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Urban Heat Islands: differentiating between the benefits and drawbacks of using native or exotic vegetation in mitigating climate

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Urban Heat Islands: Differentiating between the benefits and drawbacks of using native or exotic vegetation in mitigating climate.

By

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B. MarSc

This thesis is presented as part of the requirements for the Award of the Degree of Master of Science (Research) From the School of Biological Sciences University of Wollongong

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LIST OF ABBREVIATIONS

BOM: Bureau of Meteorology
EPA: Environmental Protection Authority
ETE: Extreme temperature event
IPCC: Intergovernmental panel on climate change
MSR: Modified simple ratio
NDVI: Normalised difference vegetation index
NDWI: Normalized difference water index
PBR: Population Reference bureau
RMS: Root mean square
SAVI: Soil Adjusted vegetation index
TDVI: Transformed difference vegetation index
TIR: Thermal infrared thermometers
TOA: Top of atmosphere
UHI: Urban heat island
UN: United nation
UNFPA: United nations population fund
USD: United States Dollar
ABSTRACT

The urban heat island (UHI) effect is one of the main weather phenomena to affect urban areas. The main cause of an UHI is the absorption of heat energy by urban structures which is then later radiated back into the environment. This slow release of heat keeps the urban area at a higher temperature compared to the surrounding rural/native habitats. The increase in temperature poses some social, economic and health related concerns. With over three billion people living in urban areas, there has been a lot of research into the effects of UHI on humans as well as the environment and methods used to ameliorate them.

Vegetation based strategies are one of the most common and widely used mitigation strategies used today in almost all cities. This is mainly due to not only its ameliorating effect towards the UHI but also due to it being easy to implement in established cities as well as its additional benefits such as increasing aesthetics of an area.

This thesis investigated whether there was an advantage or disadvantage of using exotic vegetation over native vegetation in green city plans for the Illawarra region. Initially I explored whether historical Landsat imagery could detect a relationship between land cover change and plant stress after a heat event along an urban gradient. While there were indications of stress along the urban gradient, the methodology did not show any correlation suggesting that further data or an alternative approach were needed. It highlighted the reduction of vegetation along an increasing urban gradient with all the indices used picking out the change.

Two field based experiments were then carried out to compare native and exotic vegetation at a local level. The ameliorating effect of native and exotic trees was compared using an IR imaging camera. Surface heat under trees was measured on hot (27-35°C) and normal days (18-24°C) and compared between native and exotics. There was a difference between exotic and native vegetation in their ameliorating effect and this effect varied over season and prevailing temperature. The results suggest that there is some characteristics of trees that affect the surface heat under its canopy for example density of the shaded region under the tree. The second experiment compared whether native or exotic vegetation was better adapted at surviving increasing temperatures. This was done by comparing the spectral
signatures of native and exotic vegetation in two seasons; spring (normal/average temperatures) and summer (hot temperatures). Native and exotic vegetation exhibited different responses to increasing temperatures. Exotic vegetation experienced higher water stress in response to increasing temperature and a subtle change in the composition of leaf pigments whereas native vegetation was less pronounced. The loss of water specifically for exotic vegetation was attributed to an adaptation where the tree uses water to try and buffer against the onset of extreme heat stress.

Finally a lab-based experiment was conducted to identify whether vegetation undergoing heat stress expressed any diurnal recovery or any adaptations to reduce heat stress during an ongoing heat event. Forty eight trees (24 native and 24 exotic) were placed in temperature cabinets and an eight day heat event was induced (4 days of 30°C and 4 days of 35°C). On each day during the day and night spectral signatures of 2 leaves per tree were collected and analysed for stress using stress indices. What was found was for the control, t1 and R temperature there was no diurnal recovery however for T2 exotic vegetation did exhibit lower stress levels during the night. The results suggest that native vegetation have an advantage over exotic species in ameliorating the urban heat effect as well as in their ability to cope with heat stress.
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CHAPTER 1: GENERAL INTRODUCTION

1.1 Introduction

In a review released by the United Nations in 2011, it was estimated that over 50% (3.4 billion) of the world’s population was concentrated in cities and urban areas (United Nations 2011). In the more developed nations the percentage was close to 74% of the population living in urban areas (PBR 2011). These numbers are expected to rise significantly as developing nations advance, and build industries which cause people to move from rural areas to towns and cities for work and better opportunities (United Nations 2011; PBR 2011; Nations 2008). With so many people living in urban areas there has been an increasing focus on improving and maintaining the standard of living in these areas (UNFPA 2007; PBR 2011). Maintaining and improving the standard of living in an urban area is closely linked to the ecosystems in, and around, the urban environment (Alberti 2010; Coutts et al. 2010). However with a dynamic global environment associated with factors such as climate change, maintaining urban areas has become more difficult (Pickett et al. 2010; Memon et al. 2010; Li et al. 2009). One of the main issues in maintaining urban areas that has recently become more prominent in the wake of global warming is the urban heat island (UHI) phenomenon. The aim of this review is to present a review of the literature that is available on the factors that affect UHIs and the methods being employed to mitigate them. There will be particular focus on the most significant findings and gaps in the literature to try and highlight future research areas in the field.

1.2 Urban Heat Island (UHI)

![Anthropogenic surfaces absorb and retain more heat when compared to rural areas leading to higher temperatures along an urban gradient.](image)

Figure 1: Anthropogenic surfaces absorb and retain more heat when compared to rural areas leading to higher temperatures along an urban gradient. Adapted from urban heat island, EPA 2009.
The UHI is the term given to urban areas which are significantly hotter than the surrounding rural habitats (Figure 1). The phenomenon was initially identified when temperature discrepancies between urban areas in southern Singapore and surrounding rural areas were measured (Nieuwolt & Geog 1966). The process of urbanization results in a change of land surfaces and topography; natural surfaces such as soil and vegetation are replaced with anthropogenic surfaces such as asphalt and concrete which have better thermal properties such as heat absorption. This change in surface type is one of the main factors in the formation of UHIs where cities form hot spots (islands) in a landscape and where natural surfaces create a cooler environment (Figure 1). UHIs are associated with all cities and developed areas, however the intensity of the effect can vary significantly. For example, in Oman, the temperature difference between the UHI and surrounding areas varied both with time of day and season (Charabi & Bakhit 2011). During summer, the difference between rural and urban areas was 0.5°C – 4°C, whereas, during winter, this difference was between 0°C - 1°C (Charabi & Bakhit 2011). There is also a lot of variation within urban centres. Nyuk Hien Wong & Yu (2005) found a temperature difference of 4°C between the vegetated and urban districts within Singapore. Larger cities have a greater temperature difference from their surroundings (Tran et al. 2006) and city can be 1°C to 7°C warmer than surrounding areas (Memon et al. 2008). A temperature change of a few degrees can have a dramatic influence on people living in the urban area and the environment. Before going into the factors that influence a UHI, it is important to understand how a UHI is formed.

1.3 UHI formation

An UHI is formed when attributes of an urban environment aid or induce the retention of heat in the area. This heat retention can be achieved from two sources: surface heat (Rosenzweig & Solecki 2006) and atmospheric heat (Oke 1997).

1.3.1 Surface heat

Surface heating in cities is caused when the sun heats up an area through direct radiation of energy. The incoming solar energy (Figure 2) is absorbed and stored efficiently by manmade surfaces such as asphalt and roofing tiles, heating them and storing the heat energy (Rosenzweig & Solecki 2006). On average, surface heat ranges from slightly above air temperature in the shade to between 1 to 20°C above air temperature in sunlight, depending on the intensity of sunlight and material properties (Rosenzweig & Solecki 2006; EPA 2008). The heated surface transfers heat via convection to the surrounding environment. For
example, a brick building that has been heated by the sun all day will continue to release its stored heat for a long time after the sun has set and keep the surrounding area warmer than it would have been without this heat source. Release of heat to the surroundings leads to secondary heat retention (EPA 2008).

Figure 2: Spectral radiation of the sun that reaches the earth’s surface. The blue line indicates the radiation that reaches the earth outside the atmosphere. The red line indicates the radiation that reaches the earth’s surface after interacting with the atmosphere. Source: adapted from nanopedia.case.edu accessed on 20/11/2011

Akbari et al. (2001) explored the relationship between surface heat and electricity demand. Over the past 100 years, temperatures of different cities in the USA have increased by 3°C and the energy consumption due to this increase has been 5-10% higher. They concluded that a change to surfaces with higher reflection could save 10 billion USD per year in energy use alone.

1.3.2 Atmospheric heat

Atmospheric convection is caused by hot objects in urban areas radiating heat (Velazquez-Lozada & Gonzalez 2006). This does not have to be a surface heated by sunlight; the heat can also be from waste gases from cars, factories and steam from power plants (EPA 2008). The atmospheric heat can be measured up to 1km above the urban area (Velazquez-Lozada & Gonzalez 2006). Atmospheric temperature is highly dependent on weather, time of day and wind conditions in an urban environment (Memon et al. 2008). Typically, the effect is weakest in the early hours of the morning when the heat sources have expended all their heat from the previous day and builds up during the day to its highest point after sunset when the
heat sources keep the urban area warm. After sunset, rural or native areas cool. The temperature difference between native and rural areas for atmospheric temperatures is much less when compared to surfaces temperatures. While surface heat might be 20°C warmer, atmospheric heat is rarely more than 7°C higher surrounding rural areas.

1.4 Significance of UHIs

With average temperatures rising by a degree in the 20th century and conservative models predicting a 1-2°C change in temp by 2050 as well as an increase in the frequency/ intensity of extreme temperature events (Randall et al. 2007), there has been rising concern on how this temperature will affect our urban environments, especially how the increased temperature and extreme temperature events will interact with UHIs (Coutts et al. 2010; Alexander & N Tapper 2009). The detrimental effects of an UHI can be broken down into 3 broad categories; health, economic and environmental.

1.4.1 Health

Extreme heat can lead to heat-related stresses on inhabitants, such as, but not limited to, heat stroke, sun burn, heat cramps, dehydration and heat-related mortality. Every year, there are thousands of deaths around the world that are related to heat (Keating 2003; Argaud et al. 2007; Keatinge et al. 2000; Semenza et al. 1996; Loughnan et al. 2010). Even more concerning is that there are already signs that the interaction between extreme temperature events and UHI can have serious consequences for inhabitants. The whole of Europe experienced a severe heat wave in the summer of 2003 that resulted in 50,000 deaths. Argaud et al. (2007) investigated how heat stroke or exertional stroke played a role in deaths of thousands during the heat wave and identified that it continued to affect inhabitants up to 2 years after the event (breathing disorders and need for institutional help that was not required before the heat wave). Semenza et al. (1996) studied the 1995 heat wave in Chicago which resulted in 700 deaths mostly heat-related. Inhabitants with medical problems and the elderly were most at risk.

