information on tree species, where to plant them and how many trees should be planted each year to reach set goals. Unley City Council sets an example by adopting a strategy to create urban forest with no more than 5% of one tree species, and 10% of one genus.

This approach can be adopted by other councils to increase species diversity and resilience against climate while achieving its canopy target. The lack of a well-designed urban tree strategy is likely to result in councils achieving a lower than the desired level of canopy cover, higher maintenance, lower tree diversity and ultimately less resilience against calamities and extreme weather events. This could ultimately result in the loss of trees, loss of biodiversity and the dominance of a few tree species over time. Therefore, defined numeric targets should be assigned not only for canopy cover but also for other criteria such as tree size, age, the relative abundance of native and exotic species, and desired canopy characteristics.

City of Unley and Mitcham have comparatively higher number of programmes and initiatives to improve the urban tree cover than Parramatta and Cumberland. This is mainly because of their status in the Tree Cities of the World initiative. In future, more cities will take part in the initiative as they realise the importance of trees as assets to protect biodiversity, reduce cost of energy and boost property values. As explained in the section 4.2.1, cities should be able to demonstrate the progress of their tree management plans annually to retain their status in the Tree City of the World. Therefore, it can be expected that both Unley and Mitcham councils will continue to exert their efforts in improving tree cover.

4.6 Recommendations

Following this critical analysis, the following recommendations are made to strengthen future urban tree policies that aim at mitigating UHIE. Incorporation of these recommendations by councils seem vital when mitigating the UHIE under simultaneous pressure exerted on GI by climate change and urbanisation:

- Review existing urban planning policies (LEPs) regularly. This revision process helps to assess the performance of the existing policies, identify areas of improvement in terms of heat mitigation, and integrate the latest science-based evidence into the policies.

- Include provisions in the LEPs that require developers to demonstrate how urban heat is managed in the project.
- Integration of scientific findings into urban planning policies through collaboration between researchers and policymakers. An evidence-based policy-making process will provide effective UHIE mitigation strategies.
- Design precinct-specific heat mitigation plans. This will help in increasing canopy cover in highly urbanized areas.
- Implement incentives and funding schemes to increase the involvement of different stakeholders in maintaining and increasing canopy cover. Specifically, the inclusion of private landowners through an attractive incentive system and awareness programmes seems like a successful way forward.
- Prepare a tree asset management plan and conduct regular tree audits. The tree asset management plan should be reviewed regularly (possibly every 2 years).

  Build a consolidated central tree data repository. This database should include information gathered from tree audits (e.g., species, genus, nativeness, evergreen/deciduous, canopy density, age range, height and stem diameter, specific issues (e.g., pests, disease, damage to infrastructure), annual cost of maintenance, socio-cultural significance, location, life expectancy and ownership). The resulting tree data repository would become an evidence-based decision support system for progressive policy development that aims at best-practice in management of urban trees

4.7 Conclusion

This study presented a comprehensive analysis on how urban cooling benefits provided by trees were incorporated in existing policy documents in four local governments in Australia. The analysis elucidated that LEPs of Parramatta and Cumberland Councils failed to mention the relationship between urban trees and urban heat mitigation, however the DCPs of both councils did recognize the importance of trees in urban cooling. In contrast, statutory documents of Unley and Mitcham councils (Development Plan) identified trees as a part of GI which is essential in alleviating urban heat. The Unley Tree Strategy contained several innovative action plans to increase canopy cover of the city which could be adopted by the other councils to improve urban microclimates. This analysis highlighted the importance for local governments to develop tree databases for evidence-based policy making. At the same time, creative incentive schemes should be set up to encourage private landowners to retain existing trees and increase the number of new tree plantings. Such developments appear to be effective mechanisms to expand the urban tree canopy cover and assist in mitigation of urban heat.