Both studies outline the risk of heat in urban areas on inhabitants, however, the UHI also induce other health-related effects such as the development of photochemical smog. The heat promotes the evaporation and aerosolizing of volatile compounds from surfaces and facilitates the mixing of these compounds with pollutants. This smog can then adversely affect inhabitants with respiratory diseases/distress related problems such as asthma. (A. H. Rosenfeld et al. 1995)
1.4.2 Economic

Increasing heat in an urban centre leads to increased energy consumption as air conditioners work against an ever larger heat gradient to keep buildings at optimal temperatures for the inhabitants. Ca et al. (1998) estimated that parks help reduce the atmospheric temperature within 2km around the park by 1.5°C which saves 4000 kWh of electricity or US$ 650 per hour. Akbari & Konopacki (2005) estimated that UHI reduction strategies can reduce house energy loads from 200 - 1200 kWh. UHIs also affect an area indirectly. Payton et al. (2008) found that UHIs affect the real estate value of a city. Unpleasant hot conditions as well as increased electricity costs per year dissuade possible inhabitants.

1.4.3 Environmental

UHI can cause a host of environmental problems they decrease air quality and promote the formation of smog and can influence local weather by increasing humidity, precipitation rate (rainfall intensity and duration) and affecting local wind patterns. Bornstein and Lin (2000) study found that in 1996 the UHI effect over Atlanta initiated 3 different storms and increased the precipitation over the city. A later 5 year study (Dixon & Mote 2003) found that there were 37 UHI initiated precipitation events in Arizona.

UHI also affect the surrounding ecosystems and wildlife; the increased heat and changing precipitation patterns can make vegetation prone to fire and can push species outside their thermal tolerance range (Valle-Díaz et al. 2009). Another major environmental concern is the degradation of water quality by thermal pollution due to surface heat. Rain water that falls in the city does not seep into the ground but runs over anthropogenic surfaces that are usually impervious to water and at higher temperatures, picking up addition heat loads, dust and chemicals (Finkenbine & Atwater 2000). This water can be dumped into rivers and streams increasing the water temperature (Krause & Lockard 2007) affecting the life cycles of organisms living in the stream/river. For example, stenothermal fish require a specific temperature range. Selong et al. (2001) found that bull trout require specific temperatures to spawn and as temperatures increased above 20°C both adults and juveniles were negatively affected.

With all these consequences it is important that we learn to control the development of UHIs. In this next section, I focus on the factors that affect UHI and the process/methods that have been put in place to help reduce the effect of urban heat.
1.5 Factors that influence urban heat islands

The factors that affect UHIs can be split into 2 groups; controllable and uncontrollable (Memon 2008) (Figure 3).

![Diagram of factors influencing urban heat islands](image)

Figure 3: Factors that influence the intensity and formation of urban heat islands. The factors are split into 2 groups’ factors that can be managed or controlled using schemes and adaptations to urban environments and factors that cannot be controlled e.g. weather. (figure adapted from Memon et al. 2008)

1.5.1 Vegetation

Vegetation plays an important role in controlling the temperature of an area (X. Zhang et al. 2009; X. X. Zhang et al. 2010; Mirzaei & Haghighat 2010). Rural or non-urban environments are normally covered with vegetation that helps maintain the temperature in two important ways: through shade and evapotranspiration. Shading lowers surface temperatures by reducing the amount of incoming solar radiation that hits the surfaces below the tree. The leaves on the trees have a higher reflectance rate compared to manmade surfaces. Only 30% of the sun’s energy reaches the ground surrounding the tree, as the rest is either absorbed by the tree or reflected back to the atmosphere (EPA 2008). (Scott et al. 1999) showed that difference in asphalt temperature between a shaded and un-shaded region can get up to over 20°C and shading a parking lot reduced any parked car’s internal temperatures by up to 40°C.

The second way in which trees affect temperature is through the process of evapotranspiration. Trees use evapotranspiration to primarily draw water up from the roots to the leaves where it is needed for photosynthesis. Evapotranspiration is also one of the
mechanisms by which a plant can thermo regulate itself by converting water to water vapour dissipation the stored heat (Taha 1997). Surface air temperature in the canopy was 1 to 2°C cooler than surrounding air temperatures (Kurn et al. 1993). Evapotranspiration not only reduces the heat build-up in an area, but also reduces the amount of runoff water around the plant.

1.5.2 Materials

The composition of an object plays an important role in how an object interacts with incoming radiation from the sun. Most of the sun’s energy reaching the earth comes in the visible and infrared part of the spectrum (Lean 1997) (Figure 2). Incoming IR radiation is responsible for heating surfaces and objects (Golden & Kaloush 2006; H Akbari et al. 2001; Kikegawa et al. 2003). Material properties such as solar reflectance, heat release (emissivity) and heat capacity determine how material deals with heat.

Solar reflectance, or albedo, is the amount of incoming energy that is reflected by the object. Objects with high solar reflectance reflect most of the incoming heat energy and hence less heat is stored in the object (Chudnovsky et al. 2004). Light coloured objects reflect more visible energy when compared to dark objects (Chudnovsky et al. 2004). For example, a white roof will reflect most of the incoming visible energy from the sun while a black roof will absorb most of the incoming visible energy from the sun (Figure 4).

Asphalt or concrete have a solar reflectance of somewhere between 5 to 50% which means up to half of the incoming energy is stored in the material as heat (EPA 2008; Levinson & Hashem Akbari 2002). The range of reflectance is high because all building surfaces change over time and surfaces collect dust (concrete), becoming darker and reducing the albedo (Levinson & Hashem Akbari 2002).
Emissivity is the rate at which an object releases its stored energy. An object with high emissivity will radiate more heat per unit of measure when compared to an object with low emissivity at the same temperature. Emissivity also plays an important role in determining the thermal equilibrium of an object. An object is in thermal equilibrium when the absorbed heat energy is equal to the radiated heat energy, hence the object does not gain or lose any heat and the temperature of the object remains stable. High emissivity in an object is a good attribute to reduce UHI due as it reaches its thermal equilibrium at lower temperatures. There is very little research done on emissivity as most building materials have an inherently high emissivity with the exception of metals (Figure 4). In most of the newer building procedures modified alloys or metals that have a higher thermal emissivity are used. For example, anodized aluminium is being used for window frames to help reduce heat build-up around windows.

The heat capacity of an object is closely related to its emissivity and is the amount of heat an object can store. Most building materials have a higher heat capacity when compared to soil or natural materials. Native soil and vegetation readily lose their heat when the sun goes down, whereas, urban materials have a much larger storage of heat and take longer to lose their heat; leading to higher night-time temperatures. Temperatures in the early mornings in
Melbourne CBD be 4°C warmer than the surrounding rural areas just before sunrise (Torok & Morris 2001).

1.5.3 City structure

Urban geometry affects UHI indirectly by determining how materials and anthropogenic heat contribute to the UHI. The urban landscape dictates how wind flows through the city, how much solar radiation a surface receives and a surfaces ability to emit radiation back into space. A good layout with a lot of space among buildings will allow good airflow between buildings, reducing the formation of atmospheric heat islands. A dense city will cause anthropogenic heat, as well as heat released from surfaces, to be trapped in the city increasing the heat. The low air movement also means that ground level ozone and other chemicals released into the air do not get purged and collect in the city forming smog. City structure also plays an important role in how surfaces release their heat (figure 6) and emphasises the importance of planning. For example, in a dense city, surface heat on the ground such as roads and pavements cannot effectively release their heat out of the urban region because there is a small sky view from the ground. and physical objects such as buildings absorb most of the emitted heat from the ground, keeping the heat within the city (David J. Sailor & Fan 2002). In a well-planned city the increase spaces between the buildings will allow the surfaces to release radiation directly into space.

Figure 5: Red arrows symbolize long wave IR radiation released by buildings and roads which is then trapped in the city due to physical barriers such as buildings (Oke 1982)
1.5.4 Anthropogenic heat

Recently, anthropogenic heat has been recognized as an important factor that affects UHI (Taha 1997; Ferreira et al. 2010; Deque 2007). Anthropogenic heat includes heat from exhaust fumes from cars, factories and heat produced by the activity of people living in the area (cooking, air-conditioning, etc.). The waste heat increases atmospheric heat in and around the city. Kikegawa et al. (2003) found that a reduction in the waste heat of air conditioners could result in a temperature decrease of 1°C and an efficiency increase of 6%. Ferreira et al. (2010) investigated the anthropogenic energy flux in Sao Paulo and found that human metabolism resulted in 9%, vehicular sources resulted in 50% while stationary sources, such as air conditioners, resulted in 41% of anthropogenic energy.

1.6 Mitigation strategies

All the mitigation strategies focus on altering the controllable factors to try and influence the UHI effect. The 3 main strategies are green housing, urban trees and cool roof, road and pavement schemes that involve the use of materials with increased reflectance and high emissivity.

1.6.1 Green roof schemes and urban trees

Of the controllable factors that influence UHI, vegetation is the one most used to try and mitigate UHIs in already developed areas (Scott et al. 1999; H Akbari et al. 2001; Sandifer 2002; X. X. Zhang et al. 2010). Most of the methods involve growing trees on or around man-made structures (H Akbari et al. 2001; Sandifer 2002; A. H. Rosenfeld et al. 1995). The green roof scheme being developed in USA, China, UK and Australia concentrates on growing plants on the roofs of houses and buildings to increase their solar reflectance and reduce the heat that the house/building absorbs directly. Planting urban trees increases the greenness of an urban environment.

Both schemes offer direct benefits of reducing surface temperature due to shading, however, they also reduce air temperature due to transpiration, improve water quality by providing areas in which water can drain into the soil and also reduce smog and dust pollution. While the cost of planting and maintaining the trees can be high, they can offer some serious savings in terms of electricity usage. Vines covering a wall help reduce its temperature by 20°C (Sandifer 2002). Sailor (2008) simulated the same scenario using a computer model and found an increase in soil thickness increased insulation which reduced both heating and cooling demands throughout the year. Furthermore, while increased vegetation density
reduced electricity usage during summer by reflecting solar radiation. The benefits of trees are not only expressed during the hotter months but also during winter where the trees provide a wind shield for the house reducing heating energy required in the house. Akbari & Taha (1992) studied the effect of wind shielding in 4 Canadian cities and found that the shielding effect reduced the heating electricity usage by 10 to 15%.

Planting urban trees reduces the carbon footprint and air pollution and increases aesthetics of the location, and can reduce the crime rate in areas. Donovan & Prestemon (2010) investigated 2,813 single family homes to try and determine the relationship between trees and crime rate. They found that while view-obstructing trees increased crime, larger trees resulted in reduced crime rates.

While green city plans are extremely common and beneficial there are some issues that must be addressed. The main issue is proper species selection; areas with dry climate should avoid trees that require abundant water and stick with more drought resistant species. Pataki et al. (2011) used sap flow sensors to measure the water use, it was found that different species had a wide range of water use. While species such as Plantus hybrid used 176.9 ± 75.2 kg tree⁻¹ d⁻¹, Pinus canarienis only used 32 ± 2.3 kg tree⁻¹ d⁻¹. Planting trees under power lines or with water pipes under them may cause issues if larger species are planted, Some trees emit volatile organic compounds that might add to the smog and affect people with respiratory diseases.