Chapter 5: Synthesis and Conclusion

5.1 Thesis aim

The aim of the research reported in this thesis was to address the role of urban trees in mitigating urban heat in Greater Sydney. Increasing population density and associated conversion of land from rural to urban have altered the landscape of the region since European invasion more than 200 years ago. Today, this conversion of land, urban densification and global warming have resulted in an increased risk of exposure to high summer temperatures (Maheshwari et al., 2020; Sidiqui et al., 2016). Urban heat affects physical and mental wellbeing and puts economically vulnerable populations at risk (Heaviside et al., 2017; Lundgren et al., 2013). Trees are highly effective in mitigating urban heat (Brandani et al., 2016; Rahman et al., 2017). In this thesis, the influence of urban trees on both surface temperature (Chapter 2) and air temperature (Chapter 3) variation at microscale (50-m radius) was investigated. Evidence based policy can be highly effective in mitigating heat-related risks, because it can introduce state-of-the-art scientific knowledge into policy frameworks and guidelines. To illuminate the role of current scientific understanding of urban trees as means to mitigate heat, a policy gap analysis (Chapter 4) compared several documents from local governments that achieved the status of a *Tree City of the World* to those of local governments that had not been granted this status.

Overall, three objectives were addressed in the thesis.

1. Determine how canopy characteristics of urban trees in Greater Sydney assist in cooling common surface materials.
2. Determine the effect of urban landscape heterogeneity on air temperature at the microscale.

3. Use a policy gap analysis to identify where the role of urban trees in mitigating UHIE can be strengthened in existing policies and environmental strategies in Greater Sydney.

These three objectives informed transdisciplinary work that merged environmental monitoring with material sciences, remote sensing and public policy science. The resulting analyses were presented in three chapters.

5.2 Summary of the research undertaken in the thesis

The key findings in this study indicated that urban greening regulates air temperature and surface temperature. The predominant issue in western Sydney is the extreme heat, which is compounded by climate change effects, resulting in more frequent extreme temperatures as well as a loss of vegetation and open space. At the same time, grey infrastructure is expanding rapidly. Urban heat can be effectively mitigated when the ecosystem services of trees are appropriately incorporated into the urban landscape. Planting trees for the sake of planting is not advisable, rather urban planners and policy makers should integrate trees into the landscape strategically to achieve maximum benefits. This includes selecting the right species, considering the materials for pavements and identifying heat hotspots and areas likely to change due to development. However, the inherent value of trees and green spaces is not sufficiently recognized by some council policies and strategies in western Sydney. The first experimental chapter investigated the effect of tree crown characteristics on surface temperature. Tree crown characteristics vary among species and location and thus may influence surface temperature below the tree canopy. On average, a 20 °C surface temperature reduction between sunlit and shaded surfaces was observed in the present study. Rigorous data analyses did not confirm the widely observed relationships between the surface temperature differential (ΔT) and canopy characteristics like leaf area index (LAI) and vertical crown projected area (A_C) for the urban trees studied here. Instead, I was able to document significant effects on ΔT as result of the surface type (grass, bark mulch, pavers and bare soil) that was shaded. The differences in surface temperatures were most likely attributable to variation in albedo of the surface material (Coakley, 2003; Akbari, 2009; Zeman, 2012) with thermal mass and transpirative cooling being additional influencing factors. The largest surface cooling from tree shade was observed for bark mulch followed by bare soil, bitumen, grass and pavers.

The second experimental chapter examined the effect of surface cover on air temperature variation at microscale (50-m radius). Overall, the findings showed that increasing tree canopy cover by 40% can reduce the mean summer air temperature (T_{mean}) by 1 °C and a similar degree of cooling can be achieved during the daytime by increasing the tree canopy cover by 50%. However, tree canopy cover did not show a significant relationship with the mean summer night-time temperature (T_{Nmean}). At night, air temperature was primarily influenced by Grey infrastructure components like roads and buildings. Results also indicated that Tree canopy was comparatively ineffective in reducing extremely low or high temperatures. Furthermore, when classifying locations using the Local Climate Zone (LCZs) concept of Stewart and Oke (2012), compact LCZs displayed higher air temperature (0.2–1.4 °C) than the open classes and attributed to limited Sky View Factor (SVF) and high building density.