1.6.2 Cool roofs, roads or pavements

Most of the research in mitigating UHI through the manipulation of material properties has focused on increasing the reflectance of objects. Most developed counties now employ cool materials in their new developments. Cool roof schemes are designed to reduce the amount of heat that is transferred directly to the building itself. A dark roof would absorb most of the incoming solar radiation. Heating the roof would heat the house as well as the air around the house, increasing energy consumption. Cool roof schemes focus on making roofs out of materials and colours that have a high albedo. Santamouris et al. (2011) found that houses with conventional roofing experienced a thermal range of 25°C during a typical summer day. This was reduced to a range of 8°C by using materials developed with higher reflectance. The use of high reflectance material does not necessarily incur a high cost. Bretz, Akbari, & Rosenfeld, (1997) found that there was little cost involved in converting traditionally built up roofs or single ply roofs to high albedo surfaces, as a pain coat or a lighter colour tile in the
case of single ply would increase the albedo. While albedo can be increased by lightening the colour, there are some anthropogenic materials that even when light, have a high solar absorption, e.g. asphalt. White asphalt absorbs 75% of incoming solar radiation due to asphalts inherently good thermal characteristics to absorb and retain heat (S. Bretz et al. 1998). Cool road schemes reduce the absorption of asphalt by using highly reflective aggregate in the asphalt. In most new cities, all new buildings, roads or pavements are built with materials that have qualities that help reflect the radiation. New light coloured pavements have a reflectance value of over 75%, reducing heat build-up (Garber et al. 2011) While some of these schemes do incur an initial steep cost there is also a lot of economic incentives to change.

There is abundant data on the energy and economic benefits of cool material schemes. Akbari et al. (1997) studied the shading effects of trees on 2 households by collecting temperature data from both inside and outside the house as well as the roof. They also collected electricity usage for cooling appliances such as the air conditioner. The change in microclimate due to applying high albedo coating resulted in an 80% saving daily and a 25% reduction in peak power usage. Parker & Barkaszi (1997) modified the roofs of residential buildings with high albedo coatings and found an average saving of 7.4 KWh/day with a reduction in energy used by air conditioners ranging from 2% - 43%. They also found that the savings were related to how well the houses were insulated, whether they had attics and location of the ducting.

1.7 Assessment and conclusion

While all these factors are important to mitigate the urban heat island effect, only vegetation schemes such as building green roofs and creating green cities are feasible for already developed metropolitan cities. The schemes can be developed and built around already existing infrastructure hence reducing the UHI effect without changing the structural elements of the city. Newer cities and urban areas can be built with UHI mitigation features, such as, increased vegetation in the area and construction material that has increased reflectance and emittance. Proper planning of newer cities can prevent dense stagnant cities and promote air flow. The reduction in temperature not only has some health benefits, but also huge economic benefits. H. Akbari & Konopacki (2005) reported that with the introduction of UHI mitigation measures, it was possible to reduce the energy output of Houston by 700 MW which equates to around 80 million US dollars annually. Another study by Akbari (2005) used computer models to simulate the electrical savings due to street trees and cool surface schemes. He estimated that both schemes when fully implemented would
save around 100 US dollars annually per house which would amount to 5 billion US dollars annually per year in the whole of the USA. With global trends of increasing energy consumption during summers and increasing electricity prices, it has become a necessity to mitigate UHI. Adapting cities to mitigate UHI not only equates to tremendous savings, but also helps reduce the carbon footprint of urban centres. In addition, it serves to maintain a high quality of life and protect surrounding ecosystems which will be important if our population continues growing as it has for the past 50 years. Despite this, there is a need for more specific research in different cities to understand the mitigating effects of these schemes.

This thesis, focused on vegetation-based mitigation of the urban heat island as it is one of the most easily implemented schemes in already populated urban areas. While the benefits of these schemes are significant, there are some gaps in the literature that were addressed to help improve understanding on how to improve vegetation-based activities. The underlying question that was attempted in this thesis was; is there any advantage of using native vs. exotic vegetation in the mitigation of UHIs. Exotic trees such as Liquidambar spp. and the Plantanus spp. are commonly used as shade trees due to their broad leaves and large canopies which make them excellent trees at providing shade, while native vegetation provides an added benefit of enhancing/sustaining the biodiversity of the area by supporting native insect and bird species that depend on native species of trees for some aspect of their life (McKinney 2002). However it is also important to take into consideration the predicted effects of global warming, specifically extreme temperature events, as these events can displace currently used urban tree species that are acclimatized to such environs. Extreme temperature events also increase the risk of using native species due to their susceptibility to fire.

My thesis investigated the following.

- Chapter 2- Introduction into plant stress and spectrometry, comparing stress levels of native and exotic vegetation during extreme temperature events using satellite-based spectral data (Landsat thematic mapper)
- Chapter 3- Investigating the difference in the amelioration effect between native and exotic street trees of surface heat islands using thermal imaging
• Chapter 4 – Using leaf spectral data in a field based and controlled laboratory-based setting to determine, whether native or exotic vegetation are more resilient to increased temperatures.
• Chapter 5- Overall discussion and conclusion, will tie in all chapters into the broader context and discuss the main findings of this thesis.

Each chapter has been formatted for submission into journals and there may be slight repetition of methods and introduction. Chapter 4 contains two different experiments that were condensed into one chapter to avoid excessive repetition.

CHAPTER 2: THE EFFECT EXTREME HEAT EVENTS ON PLANT STRESS IN THE ILLAWARRA

2.1 Abstract
The study investigated the interaction between extreme temperature events (ETE) and stress levels of plants. Bureau of Metrology weather data was used to identify days of extreme temperature (>35°C) and normal days (22-25°C) and remotely sensed data (Landsat images) was compared for these groups. Four extreme temperature days were compared to four random normal days over four different habitat types that represented an urbanized gradient. The habitats were classified using aerial images to identify the amount of vegetation in each of the sites. Five different indices were used to calculate a measure of vegetation stress. The response of vegetation stress to temperature over different habitat types was not significant; however, all indices did show a significant difference between habitat type and greenness. The effect was most pronounced in the NDWI index which was able to detect a change in water levels in plants between hot days and normal days over all habitat types. It was concluded that while ETE might have a significant effect on plant stress levels, there are other factors such as water availability and plant condition that act as a buffer against heat stress.
2.2 Introduction

Over the last 20 years, there has been a small but constant change in climate globally (temperature precipitation etc.) (Colombo 1999, IPCC 2007). While ecological communities and human society can adapt to these small changes in climate (Jump 2005, Woodroffe 2007 and Hughes et al. 2003), it is the extremes of climatic conditions that have the greatest impact on ecosystems and human society (Bassow 1994, Meehl 2004, Luber 2008). In recent years there has been a marked increase in the number, duration and intensity of extreme temperature events (X. Xu et al. 2011; Brunetti 2004). With modeling suggesting that extreme temperature events will become ten times more frequent by 2070 (Deque 2007), there has been an increased focus into understanding how extreme temperature interacts with human activities and with ecological communities.

2.2.1 Extreme Temperature event (ETE)

A weather phenomenon at the extremes of the historical climate distribution of an area is termed an extreme temperature event (IPCC 2001). The IPCC classifies extreme temperature events as events that are extremely rare and occurs only 5% of the time (Figure 6). However with anthropogenic factors such as greenhouse gasses and urban heat islands influencing climatic patterns, temperatures classified as extreme temperature events (ETEs) in the past might be normal temperature days in the present or future due to a shift in the mean climatic temperature of the area (Figure 6a). This makes past and current ETEs a valuable source of information when trying to understand the effect future climatic change will have on human and natural communities.
In the context of this study, I will be focusing on extreme temperature events with a higher than average temperature. The Australian Bureau of Meteorology classifies an extreme heat event as 3 consecutive days with temperatures over 29°C for the Wollongong region.

2.2.2 Consequences of Extreme Heat Events (EHE)

Extreme heat events can have serious consequences (Argaud 2007, Dematte 1998). The heat wave that Europe experienced in 2004 resulted in over 14 thousand deaths in France alone (Argaud 2007) and the 1995 heat wave in the Chicago USA resulted in 750 deaths over a 7 day period (Dematte 1998). In these cases the majority of deaths/damage occurred in heavily urbanised areas. The main reason for this is the compounding effect that urban heat islands (UHI) have with an EHE. In an UHI the change in surface structure from native to man-made building surfaces such as asphalt and concrete leads to a build-up of heat that can be from 1-
20°C hotter than the surrounding native regions (HARC 2009). ETE’s also have detrimental effects on plant and animal communities (Wollenweber 2003, Mills 2009). Plants and animals may be pushed out of their temperature range resulting in increased stress levels and death (Wahid 2007). In Melbourne 2009, vegetation in and around the CBD experienced extreme heat mortality due to temperatures above 40°C that lasted 4 days.

2.2.3 Plant heat stress

For a plant, heat stress occurs when the increase in temperature is detrimental to either plant function or development (Hall 2001). The level of heat stress depends on the intensity, duration and the rate of temperature increase (Wahid 2007, Hall 2001). For a plant as a whole an increase in temperature increases the evapotranspiration rate of the plant (evapotranspiration is one of the mechanisms by which a plant regulates its temperature). This leads to increased water use and eventually water stress. At a cellular level heat affects photosynthetic cells by disrupting the process taking place in photosystem II (PSII) causing rapid reprogramming of cellular activity to ensure cell survival. Heat also affects membrane function and increases fluidity in cells affecting stomatal control as well as transportation of vital nutrients around the plant (Farquhar & Sharkey 1982). At temperatures over 45°C tissue death takes place with the denaturing proteins in cells and lipids in cell membranes (Timperio 2008). The increased heat can also affect the plant function by pushing the enzymes found in the chloroplasts and mitochondria outside their temperature range. This will inhibit protein synthesis leading to both loss of function, development and eventually plant death (Wahid 2007). Elevated temperatures can increase transpiration (Calvet 2008, Riederer 2001), increasing water loss reducing turgidity and plasmolysis of cells. Heat stress is also closely related to water stress due to the increased loss and use of water.

2.2.4 Remote sensing to detect plant stress

The randomness and the low rate of occurrence make EHEs hard to track or predict. Most studies of plants are laboratory-based where the plants are put under specific EHE conditions and their responses are recorded. Remote-sensing can provide a useful tool for measuring landscape responses to EHEs. Multi/hyper spectral sensors are able to determine plant stress levels by recording changes in leaf reflectance in the visible and IR regions of the spectrum caused by stress (BOM 2011, Kidwell 1997).
Plants absorb most of the visible part of the spectrum for photosynthesis except for green light which is reflected (Huete 2006). Different forms of chlorophyll absorb different parts of the visible spectrum. For most plants visible energy with the wavelength of 680nm to 700nm (red light) and 440nm-460nm (blue light) is the most important as it is the peak absorption points for the plants photosystems PSI and PSII (Figure 7) (Paul 2011). These photosystems play a key role in the synthesis of ATP which is important for plant growth and function. The mesophyll layer in plant leaves reflect most of the incoming infrared radiation (Woolley 1971) (Figure 7). The behavior of a plant to a stress event and how this is manifested in the spectrum, allows for the use of remote sensors to detect how vegetation responds to heat stress (NASA 2011b). A healthy plant will absorb most of the blue and red part of the spectrum and reflect most of the incoming IR energy, however a stressed plant will have a lower number of chloroplasts hence absorb less blue and red energy and a lower amount of IR radiation will be reflected due to the changes in cell structure (Huete 2006, NASA 2011b). This change in cell structure is mainly due to the death of plant tissue or due to the reduction of water content.