Urban tree cover in a city is primarily controlled by the urban planning policies (Phelan et al., 2018). Additionally, tree ordinances, urban tree strategies and programs also influence tree cover (Daniel et al., 2016; Gibbons & Ryan, 2015). The fourth chapter was dedicated to a policy gap analysis to identify where the role of urban trees in mitigating UHIE can be strengthened in existing policies and environmental strategies in Greater Sydney based on science-based finings and good practices from other councils. The policy analysis showed that all the councils had a high awareness of urban heat. Urban heat management was heavily integrated into all non-statutory documents of the councils. However, the key statutory planning documents of Parramatta and Cumberland councils did not have provisions related to urban heat mitigation. On the contrary, urban trees were identified as a type of green infrastructure to alleviate urban heat in Development Plans in the Cities of Unley and Mitcham. The Unley Tree Strategy contained a high number of innovative canopy management plans which could be adopted by the other councils to fill policy gaps and strengthen the role of urban trees in microclimate regulation.

5.3 Conclusion and recommendations

My transdisciplinary research amalgamated environmental science, remote sensing and policy around urban trees whereby I was able to recommend best practices to maximize tree-based cooling benefits for cities. The Urban Heat Island Effect (UHIE) is a result of impervious surfaces with lower albedo, lack of urban vegetation and associated shade and transpirative cooling while at the same time increased heat emission from anthropogenic activity. Even though trees can alleviate urban heat to a certain degree, it is always wise to minimize the sources that contribute to UHIE. Urban planning policies play a vital role in providing development controls to manage the urban heat. The primary planning documents like Local Environmental Plans (LEPs) of New South Wales should be reviewed and sections should be added that clearly address active strategies and targets related to reduction of urban heat.

In Chapter 2, transpirational cooling may be taken into account in future studies, which will probably reveal a great deal of variation among species. Another interesting addition would have been canopy temperature which could have been retrieved via drones carrying an infrared camera. Chapter 2 of the thesis does not analyse canopy shape and density and their relationship to surface temperature. While the extent of the shaded area is strongly dependent on age, it is also influenced by the shape and density. The combined influence of these two factors on the surface temperature can be examined in further research.

The population of Greater Sydney is predicted to increase, thus more rural areas will be converted into urban areas and green space will be transformed to grey space. It seems unlikely that existing urban parks and private gardens will be sufficient to counterbalance the additional heat load expected in the future. Although LEPs have minimum landscape requirements for different developments, provisions in the LEPs should provide clear guidelines for the selection and planting arrangement of tree species and regulate the surface types used underneath tree crowns. The findings of Chapter 3 highlighted the importance of planting arrangements and crown characteristics to maximize cooling benefits of trees. All these factors should be collectively integrated into planning documents to create a heat-responsive landscape. Having 40% tree canopy cover within a 50-m radius (7850 m^2) led to 1 °C cooling in the study. However, the spatial configuration of microsites differs widely and more research is needed to define site-specific canopy targets and quantify cooling/warming effects when spatial cover of surfaces is altered.

More than 75% of the locations analysed in the second experimental chapter recorded absolute maximum air temperature >40 °C in summer 2018/2019. The majority of these locations belonged to the Cumberland LGA and coincided with relatively low canopy cover. This is a serious issue which can have detrimental impacts on quality of life and requires a fast intervention. Since trees are highly effective in reducing daytime air temperature, Cumberland Council should initiate programs to encourage private landowners to plant trees in their gardens. Taking actions that engage private landowners in this course is crucial as space is very limited to establish more urban parks within the LGA. Alternatively, council could adopt the *rural to urban transect tool* developed by Andres Dunay (2002) to identify the areas where tree planting should be prioritized. The rural to urban transect is comprised of seven zones; *T1: Natural zone, T2: Rural zone, T3: Sub urban zone, T4: General urban zone, T5: Urban central zone, T6: Urban core zone and SD: Special district*. Zones like *T5: Urban central zone* and