Remote sensing data can also be used to distinguish among different types of plant species due to differences in the chlorophyll, cell structure and moisture level between plant species. E.g. wheat has lower moisture content in its mesophyll layer compared to a large deciduous tree resulting in a change in NIR reflectance between the 2 species (Figure 7). Indices are normally used different parts of the spectrum to define how the spectrum changes in response to a stress or treatment. In this experiment most of the indices will show an increase in value as stress increases except NDWI, SAVI and NDWI which will show a decrease.

Figure 7: Solar absorption of different plant species. Highlighting the different absorption troughs in the visible, near infrared (NIR) and short wave infrared (SWIR) (picture from mission science NASA, accessed on 12/04/12)
This ability to distinguish healthy and stressed plants of different species makes collecting data on EHE using remote sensing a valuable tool in understanding the dynamics of how different plants interact with ETE. This study tested if short heat events (1-3 days) negatively affected vegetation.

Specifically I predicted that:

- Vegetation will suffer from heat stress after an extreme temperature event.
- Vegetation from different habitats along an urban gradient will vary in heat induced stress levels after an extreme temperature event due to the interaction between the extreme temperature event and the UHI

2.3 Methods

2.3.1 Study area

Figure 8: The study area was the Illawarra region, NSW, Australia. (Source: true colour composite, RBG321 of 2/3/2011 Landsat7 image downloaded from GLOVIS)
2.3.2 Identifying ETE

Extreme temperature events were identified using weather data from the Bureau of Meteorology website. For the 7 year period (2003-10) all days with temperatures over 35°C were recorded. A seven year time period was used during this time period the urbanisation and structure of Wollongong and the surrounding suburbs have remained roughly the same for the past 7 years (this check was done using the historical image viewer in Google earth).

2.3.3 Image acquisition

Landsat 7 was used as the source of spectral information due to its fine spatial resolution (30 metres) which was beneficial to observe different conditions over an urban gradient as well as its relatively good temporal resolution of 16 days and historical database which allowed for a historical record of extreme temperature events. The Landsat satellite is a multispectral sensor which has spectral coverage over 0.45nm and 2.08nm (Band 7 the thermal band covers 10.4-12.5) which is required for the processing of different vegetation indices. Most of the newer sensors lacked historical databases and MODIS was not used due to its large spatial resolution.

For each ETE day identified during the time period, the Landsat database (GLOVIS) was checked to determine if there were any images without cloud. Any images found within 3 days after an extreme temperature event were selected (provided there were no more temperature events in the intervening 3 days). These days were then checked against rainfall data from the BOM website (Australian Bureau of Meteorology (BOM) 2012) to ensure that none of the plants were under drought stress conditions. The criteria for this were that the ETE days had to have at least (18mm) rainfall in the 14 days before the ETE. Two of the extreme temperature days were eliminated due to drought condition. There were 4 ETE days identified that matched these conditions. Images for 4 random normal days (average temperate) were also collected. All the normal days were days with clear weather conditions and temperature between 20°C and 25°C (Table 1).
Table 1: Dates when extreme temperature events (ETE) occurred and the first Landsat images that were collected after the ETE. Rainfall is the sum of all the precipitation for a week before the Landsat image.

<table>
<thead>
<tr>
<th>ETE/Normal</th>
<th>Date</th>
<th>Temperature (max temp of 3 days before image)</th>
<th>Landsat image</th>
<th>Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETE</td>
<td>11/10/2004</td>
<td>34.4°C</td>
<td>11/10/2004</td>
<td>61 mm</td>
</tr>
<tr>
<td>Normal</td>
<td>26/10/2004</td>
<td>23°C</td>
<td>27/10/2004</td>
<td>191.8 mm</td>
</tr>
<tr>
<td>ETE</td>
<td>22/09/2009</td>
<td>34°C</td>
<td>23/09/2009</td>
<td>18.6 mm</td>
</tr>
<tr>
<td>Normal</td>
<td>09/12/2009</td>
<td>25.3°C</td>
<td>12/12/2009</td>
<td>21 mm</td>
</tr>
<tr>
<td>Normal</td>
<td>10/09/2010</td>
<td>24.0°C</td>
<td>10/09/2010</td>
<td>22.4 mm</td>
</tr>
<tr>
<td>Normal</td>
<td>31/12/2010</td>
<td>28°C</td>
<td>31/12/2010</td>
<td>30 mm</td>
</tr>
<tr>
<td>ETE</td>
<td>01/02/2011</td>
<td>37°C</td>
<td>02/03/2011</td>
<td>61.3 mm</td>
</tr>
</tbody>
</table>

2.3.4 Image processing

Image processing was performed using the Exelis Visual information Solutions geospatial image processing and analysis package ENVI 4. The Landsat metadata images were directly imported into ENVI and each image was geometrically corrected by establishing ground points between an existing, previously corrected Landsat image of the area and the new images (image to image rectification). All the images were corrected to an RMS (root mean square) error of less than 0.2 ensuring all the images were geometrically positioned correctly. All the images were cropped to the study area to reduce post processing time. The Landsat 5 pre-processing calibration utility in ENVI was used to calibrate the images which converted all the images data from DN (digital number: radiation value) values to TOA (top of atmosphere) reflectance. The images were also atmospherically corrected using FLAASH atmospheric correction (Exelis: Visual information solutions ENVI) to reduce any atmospheric effect on the reflectance of the images. Both corrections used data such as sun angle and acquisition time which was found in the metadata files that accompanied the images. Five indices (Table 2) were applied to the images using the band math tool (ENVI).
Table 2: A list of the vegetation indices used and their corresponding formula as well as a brief description of each index. B1-7 correspond to satellite observation bands e.g. band 1 for Landsat TM collects data in the 0.45-0.52 nm region of the electromagnetic spectrum.

<table>
<thead>
<tr>
<th>Index</th>
<th>Formula</th>
<th>Description/reason for use</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDVI – Normalized difference vegetation index (Rouse et al. 1973)</td>
<td>$\frac{b_4 - b_3}{b_4 + b_3}$</td>
<td>Vegetation index, used to determine greenness/biomass in an area. Most commonly used vegetation index. Has an issue with oversaturation of greenness at high vegetation density.</td>
</tr>
<tr>
<td>NDWI - Normalized difference water index (Gao 1996)</td>
<td>$\frac{b_4 - b_5}{b_4 + b_5}$</td>
<td>Water index, used to determine vegetation liquid water levels. Used to map drought effects</td>
</tr>
<tr>
<td>MSR - Modified simple ratio (C. Wu et al. 2008)</td>
<td>[ \frac{b_4}{b_3 - 1}/ \sqrt{\frac{b_4}{b_3 + 1}} ]</td>
<td>A modification of the simple ratio of NDVI index. Unlike NDVI the MSR compensates for environmental factors such as soil and cloud By incorporating corrections for specular reflections and using bands in the red edge.</td>
</tr>
<tr>
<td>TDVI - Transformed difference vegetation (Bannari et al. 2002)</td>
<td>$1.5 \times \frac{b_4 - b_3}{\sqrt{b_4^2 + b_3^2 + 0.5}}$</td>
<td>Vegetation index. Addresses the problems NDVI has with saturation. This gives it a higher sensitivity in denser vegetation.</td>
</tr>
<tr>
<td>SAVI - Soil adjusted vegetation index (Huete 1988)</td>
<td>$1 + 0.5 \times \frac{b_4 - b_3}{b_4 + b_3 + 0.5}$</td>
<td>Soil-vegetation index, used to determine biomass/greenness in an area. Takes into account the effect of soil reflectance below/around the canopy being measured.</td>
</tr>
</tbody>
</table>
2.3.5 Urban habitats

Five different urban land classes were sampled in this experiment (Table 3). The land classes chosen represented an urbanisation gradient from highly vegetated to no vegetation at all. Using Google Earth, 4 sites for each of the land classes were identified by setting a 5km radius around each site and visually classifying each site a buffer of 3km was kept around each of the sites chosen to avoid sampling similar patches. For the older Landsat images e.g. 28/11/2004, Google Earth historical view was selected and the date set to 2005. This was done to ensure that the general classification that was done in Google Earth was done using images from time periods matching the Landsat images. Coordinate data, habitat type and vegetation cover were recorded for each of the sites.

Table 3: list of the land classes used in the experiment and their level of vegetation cover.

<table>
<thead>
<tr>
<th>Land Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal vegetation</td>
<td>Coastal vegetation consisting mainly coastal plants (all sites were dominated by mangroves)</td>
</tr>
<tr>
<td>Inland vegetation</td>
<td>Consisted of mainly trees with dense canopies</td>
</tr>
<tr>
<td>Urban</td>
<td>Very little vegetation – most sites had between 5-15% vegetation</td>
</tr>
<tr>
<td>Industrial</td>
<td>No vegetation</td>
</tr>
<tr>
<td>Suburban</td>
<td>Housing with large gardens and lawns 30-50% vegetation</td>
</tr>
</tbody>
</table>

2.3.6 Data Extraction

Using the GPS coordinate for each site the corresponding pixel on the Landsat image was located using the find pixel tool. To check that the GPS coordinates corresponded to the same sites on the Landsat image the cricket field in Wiseman’s park was used as a reference. The GPS data was taken for the cricket field from Google Earth and then checked against a native (3, 2, 1) RBG composite of the Landsat image.

In each of the land cover sites, 4 pixels were selected around the GPS marker using the ROI tool in ENVI. Each pixel represented an area of 30x30 metres hence each of the sites were 60*60 metres. Four pixels were used for each site as four pixels provided slightly more room for error (4 pixels will better encompass the required area compared to 2 pixels) especially when trying to match specific GPS coordinates of vegetated urban areas and suburban areas to the Landsat image. The 4 pixels were then averaged using the statistic tool and the index value for each site was recorded.
Overall 8 images were processed, 4 extreme temperature events and 4 normal days. On each of the images all 20 sites were identified (5 land classes, 4 replicates per land class) and the 5 indices were applied to each site.

The data was statistically compared using JMP statistical package (JMP®, Version 9. SAS Institute Inc.). Differences in indices were compared amongst habitat types and temperature using ANOVA where day was nested within temperature.