T6: Urban core zone are highly urbanized with tall buildings, more impervious areas, and high population density, therefore introducing shade trees along the streets and vertical gardening would be more appropriate. Furthermore, when prioritizing tree planting, attention should be given to areas with both high heat and socio-economic vulnerability. Councils can formulate a heat management strategy specific to such areas (similar to the Civic Link in Parramatta) to increase tree canopy cover. Furthermore, trees can be planted in areas with high frequency foot traffic (e.g., pedestrian zones, around community and shopping centres, throughfares, main streets, transport hubs or schools).

Though trees are highly effective in reducing urban heat, tree use has limitations. Therefore, the built environment should be designed to minimize the thermal load and provide protection from heat. Mapping of tree canopy cover across an LGA should be done frequently to analyses natural and non-natural dynamic changes of tree canopy cover across private and public land. This will immensely help the councils to track tree canopy cover for management purposes and to monitor progress towards set canopy cover goals. It would be worthwhile to investigate the socio-economic vulnerabilities of compact climate zone classes under climate change scenarios and population changes in the future.

The success of planting programs that address such goals and physical changes to urban landscapes that will reduce heat depend on availability of funds. Councils could design and implement novel funding mechanisms that support their cooling efforts. For example, councils could use income from tree removal and building permits to finance planting of new trees. The City of Surrey (Canada) introduced the "Green City Fund" where revenue from building permits was allocated to help mitigate the impact of new developments on existing urban forests (City of Surrey, 2020). The City of Delta (Canada) used income from their tree permits to plant trees in other locations of the city (City of Delta, 2020). Parramatta City and Cumberland Council could aspire to become a *Tree City of the World* which will ensure further promotion and implementation of functional, accessible and adaptable GI to its communities. The Councils can set up tree bond programs, enforce higher fines for illegal tree removal and payments, and councils may lower rates for people who maintain large trees on their properties for the benefit of the local community. Among other measures, incentive programs that encourage the planting of large trees, the distribution of free trees by Councils, and monitoring progress can also be highlighted. Lake Macquarie City, NSW has been listed among the Tree Cities of the world. The planning and strategy documents of Lake Macquarie City can be examined for insight into what makes them unique as well as what can be adapted to other cities. Future research could draw on regional strategies, such as the Greater Sydney Regional Plan and Western City District Plan to assess the alignment between their planning priorities related to urban trees with local strategies. This study has very wide applicability, as the findings can be applied to other countries that share the same climate as western Sydney. There is, however, a possibility that these results will not be valid for cities with tropical climates.

In addition to rapid urbanization, frequent occurrence of heatwaves exacerbates the UHIE in cities of Australia. However, the existing planning policies have a limited number of provisions to support urban cooling. On the contrary, urban heat management is emerging as a central part of urban planning policies in other countries. In conclusion, findings of this thesis should be integrated into policy frameworks of Australian cities in response to progressing urbanization and climate change. Thinking further afield, my research findings could equally well be applied in cities outside Australia where similar socio-environmental conditions exist.

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Appendix: Supplementary Material

Table S1: Tree species with their mean, minimum and maximum T_{AS}, T_{ASL} and ΔT_A.

Species	Mean T_{AS}±SD (°C)	Min /Max T_{AS} (°C)	Mean T_{ASL}±SD (°C)	Min/Max T_{ASL} (°C)	Mean ΔT_A±SD (°C)	Min /Max ΔT_A (°C)
Camphor laurel	31.0 ±2.6	28.5/38.5	31.2 ±2.6	28.7/38.6	-0.2 ±0.1	-0.3/-0.1
Casuarina equisetifolia	29.7 ±3.5	23.3/34.0	29.9 ±3.5	23.4/34.3	-0.2 ±0.1	-0.3/-0.1
Corymbia citriodora	31.3 ±0.2	30.8/31.6	31.4 ±0.2	30.9/31.7	-0.1 ±0.0	-0.1/-0.1
Eucalyptus saligna	30.3 ±1.7	27.2/32.1	30.4 ±1.7	27.3/32.1	-0.1 ±0.1	-0.2/0.0
Ficus macrocarpa	33.9 ±2.5	30.1/36.3	34.1 ±0.6	30.2/36.6	-0.2 ±0.1	-0.3/-0.1
Jacaranda mimosifolia	31.3 ±0.6	30.4/33.8	31.5 ±0.6	30.6/34.1	-0.2 ±0.1	-0.3/-0.1
Lagerstroemia	29.3 ±0.6	28.4/30.7	29.5 ±3.0	28.6/30.9	-0.2 ±0.1	-0.4/0.0
Liquidambar styraciflua	30.3 ±1.7	28.3/34.8	30.4 ±1.7	28.4/35.1	-0.1 ±0.1	-0.3/0.0
Lophostemon confertus	31.2 ±3.0	27.9/38.7	31.4 ±3.0	28.0/38.9	-0.2 ±0.1	-0.3/-0.1
Melaleuca quinquenervia	29.4 ±2.6	27.9/38.2	29.5 ±2.6	28.0/38.3	-0.2 ±0.1	-0.3/-0.1
Platanus acerifolia	31.5 ±2.3	27.4/35.1	31.7 ±2.3	27.5/35.3	-0.2 ±0.1	-0.3/-0.1
Pyrus calleryana	32.4 ±3.0	28.4/38.0	32.6 ±3.0	28.5/38.1	-0.2 ±0.1	-0.3/-0.1
Waterhousea floribunda	35.1 ±2.7	30.5/41.1	35.3 ±2.7	30.7/41.3	-0.2 ±0.0	-0.2/-0.1

Table S2: Mean, minimum and maximum T_{AS}, T_{ASL} and ΔT_A recorded in bare soil, grass, bark mulch, pavers and bitumen.

Surface types	Mean T_{AS}±SD (°C)	Min /Max T_{AS} (°C)	Mean T_{ASL}±SD (°C)	Min/Max T_{SL} (°C)	Mean ΔT_A±SD (°C)	Min/Max ΔT_A (°C)
Bare soil	32.1±2.4	25.6/35.1	32.4±2.4	25.8/35.9	-0.3±0.1	-0.3/-0.2
Bark mulch	32.9±2.8	27.2/38.0	33.1±2.8	27.3/38.1	-0.2±0.1	-0.3/-0.1
Bitumen	30.9±2.2	27.4/38.5	31.5±2.2	27.5/38.6	-0.2±0.1	-0.4/-0.1
Grass	31.3±3.2	23.3/41.1	31.1±3.2	23.4/41.3	-0.2±0.1	-0.4/0.0
Pavers	31.4±2.2	23.3/38.5	31.5±2.2	23.4/38.6	-0.2±0.1	-0.3/0.0

Table S3: Tree species with their mean, minimum and maximum shaded surface temperature (T_{SS}), sunlit surface temperature (T_{SL}) and surface temperature differential (ΔT_S).