### 2.4 Results

All of the indices were able to distinguish between vegetated habitats and urban habitats (NDVI: $F_{4,40}=695.363$, $p=0.001$; NDWI: $F_{4,40}=231.91$, $p=0.001$; MSR: $F_{4,40}=157.19$, $p=0.001$; TDVI: $F_{4,40}=207.13$, $p=0.001$; SAVI: $F_{4,40}=104.48$, $p=0.001$). TDVI and NDWI expressed the highest change between urban and non-urban habitat cover, with NDWI expressing negative values for highly urban areas. NDWI was also able to detect a significant change in water content between hot and normal days over the different land classes ($F_{1,4}=0.433$, $p=0.0433$). Over the different land classes all showed a reduction in water content on hot days when compared to normal days.
Figure 9: Calculated index values for vegetation from Landsat images collected on hot and normal days along an urban gradient (habitat) between 2003-2010. Error bars are ± SD, n=4. For all indices except SAVI and NDWI an increase in value signifies increased stress.

2.5 Discussion

Using remote data, I was unable to detect any stress in plants following an ETE. This was unexpected as there has been plenty of evidence in the literature suggesting that plants are negatively affected by heat events (Ahmed 1993, Ismail 1999). For example Wang (2008) found that plant development was severely hampered by heat. He concluded that in the future with more intense heat waves occurring at frequent intervals plant growth would come under further strain. However he also found that many abiotic factors act as a buffer to heat stress. As plants are likely to vary in their response to ETEs, resilient species may have dominated in urban areas, masking the heat stress experienced by vulnerable species in the average index. Wollenweber (2003) found that different crops exposed to extreme temperatures during the reproductive cycle and growth cycles had varying responses from no effect to reduction in growth and yield. It is unlikely however that all vegetation in both urban and un-urban areas were acclimatized to high temperatures as a historical search for extreme temperature reveal that ETE are extremely rare in the Illawarra with only 7 over the last 10 years. At present there is little knowledge about how urban plants cope with ETEs.

Heat stress is likely to be relieved in many urban areas particularly where adequate rainfall or watering alleviates water stress. The rainfall in the Illawarra region is high (200-300mm) when compared to the Australian average. This rainfall may act as a buffer for most vegetation against heat stress, particularly if stored in lower soils levels and accessible to deeper plant roots. Furthermore, both the lack of regular intense heat events and the above average rainfall may mean that plants that are exposed to heat are normally in low stress.
condition leading to a greater lag response before the vegetation starts showing signs for heat stress. Chaves (2002) found that large trees can take up to 2-3 weeks to show any signs of stress. Although rainfall was accounted for in the preceding 3 days, it is almost impossible to estimate the level of water underground through remotely sensed data. Only one index, NDWI, captured a change as a result of ETEs. NDWI may indicate an increase in transpiration which can alleviate heat stress. In the Australian context most native plants have a high resilience to drought and extreme temperature. Bush fires and droughts are common environmental factors that Australian native plants are exposed to and have adaptations to deal with. There is abundant literature on how Forest fires and heat generated by these fires affect plants (Williams 1999, Pyke 2010) as well as the effects of drought on plants and their responses (Munns 2002, Munné 2004). Most native Australian plant life cycles revolve around forest fires and the plants have grown adaptations to help deal with the heat in forest fires that can reach 500°C (Gignoux 1997). Some of these adaptations include heat shock proteins (Timperio 2008) glossy leaves to reflect heat and waxy thin leaves that help reduce water loss through transpiration. This resilience towards heat and drought found in native Australian plants makes them better able to withstand heat events. However it is impossible to tell whether the plants in the pixels were native or exotic at this specific resolution (30m). If we were to assume that remnant areas are dominated by native vegetation and urban areas include natives and some exotic species, then the NDWI does point to a difference between native and exotics. Further investigation is needed at a finer scale to determine whether exotic species differ from natives.

This study would benefit from being undertaken in areas with lower rainfall, to investigate the patterns with a larger sample size. The sample size was restricted due to the low EHE frequency at the location (on average 1-2 per year), time restrictions on the availability of an image every 14 days and the lack of good imagery from Landsat (due to cloud cover and temporal problems). This variability of location specific conditions is one of the reasons why field based studies are so important to validate lab based experiments.

2.6 Conclusion

We found that there was a change in vegetation levels along an urban gradient that could be detected on satellite based spatial data. This type of data can be used for long term classification of an area to track the level of urban change or loss in remnant vegetation. We also found that there is a change in the NDWI value after a heat event that could reflect a reduction of water in canopies after a heat event. Further research is needed to try and
determine whether this difference in stress is due to a change in vegetation type or a response to the increased urbanisation. Another option would be to incorporate water stress with heat stress as the 2 are closely interrelated this will allow for a larger sample size due to not having to account for rainfall.
CHAPTER 3: URBAN HEAT ISLANDS: A COMPARISON OF THE AMELIORATING EFFECTS BETWEEN NATIVE AND EXOTIC STREET TREES.

3.2 Abstract
With over 3.6 billion people living in urban environments it has become increasing important to mitigate factors that negatively influence the urban environment. Green plans and green roof schemes have become increasingly popular over the last decade in combating the increase in temperatures associated with urbanisation, known as the urban heat effect. In this paper I look at differences in using exotic over native vegetation in green city plans to ameliorate the urban heat effect. I was also interested whether the strength of any ameliorating effect changes with ambient temperature. To that end the surface temperature of asphalt around 6 species of street trees (3 exotic and 3 native) at 8 sites each was recorded using a FLIR Infrared camera over 2 seasons. I found that surfaces under native vegetation exhibited lower temperatures when compared to exotic vegetation. The results suggest that there were some characteristics of native vegetation such as density of shade that influenced the heat on the surfaces. I concluded that native vegetation is better at ameliorating surface heat islands which will be an important consideration for green plans.

3.3 Introduction
The study of urban climatology has become increasingly important over the last decade as urban populations continue to expand. The UN’s Department of Economic and Social Affairs (Population division) (United Nations 2011) indicates that 52% (3.6 billion) of the world’s population now inhabit urban areas. The population will increase to a total of 6.3 billion by 2050 (UN 2011). With so many people living in urban environments it’s important to better understand the various factors that influence the temperature of these areas.

Surface temperature modulates atmospheric temperature in an urban environment by influencing the air that is in contact with it. This interaction has various repercussions such as influencing the energy exchange from buildings, affecting the internal climate of buildings (Guan 2012; Kikegawa et al. 2003; Kolokotroni et al. 2012), creating diverse and erratic microclimates (Colombo et al. 1999; Giridharan et al. 2004) and affecting the comfort and wellbeing of people living in the city (Tomlinson et al. 2011; Frumkin 2002; Mills 2009).

The phenomenon where the urban temperature is hotter than the surrounding rural temperature is called the urban heat island (UHI).

UHIs are created due to the difference in the thermal properties (emissivity and conductance) between urban surfaces, such as asphalt, concrete and tiles. These surfaces have higher heat
absorption and retention than the surrounding rural areas where the surface is dominated by soil and vegetation which have a lower thermal capacity and emissivity. There are various other factors that also influence UHIs but surface change is the predominant factor. Studies of surface temperature change have normally been recorded using surface thermometers or narrow thermal infrared (TIR) thermometers. These instruments while having a high degree of accuracy have a low spatial resolution, thus limiting the scope of studies using them. However, with IR imaging technology becoming more widely available, it has allowed for a greater understanding of the urban microclimate. Platform-based IR sensors, such as satellite sensors, give us a greater spatial resolution over the whole urban city; while improvements in hand held IR imaging technology means that even at a low spatial resolution a lot more detail can now be captured (compared to spot measurements of IR guns and surface thermometers).

With detection and understanding of the UHI growing there has been increased focus on mitigation. Decreases in the intensity of the UHI may be achieved by increasing the albedo of urban surface materials (Haider Taha et al. 1988; Haider Taha 1997; Santamouris et al. 2011), increasing urban vegetation cover (H Akbari et al. 2001; Shashua-Bar & M. Hoffman 2003; Tsiros 2010), reducing anthropogenic heat (Ferreira et al. 2010; Haider Taha 1997), and designing city structure (Shashua-Bar & M. Hoffman 2003). It is widely accepted that increased vegetation is the most cost effective and beneficial way of combating the UHI in developed cities (Santamouris et al. 2011). Not only does it combat the UHI effect by evaporative cooling and shading, it also reduces runoff from trees, reduces CO2 and noise pollution, increase wellbeing of the inhabitants, and increases the economic value of the real estate (Payton et al. 2008). While there is a lot of work done on the benefit of trees, in general, there has been little work done on the benefits of using one type of vegetation/tree over the other. Green city plans in Australia often use a variety of exotic trees as shade trees. Most commonly used are the Liquidambar spp. and the Plantanus spp. due to their large leaves and large canopies which make them excellent at providing shade. Native vegetation on the other hand is perceived to be not as effective at providing shade. However native do provide added benefits of enhancing/sustaining the biodiversity of the area by supporting native insect and bird species that depend on native trees. This study hopes to clarify whether there is a difference in shade between native and exotic vegetation by assessing the surface temperatures under the tree. This will also help to assess whether native or exotic vegetation are better at mitigating the urban heat effect.
The main objectives were to: 1) compare the ameliorating effects of native vs. exotic trees, and 2) assess the effect of ambient temperature has the capacity of trees to ameliorate surface temperatures. Temperatures of asphalt surfaces in the sun and shade near plants were compared to identify the effectiveness of trees in reducing surface temperatures.

3.4 Methods

3.4.1 Study area

This study was conducted in the Wollongong region of NSW, Australia (34°25’59”S, 150°52’59”E; population > 290,000). The region is located on the south-eastern coast of Australia; it lies on a coastal plain that has the Illawarra escarpment to the west and the Tasman Sea to the east. The region experiences low seasonal temperature variability (mean summer range 24.6°C max, 17.1°C min; mean winter range 17.5°C max, 9.3°C min) and uniform precipitation throughout the year. The annual average precipitation is 1329mm, slightly higher than the rest of the east coast due to the escarpment. The rainfall and seasons are also strongly influenced by the southern oscillation (ENSO).

The experiment was carried out over 4 months, two months in spring (October - November) with the average ambient temperature at 16-22°C and two months in summer (February - March) where temperatures frequently reached the late 20s and early 30s. This ensured a wide spread of temperatures in the experiment.

3.4.2 Species and site selection

Species of street trees were ranked based on how popular they were in local green plans as well as abundance in the Illawarra region. Six common species were chosen for this study (Table 4); three exotic and three native. For each species, eight sites were chosen based on the following criteria;

a) The site was less than 40 minutes from the University,

b) The site had only one of the selected species (this was to avoid interference from other species and thus the ameliorating effect of individual species could be determined),

c) Trees had to be fully mature (maturity was determined by assessing tree height, canopy shape and width as well as leaf shape)

d) Trees had to be surrounded with at least 60% urban cover around them. Street trees around parks were not used. Urban cover was determined visually in situ and using
Google Earth. Only road side trees (street trees) were used to limit the surfaces over which temperature was recorded.

e) All street trees were near asphalt road surfaces which were the surfaces on which all the heat measurements were recorded. Each site was selected so at least 50% of the image would be asphalt. This ensured the temperature difference that was measured was related to tree shade rather than an artefact of material properties.

Table 4: Tree species used, their common name and the number of sites.

<table>
<thead>
<tr>
<th>Species</th>
<th>Common name</th>
<th>Native/ Exotic</th>
<th>Acronym used</th>
<th>Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Platanus x hybrida</em></td>
<td>Plane tree</td>
<td>Exotic</td>
<td>Plain</td>
<td>8</td>
</tr>
<tr>
<td><em>Liquidambar styraciflua</em></td>
<td>Sweet gum / liquidambar</td>
<td>Exotic</td>
<td>La</td>
<td>8</td>
</tr>
<tr>
<td><em>Jacaranda mimosifolia</em></td>
<td>Jacaranda</td>
<td>Exotic</td>
<td>Jac</td>
<td>8</td>
</tr>
<tr>
<td><em>Melia azedarach</em></td>
<td>White cedar</td>
<td>Native</td>
<td>wc</td>
<td>8</td>
</tr>
<tr>
<td><em>Melaleuca quinquenervia</em></td>
<td>Broad-leaved paperbark</td>
<td>Native</td>
<td>bl</td>
<td>8</td>
</tr>
<tr>
<td><em>Tristaniopsis laurina</em></td>
<td>Water gum</td>
<td>Native</td>
<td>Tris</td>
<td>8</td>
</tr>
</tbody>
</table>

3.4.3 Thermal imaging measurements

Thermal data was collected using a FLIR thermal imaging camera (ThermaCAM-S65). Image acquisition was undertaken after sundown to limit the amount of reflected solar radiation the camera would pick up from the surface. Correcting for this error was not possible as reflected solar output would have changed throughout the hour of image collection due to clouds and varying atmospheric conditions. It was possible to take images at sunset due to the fact that the surfaces would still exhibit an elevated temperature from the absorbed solar radiation during the day. The temperature would depend on the amount of exposure the surface had to solar radiation. Shaded areas during the day would have absorbed less solar radiation when compared to exposed areas.

Data collection began on the 20th week of October (spring). Images were collected on every day with clear weather till the 20th week of November and again from the beginning of February till the 20th week of March. Days with temperatures from 15-20°C were measured as normal (average) days and any days with temperatures from 25-30°C were considered as hot days. For two random trees within each site, two pictures were taken from opposite sides of the tree (10m away from the tree) ensuring that a 5m diameter of the ground around the tree was captured (Figure 10).
3.4.4 Accuracy

The accuracy of TIR images is dependent on surface and atmospheric conditions. As a result, the following guidelines were strictly followed to ensure that the surface temperature estimation was as accurate as possible. Firstly, at every site, atmospheric conditions (temperature, humidity and wind speed) were measured using a calibrated weather station (Kestrel 3500 pocket weather meter) and this data was later used in post processing to ensure accuracy (see below). The weather had to be clear and the road surfaces had to be dry and oil-free as these would skew the temperature reading.

In the experiment it was decided to avoid using fixed weather stations or satellite-based sensors to either get a general idea of the atmospheric temperature in a region or as a data source to measure the urban heat effects. Instead hand held sensors were used to give a better estimate on how hot the atmosphere in the sites actually were. A study done by Lathlean et al. 2011 found that satellite based estimates were 1-6 °C over the actual air temperature whereas fixed weather station were up to 23°C (on average 4° lower) lower than the actual air temperature.

3.4.5 Image processing

The images were processed using Thermacam Researcher Pro software. The images were first imported into Researcher Pro and each corrected using the atmospheric data (humidity and atmospheric temperature) from the kestrel weather station. In each of the images the
emissivity was set to 0.95 as instructed in the FLIR guide book (asphalt= 0.93-0.95) and the distance to object was checked and corrected if necessary. The thermal images of the site were split into shaded and unshaded regions. In each region, two boxes of 0.25m*0.25m were used to get a sample of the temperature (Figure 11). The four IR images of each site (two for each of the two trees per site) gave a total of 8 estimates of shaded and unshaded for each of the six species.

Figure 11: Thermal infrared (TIR) image of a site with a subset of temperature measurements taken (blue squares) using Thermacam Researcher Pro (FLIR Systems Inc.)

3.4.6 Statistical Analysis

Differences in surface temperatures were compared between native and exotic species in each high and low ambient temperature using an ANOVA in the JMP statistical package (JMP®, Version 9. SAS Institute Inc.). Species were nested within origin (native/exotic). An SNK test was then used to determine where significant differences were within each significant interaction.

3.5 Results

The surface temperature in the shaded and un-shaded regions around a tree was affected by prevailing ambient temperature ($F_{4, 145}=16.6274$, $p=0.001$, Figure 12). Another trend was shaded regions on hot days had similar temperatures to unshaded regions on cool days. (Figure 12)
Within the shaded and unshaded areas there was a significant difference in the temperature of the surface heat island among species (interaction: $F_{4, 17.99} = 7.042$, $P=0.001$). Native and exotic species did not differ in their influence on temperature in the unshaded region, however, the shade under native trees was cooler than under exotic trees. Native species (shaded or unshaded) did not differ in their impact on temperature, however, for exotic species, liquidambar trees tended to have warmer shaded and unshaded areas than other species (Figure 13).
Figure 13 the temperatures of surfaces in the shaded and unshaded parts under the trees on hot days were compared for all six species. Bars with the different letters signify statistically different means, E= exotic N= native. Error = 1 SD. n=128 for each species. bl= broad leaf paperbark, jac= jacaranda, la= liquidambar, plain= plane tree, tris = tristaniopsis (water gum), wc= white cedar.

There was no difference in the temperature under exotic and native trees on a normal day however, on hot days, the exotic vegetation had significantly higher surface temperatures around them when compared to native vegetation (interaction: $F_{1, 17.99}=7.87\ p=0.012$) (Figure 14). On a normal day under both native and exotic vegetation had a mean surface temperature surfaces had a mean temperature of around $27^\circ C$ ($27.2^\circ C$ for exotic and $26.8^\circ C$ for native) however on a hot day surfaces under exotic vegetation were on average $2^\circ C$ higher than native vegetation.
Figure 14: comparison of surface heat islands around native and exotic street trees on hot or normal days. Bars with the different letters signify statistically different means. Error bars = 1 SD, n= 128.

3.6 Discussion
There was a difference in the ameliorating effect of native and exotic trees and the intensity of this effect varied with the day temperature. It was found that the surface under exotic street trees had a higher temperature when compared to that under native trees. There was also a difference among species in their ameliorating capacity. This difference was only exhibited in the exotic street trees where *J. mimosifolia* and *Platanus x hybrida* had significantly lower temperatures under their canopy when compared with *L. styraciflua*.

The ameliorating effect of the trees were limited to the shady area under the trees; the shaded region exhibited the greatest variation between native and exotic, while further away in the sunlit areas, the influence of the trees’ shade was not different. This was expected as it is the shade that prevents solar radiation heating up the surface (H Akbari et al. 2001).

Differences between the surface temperature under native and exotic trees can be affected by atmospheric or air temperature above the surface. Trees affect surface heat islands directly by providing shade but they also reduce atmospheric heat by evapotranspiration (Jim & Tsang 2010; Pataki et al. 2011). Differences in transpiration rates can lead to different atmospheric temperatures under the tree creating a temperature potential for heat to be transferred from
the surface to the atmosphere. The greater the temperature difference, the faster the heat is
transferred. Trees with higher evapotranspiration should have lower atmospheric
temperatures (ambient air temperature) around them allowing more heat to transfer from the
surface to the atmosphere (Haider Taha 1997; Oke 1987). Interestingly, Ataki (2011) also
found that transpiration rate and water use varied amongst different species, categorising
*Platanus spp* as one of the high use water species. However, in my experiment it was found
that the *Plantanus spp* and *Liquidambar spp* had highest surface temperatures in the shaded
region when compared to the natives and the other exotic, suggesting that transpiration rates
may not account for the patterns that were found. Perhaps the dense canopy of both of these
trees restricts air convection from under the canopy when there is little to no wind, increasing
the air temperature under the canopy and reducing the heat potential difference between the
surface and the air (Jim & Tsang 2010).

Due to time limitations only the 3 most commonly used species of each native and exotic
were studied in this experiment. While this does give us a good representative sample for
natives and exotics in Sydney/illawarra region from which conclusions on natives vs exotics
can be drawn for this region. Further study is needed before general conclusions on natives vs
exotics can be made.

For future studies I would suggest studying the ameliorating effect of street trees during
summer and winter. While this study does show that natives are better at ameliorating surface
heat islands during summer, it would be interesting to see whether these trends hold during
winter such that native street trees create colder environments when retention of heat is
preferred. There have been a lot of studies done on the economic benefits of street trees
during summer e.g. Akbari et al. 2001 found that in California a temperature increase of 1 °C
would increase the city’s energy consumption by 500 megawatts. However Morris (2001)
found that the Melbourne CBD was 4°C warmer than the surroundings during the summer
months, with the temperature difference dropping to 3.2 °C during the winter months. This
indicates that there is some seasonal variation of UHIs that could be affected by trees.
Unfortunately in my experiment I was unable to comprehensively compare seasons. One
obvious benefit would be the reduced air-conditioning costs during winter due to the increase
in surface heat. There is however very little work done on the winter benefits of UHI.
3.7 Conclusions

Our results have also demonstrated the importance of UHI mitigation schemes. These schemes have social economical as well as ecological benefits. More care should be taken when choosing street trees for these green plans as different species provide varying amount of mitigation against urban heat islands. The results indicate that any tree is better than no tree (the areas that were under shade during the day were always lower in temperature when compared to unshaded areas), however the popular native trees used appear to have greater amelioration potential than popular exotic species.
CHAPTER 4: COMPARING THE EFFECTS OF HEAT STRESS ON NATIVE AND EXOTIC VEGETATION IN A LAB AND FIELD SETTING.

4.1 Introduction

Green city plans and green roof schemes are becoming increasingly popular in urban centres due to their various social, economic and environmental benefits. It has been well documented that vegetation not only increases the aesthetics of an area, but also increases the economic value of the real estate (Payton et al. 2008). People are willing to pay a premium for housing in a greener urban environment; this may be linked to studies that have found that urban vegetation can reduce crime (Kuo & Sullivan 2001; Donovan & Prestemon 2010; Branas et al. 2011) and increase the sense of wellbeing of the inhabitants in the area (Branas et al. 2011). Trees also reduce noise and dust/particle pollution (Beckett et al. 1998), help contain surface water runoff in the soil by providing drainage points and the roots of the trees hold the water in the area. However, vegetation is also becoming increasing important in an urban environment due to the ameliorating effect it has against the urban heat island effect (Shashua-bar et al. 2010; Tsiros 2010).

The urban heat island is the phenomenon where urban areas have a higher temperature than the surrounding rural habitats. This difference in temperature is mainly due to the change in land surface usage from soil and vegetation to asphalt and concrete which retain heat better than their natural counterparts. Most of the effects caused by urban heat islands can be ameliorated or controlled to some degree by using vegetation. Surface heat islands and atmospheric heat islands can be reduced by street trees through shading and evapotranspiration which in turn reduces the health risks of people living in the surrounding urban environment (heat stroke, heat stress etc.) and the economic cost of cooling surrounding houses.