Species	Mean T_{SS}±SD (°C)	Min /Max T_{SS} (°C)	Mean T_{SL}±SD (°C)	Min/Max T_{SL} (°C)	Mean ΔT_S±SD (°C)	Min /Max ΔT_S (°C)
Camphor laurel	32.0 ±2.8	27.5/40.8	51.4 ±5.9	30.1/64.8	-19.6 ±5.5	-29.3/-7.0
Casuarina equisetifolia	31.3 ±4.1	22.5/44.2	49.5 ±6.8	36.4/65.7	-18.2 ±5.7	-33.8/-6.3
Corymbia citriodora	32.9 ±1.5	31.3/36.8	53.2 ±2.2	50.1/56.6	-20.3 ±1.7	-23.8/-17.6
Eucalyptus saligna	33.1 ±4.2	26.5/43.5	52.4 ±4.6	45.3/62.3	-19.3 ±6.7	-30.9/-7.6
Ficus macrocarpa	31.2 ±2.2	27.8/41.6	51.6 ±6.0	40.2/63.6	-20.4 ±5.6	-31.7/-9.9
Jacaranda mimosifolia	32.1 ±3.6	25.1/44.9	51.7 ±6.7	31.7/64.8	-19.6 ±5.9	-33.5/-6.6
Lagerstroemia	30.3 ±2.6	26.8/39.3	49.6 ±5.2	40.4/60.9	-19.3 ±4.6	-29.2/-10.6
Liquidambar styraciflua	30.3 ±3.0	25.3/38.8	51.0 ±6.7	40.4/62.8	-20.7 ±6.6	-35.9/-8.8
Lophostemon confertus	32.4 ±4.2	27.3/54.7	53.4 ±8.3	33.6/74.1	-21.5 ±6.5	-41.1/-9.7
Melaleuca quinquenervia	30.7 ±3.5	20.4/37.5	49.3 ±4.8	39.6/58.2	-18.6 ±5.4	-29.6/-10.7
Platanus acerifolia	31.8 ±2.8	26.2/36.7	51.2 ±6.3	35.1/61.5	-20.0 ±5.5	-30.0/-8.2
Pyrus calleryana	33.1 ±3.8	27.6/44.7	52.9 ±6.4	40.7/71.1	-19.8 ±6.2	-37.5/-9.5
Waterhousea floribunda	34.4 ±3.3	29.5/43.1	52.3 ±6.8	42.8/76.9	-17.9 ±5.5	-36.6/-7.5

Table S4: Tree species with their mean, minimum and maximum GT_S, GT_{SL} and ΔT_G.

Species	Mean GT_S±SD (°C)	Min /Max GT_S (°C)	Mean GT_{SL}±SD (°C)	Min/Max GT_{SL} (°C)	Mean ΔT_G±SD (°C)	Min /Max ΔT_G (°C)
Camphor laurel	35.2±2.9	30.5/44.5	43.9±3.6	33.7/54.1	-8.7±1.7	-13.3/-4.1
Casuarina equisetifolia	32.3±4.0	25.3/39.0	36.3±4.9	28.4/43.2	-4.0±1.6	-7.2/-3.1
Corymbia citriodora	34.2±1.8	32.8/37.6	37.5±2.2	35.9/41.7	-3.3±0.4	-4.1/-3.1
Eucalyptus saligna	33.2±1.9	29.2/37.0	37.7±3.1	32.3/42.0	-4.5±1.9	-7.2/-3.0
Ficus macrocarpa	37.7±3.3	32.1/41.9	41.1±4.5	35.2/48.2	-4.1±1.6	-7.3/-3.1
Jacaranda mimosifolia	34.8±1.9	32.4/39.8	38.8±2.6	35.6/44.1	-4.0±1.1	-7.3/-3.1
Lagerstroemia	31.8±1.3	30.4/35.7	35.5±2.2	33.6/41.2	-3.7±1.2	-7.3/-3.0
Liquidambar styraciflua	33.4±2.5	30.3/40.8	38.1±3.2	33.4/45.1	-4.1±1.5	-7.1/-3.0
Lophostemon confertus	34.7±3.5	29.9/40.9	38.9±4.3	33.0/47.1	-4.2±1.5	-7.3/-3.1
Melaleuca quinquenervia	32.1±3.4	29.9/40.2	35.8±4.1	33.0/43.8	-3.7±1.2	-7.3/-3.1
Platanus acerifolia	34.8±2.8	29.4/40.1	39.4±4.1	32.5/47.3	-4.6±1.8	-7.3/-3.1
Pyrus calleryana	36.3±2.9	31.1/43.0	46.2±3.5	34.2/58.3	-9.9±1.3	-10.9/-8.9
Waterhousea floribunda	37.0±2.5	32.6/43.1	41.4±3.1	35.8/47.4	-3.6±1.2	-7.2/-3.1