While the urban forest has benefits, an urban area is a challenging environment in which to grow and survive. Trees must contend with resource shortages and disturbances that lead to increased stresses (Pataki et al. 2011). Water shortages are caused by limited drainage points and the impervious top layer of asphalt or concrete which directs water into drains. Heat stress may be caused by the urban heat island. With global temperatures increasing and conservative models predicting a global temperature increase of 2-4°C in the next 50 years (Meehl et al. 2000), added to the fact that extreme heat events are becoming more common and severe (Meehl et al. 2000), the interaction between the urban heat island and increased
global temperatures may increase heat stress in urban plants. While studies on drought- and heat-induced tree death has been undertaken in established ecosystems (B. Huang & C. Xu 2008; Willits & Peet 2001; Timperio et al. 2008; Swatantran et al. 2011; Munné-Bosch & Alegre 2004) there has been little to no work done for urban plants.

One of the main issues that are limiting the study of heat effects in an urban environment is the inability to predict when and where a heat event will take place and the difference in the type of responses each species will have to heat stress. Traditional methods of stress assessment include ground and areal visual surveys, which gives a subjective assessment of canopy/tree health (Stone et al. 2003). However, these methods have some major drawbacks in an urban environment; firstly, visual surveys cannot identify what type of stress the tree is experiencing and secondly, some of the methods (field based visual surveys for example) don’t have a measure by which the stress can be quantified and detected early. In understanding heat stress on plants the latter point is the most important as many plants have a delay before the heat stress causes any visual signs of damage.

One solution to this problem is remote sensing technology. Hyperspectral data obtained from imaging spectrometry is now widely used in the field which can measure indicators such as leaf pigments (Sims & Gamon 2002; Blackburn 1999; Stone & Chisholm 2005) and cell break down to detect plant stress (Stone & Chisholm 2005; Coops et al. 2004). Spectrometry measures the reflected/emitted electromagnetic spectrum of an object. In the case of trees, any stress that causes a change in pigmentation will be recorded as a change in the reflectance and absorption of visible light from the leaves (Datt 1998). For example, heat stress can cause the breakdown of chlorophyll which causes a reduction in the green radiation being reflected as well as an increase in the chlorophyll absorption troughs.

Carter and colleagues (Carter & Miller 1994; Carter 1993; Carter 1994) found that when comparing spectral responses across different plant species and stressors, there was a more constant alteration in spectral reflectance across the visible (400-720nm) when compared to the infrared (IR, 720-2500nm) part of the spectrum. A generic response to stress in the visible region of the spectrum can be split into two sections; increased reflectance in the far red (690-720nm) along with a blue shift of the red edge (the steep increase at the 700nm range) and a general increase in reflectance across the 530-650nm range.(Figure 15). There
are numerous vegetation stress indices that have been specifically derived to measure inferred plant stress. (Solaimani & Shokrian 2011)

Figure 15: A general spectral response of a plant to stress in the visible-near infrared region (400-850) of the spectrum. A, B are the areas of the spectral curve that were compared between Natives and Exotics.

As both native and exotic trees are used in green city plans throughout the Illawarra region, there may be distinct differences in the capacity of these species to survive under more frequent heat stress. It is expected that native vegetation are better than exotic vegetation at coping with higher temperatures as native vegetation has evolved within a drier climate. The responses of native and exotic trees to heat events will be measured using leaf spectral data in a lab-based experiment and in the field. In the field-based experiment, I will investigate differences between native and exotic species in how the spectral reflectance of street trees will vary following normal and hot days. In the lab-based experiment I will investigate whether native or exotic trees exhibited any diurnal recovery after an extreme temperature event during the day. A diurnal recovery might suggest that a tree does not suffer any permanent damage during an ETE but instead undergoes some elastic change in either structure or function. This is important when measuring plant stress as it will allow for a threshold from which plants can recover without any permanent damage.
4.2 Materials and methods

4.2.1 Study area

This study was conducted in the Wollongong region of New South Wales, Australia (34°25’59”S, 150°52’59”E; population > 290,000)(Australian Bureau of Statistics (Abs) 2011) The region lies on a coastal plain that has the Illawarra escarpment to the west and the Tasmanian Sea to the east. The region experiences low seasonal temperature variability (mean summer range 24.56°C max -17.13°C min; mean winter range 17.5°C max -9.3°C min) and uniform precipitation throughout the year (Australian Bureau of Meteorology (BOM) 2012). According to the BOM climate classification, Wollongong falls under temperate - no dry season. The annual average precipitation is 1329mm, which is slightly higher than the rest of the east coast. This is attributed to the orographic lift caused by the escarpment. In addition, the rainfall and seasons are also strongly influenced by the southern oscillation (Bryant 1985).

4.2.2 Heat stress measurement

Leaf spectral measurements were recorded using an Analytical Spectral Device (ASD) FieldSpec Pro FR spectroradiometer (Analytical Spectral Devices Inc., Boulder, USA). The spectrometer is a full spectrum spectroradiometer capable of measuring from 350nm to 2500nm (Analytical Spectral Devices Inc., Boulder, USA). Further detail on specific instrument setup will be mentioned in each individual experiment below.

4.2.3 Field based experiment

4.2.3.1 Species and site selection

For the field-based study, the 3 (each) most common exotic and native street tree species were selected (Table 5) from a compiled list of locally used street trees (Sydney and Illawarra). For each species, eight sites were chosen based on the following criteria;

a) The site had to be less than 40 minutes from the University to limit the time the leaves spent off the tree. A study done by Foley et al. 2006 found that spectral reflectance of a leaf does not change over 12 hours if leaf moisture is maintained.
b) The site had to be made up of only one of the selected species, this was to avoid interference from other species and thus the ameliorating effect of individual species could be determined

c) Trees at the site had to be fully mature (at least 2 meters tall).

d) Trees had to be surrounded with at least 60% urban cover based on hard surfaces such as concrete and asphalt. Street trees around parks were not used. Urban cover was determined visually by overlaying a grid on the Google earth image and counting the number of urban squares (20m diameter circle area).

Table 5: Exotic and native tree species measured in the field, with their common names and acronym.

<table>
<thead>
<tr>
<th>Species</th>
<th>Common name</th>
<th>Deciduous/ Evergreen</th>
<th>Native/ Exotic</th>
<th>Acronym used</th>
<th>Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Platanus x hybrida</em></td>
<td>Plane tree</td>
<td>Deciduous</td>
<td>Exotic</td>
<td>Plain</td>
<td>8</td>
</tr>
<tr>
<td><em>Liquidambar styraciflua</em></td>
<td>Sweetgum/ liquidambar</td>
<td>Deciduous</td>
<td>Exotic</td>
<td>La</td>
<td>8</td>
</tr>
<tr>
<td><em>Jacaranda mimosifolia</em></td>
<td>Jacaranda</td>
<td>Deciduous</td>
<td>Exotic</td>
<td>Jac</td>
<td>8</td>
</tr>
<tr>
<td><em>Melia azedarach</em></td>
<td>White cedar</td>
<td>Deciduous</td>
<td>Native</td>
<td>Wc</td>
<td>8</td>
</tr>
<tr>
<td><em>Melaleuca quinquenervia</em></td>
<td>Broad-leaved paperbark</td>
<td>Evergreen</td>
<td>Native</td>
<td>Bl</td>
<td>8</td>
</tr>
<tr>
<td><em>Tristaniopsis laurina</em></td>
<td>Water gum</td>
<td>Evergreen</td>
<td>Native</td>
<td>Tris</td>
<td>8</td>
</tr>
</tbody>
</table>

4.2.3.2 Leaf collection (field)

On the 3rd week of October (spring) a base line stress reading for one healthy tree at each site was measured. The baseline reading was taken in October as it is the middle of the spring season in Wollongong and has an average temperature of 22°C (Australian Bureau of Meteorology (BOM) 2012). There was also abundant rainfall in the previous two weeks (close to 100mm), reducing the chance that the trees were either heat or water stressed during the base line readings. For *Jacaranda mimosifolia* the baseline was delayed to the end of November as they are leafless during the early spring season.

A 50 cm clipping of a tree branch with leaves was taken from mid-canopy level. Leaves at the mid-canopy level were used due to the lower canopy of some trees being constantly disturbed by pedestrians. The upper canopy was avoided due to it having higher proportion of
active shoots for most species signifying higher leaf age variation (Pook 1984). For *Liquidambar styraciflua* where only 4-5 leaves were present per 50 cm, multiple branches were collected (up to 3 branches). In total, 15 – 40 leaves were collected from one tree per site. The branches were placed into zip lock bags with a wet cotton ball to act as a moisture strip and the bag stored on ice to delay negative effects from excision (Garnier et al. 2001). At each site, the atmospheric temperature, wind and humidity were also recorded using a kestrel pocket weather station. This temperature would also act as a baseline for future comparisons. Due to the large number of sites, it was not possible to visit all the sites on one day and hence leaf collection was randomly staggered among sites of a species over 3 days with similar weather conditions; temperature had to be within 2°C of the previous collection day.

Following the baseline collection, between the 3rd week of October and the end of November, all the sites were sampled (leaves collected similar to baseline collections) four times during normal (average) temperature days (20-24°C) in spring. Sites were sampled another 4 times in the middle of February to obtain samples during hot days (hot days, 26-35°C).

4.2.3.3 Data collection

The spectrometer was set up in a dark room, with the only source of illumination being two ProLamp halogen bulbs that were positioned at opposite ends to ensure that the surface was evenly illuminated. For the field experiment the spectrometer was set up, similar to that outlined by (Stone & Chisholm 2005) with a bare fibre optic cable (field of view of 25°), 31 cm above the table top (Figure 16). This gave a field of view on the table with a radius of 6.6 cm.

![Figure 16: Setup for the spectrometer, lights and Fibre optic cable](image)
Only mature leaves and those free from damage were used. All the leaves from each tree were stacked 5 cm thick (Datt 1998). Four readings of reflectance were taken, shuffling the leaves between each reading, which was then averaged to give a site reflectance value. A white reflectance measurement of a Spectralon panel (Labsphere, NH, USA) was taken between readings to ensure appropriate calibration.

4.2.4 Laboratory-based experiment

4.2.4.1 Species selection (laboratory)

Three native and three exotic trees were compared in the laboratory-based experiment (Table 6). All of the trees were ordered from the same nursery to limit the difference in the watering regime, fertilizer used, pot size (250mm pots, 1 plant per pot) and soil type (mulch). Eight trees for each species were used. The plants were stored under shade cloth until the experiment began and were watered with a drip watering system and additional mist sprayers twice a day for 5 minutes. This resulted in approximately 3 litres of water per pot per day. The pots were well drained to ensure that the plants did not get flooded. The amount of water was recorded to ensure that the pots received the same amount of water in the latter stages of the experiment.

Table 6: List of species used in assessing if vegetation exhibit diurnal recovery from stress along with their origin and common name

<table>
<thead>
<tr>
<th>Species</th>
<th>Native / Exotic</th>
<th>Common name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acmena smithii</td>
<td>Native</td>
<td>Lilly Pilly</td>
</tr>
<tr>
<td>Callistemon citrinus</td>
<td>Native</td>
<td>Crimson Bottle Brush</td>
</tr>
<tr>
<td>Eucalyptus terericornis</td>
<td>Native</td>
<td>Forest Red Gum</td>
</tr>
<tr>
<td>Camellia japonica</td>
<td>Exotic</td>
<td>Japanese Camellia</td>
</tr>
<tr>
<td>Lagerstroemia indica</td>
<td>Exotic</td>
<td>Crepe Myrtle</td>
</tr>
<tr>
<td>Photinia x fraseri</td>
<td>Exotic</td>
<td>Red Robin</td>
</tr>
</tbody>
</table>

4.2.4.2 Experiment set up (laboratory)

On the 10/02/2012, the trees were moved into 2 Thermoline temperature cabinets (Thermoline Scientific) at sundown to limit the stress on the plants caused by going from natural illumination to illumination by artificial lights. The plants were kept in the cabinets
for 3 days at control temperature (Table 7) and watered everyday by hand; using a 3 litre container to ensure each plant got the same amount of water. The following three days the plants were kept under control conditions and every subsequent 4th day the temperature was increased to the next temperature group (Table 7) allowing for a day gap in-between the temperature periods.

Table 7: Outline of the temperature regime subjected to the vegetation to determine the effects of heat stress. A max temperature of 35°C was set to avoid overburdening the temperature cabinets. Humidity was kept constant. Day time temperature was increased every fourth day ensuring each time period had three full days at one temperature.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Humidity (%)</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day</td>
<td>Night</td>
</tr>
<tr>
<td>Control</td>
<td>27°C</td>
<td>25°C</td>
</tr>
<tr>
<td>Transition day</td>
<td>30°C</td>
<td>25°C</td>
</tr>
<tr>
<td>Transition day</td>
<td>35°C</td>
<td>25°C</td>
</tr>
<tr>
<td>Cool off (recovery)</td>
<td>26°C</td>
<td>25°C</td>
</tr>
</tbody>
</table>

4.2.4.3 Data collection (laboratory)

The spectrometer was set up with the plant probe head on the bare fibre optic cable to take readings without picking the leaves. On every day starting from the 1st control day (13/02/2012), data was collected twice a day; two hours before sun down (to measure high stress) and two hours before sunrise (to measure recovery). Three mature leaves, randomly chosen on each tree (6 species x 8 replicates) were sampled (non-destructively) and checked for signs of damage.

4.2.5 Data processing and statistical analysis (laboratory and field)

Both field and laboratory Data was extracted using View Spec Pro (Analytical Spectral Devices Inc., Boulder, USA.), which both graphed and converted the spectra data into a text
format which could be imported into Excel (Microsoft Office). Each sample was a full spectral curve from 350nm to 2500nm. Information on leaf stress was extracted in 2 ways.

I compared specific regions of the mean spectral curves between exotic and native vegetation using a t-test. The specific areas of the curve chosen for comparison are the 720nm (Figure 15, B) and the visible peak at 550-570nm was averaged for each nm increment to give a single value (Figure 15, A). Both regions are known to be good indicators of stress (Liang et al. 2010). For the field experiment the mean values of the curves for native and exotic trees on hot and normal days were compared and for the laboratory-based experiment the mean values of the curves for native and exotic trees during the day and night were compared using t-tests.

I also compared native (N) and exotic (E) species using the mND 705 index (Sims & Gamon 2002). The mND 705 index is a chlorophyll-based index that is based around the red edge (a sharp change in leaf reflectance that is between the 680 -750 range) that takes into account chlorophyll change (705nm), leaf structure changes (750nm) as well as accounting for leaf surface reflectance (445nm). The index provides an overall view of stress processes taking place in the leaf both in the pigment concentrations as well as changes in the mesophyll layer. The higher the index value the more stressed the plant is experiencing. The data was compared using the JMP statistical software (JMP®, Version 9. SAS Institute Inc). The field experiment compared heat stress in natives and exotics vegetation on hot and normal days using an ANOVA. The laboratory experiment analysed each of the time periods separately using an ANOVA to compare diurnal stress levels between native and exotics vegetation. An SNK test (post ANOVA Multiple comparison test) was then used on both (natives and exotics) to determine whether there were any species that were driving the changes seen between exotic and natives.

4.3 Results

4.3.1 Heat stress in the field

A comparison of the mean spectral curves of natives and exotic vegetation on hot and normal days highlights the areas in which heat stress is expressed in the leaves. Both natives and exotic vegetation exhibit significant differences in specific regions of the spectrum on hot days when compared to normal days. This difference is generally observed as the raising of
the spectral curve on hot days when compared to normal days. In the visible region (380-760nm) there is an increase in reflectance between the 540nm and 600nm range ($t_8=52.81$, $p=0.001$). In the NIR (near infrared 750 nm to 1400 nm) and SWIR (Short wave infrared 1400 nm to 3000 nm) there is lifting of the IR plateau on hot days for both natives as well as exotics($t_8=-98.60$, $p=001$). The difference between hot and normal days in the IR plateau is more pronounced for the exotics when compared to the natives (Figure 17).
A comparison of plant stress using the mND705 index reveals that exotic trees are more stressed when compared to native trees on hot days. It was also found that natives appeared to exhibit higher stress levels on normal days when compared to hot days (F$_{4, 30}=55.69$, p=0.0001) (Figure 19).

Analysing this trend even further by breaking native and exotic down into species it was found that there is a significant interaction between the stress level of species on hot and normal days. (F$_{4,30}=22.53$ p=0.001). It was found that most of the change in the native group was driven by *T. laurina* (tris) which appeared less stressed on hot days and in the exotic group, by *L. styraciflua* (la) which appeared less stressed on normal days.
4.3.2 Heat stress in laboratory experiment

I compared differences between the day and night spectral curves to identify when plants were experiencing stress using the mND705 index. During the control (27°C), T1 (30°C) and R temperature periods there was no difference between day and night stress levels (C: F<sub>1,4</sub>=0.0079, p=0.9335; T1: F<sub>1,4</sub>=0.0013, p=0.9733; R: F<sub>1,4</sub>=0.8150, p=0.4177). However for T2 (35°C) exotic species exhibited significantly higher stress during the day when compared to the night and this diurnal difference in stress was not mirrored in the native species. (F<sub>1,4</sub>=25.7677, P=0.0071) (Figure 20).
Figure 20: A comparison of stress using mND705 index for native and exotic vegetation in the T2 (35°C) time period. Different letters in the bars signify statistically significant difference. ± SD

A comparison of the mean spectral curve from 490nm to 950nm for exotic vegetation in T2 time period highlights the difference in the spectral responses between day and night in the visible (490-700nm) and the NIR range (700-900nm). In the visible, there is an increase in the reflectance at the chlorophyll peak (550nm) and absorption trough (570-590nm) for the day when compared to the night ($t_4=3.68$, $p=0.03$). At the Red edge (700-760), a shift during the day towards the blue spectrum was observed (blue shift) however at the start of the NIR plateau there is no difference in reflectance between the day and night spectral signatures ($t_4=0.306$, $p=0.7$) (the red edge was analysed using the mND705 index).
4.4 Discussion

Natives exhibited lower stress levels with increasing temperature in both the field and laboratory settings. However some unexpected results were found, such as the contrasting response to increasing temperatures by native and exotic vegetation in the field (mND705 comparison), the lack of diurnal change in stress levels for T1 time period and no difference in the NIR plateau in the laboratory based experiment, suggest that stress in each experiment was associated with different physiological responses.

While there was decrease in absorption in the visible region over the two experiments for both natives and exotics suggesting increased stress (Figure 15), there was also a difference in the NIR region in the 2 experiments and between natives and exotics. In the lab experiment, there was no change to the NIR region of the spectral curve, however, in the field

Figure 21: Part (from 490-950nm) of the averaged spectral curve for day and night of exotic trees in T2 time period (35°C).
experiment there was a lifting of the NIR plateau which was more pronounced for exotics tree species, indicating increased stress. Such differences may indicate a difference in plant water stress levels. The NIR region is heavily influenced by both cell structure and water levels in the leaves (Hunt & B. Rock 1989). While the plants in lab experiment had a constant supply of water, in the field water could not be controlled. The difference stress levels observed in the NIR between experiments suggest that street trees could be using water as a buffer against heat damage to the structure of the leaves (Hunt & B. Rock 1989; Riggs & Running 1991).

Water (drought) stress can also explain why exotic trees had higher stress levels. Ataki (2011) found that transpiration rate and water use varied amongst different species, categorising some of the exotic species used in this experiment such as the *Platanus* spp. as one of the high use water species.

The difference between natives and exotics was strongly affected by individual species responses. *T. laurina* (a native) exhibited lower stress levels during hot days than other natives, suggesting this species may be more acclimatized to hotter temperatures. It was expected that stress levels in street trees would increase with increasing temperature as exhibited by the exotic species of street trees (Weis & Berry 1988; G. A. Carter & Napp 2001; Willits & Peet 2001) and the mechanisms for acclimatization need to be better understood.

The laboratory results suggests at lower temperatures both natives and exotics show no heat stress during the day, however, there was also no change in our first time period (T1) where the temperatures were increased to 30°C during the day. No species appeared near its thermal tolerance, perhaps a result of earlier tolerance while occurring in nursery conditions and a pot. Plants that undergo moderate stress are more resistant to subsequent stresses (J.-H. Zhang et al. 2005) as plants synthesise heat shock proteins (HSP) and different molecular chaperones that act in concert to help protect necessary proteins from heat stress (B. Huang & C. Xu 2008; Timperio et al. 2008; Wahid et al. 2007).

In the second time period (T2, 35°C), the increase in stress levels during the day were expected. After a day of high temperatures, exotic species did express low levels of stress during the night, suggesting trees experienced some diurnal recovery but it was not complete. The stress was expressed in the spectral curve by the raising of the chlorophyll trough and a blue shift (movement towards shorter wavelengths) of the red edge related to leaf stress and
chlorophyll concentration (Vogelmann et al. 1993; Pinar & Curran 1996; Liang et al. 2010; Boochs et al. 1990; B. N. Rock et al. 1988). Karim et al. (1997) found that high temperatures lead to major alterations of chloroplasts, such as changing the structure of the thylakoids, loss of grana stacking and swelling of the photosynthetic membrane all of which result in a loss of photosynthesis and plant productivity.

Despite this blue shift of the red edge, plants did not reach their thermal tolerance as there was no increased reflectance of the NIR radiation. Severely heat stressed plants, show an increase in NIR reflectance which corresponds to damaged mesophyll cells, water loss and increased permeability of plasma membrane (J.-H. Zhang et al. 2005). In the future experiments increasing the temperature to 45°C to try and expose the trees to temperatures close to their thermal limits might help amplify any stress effects.

To conclude both laboratory and field based experiments found that as temperature increased there was an increase in stress levels amongst native and exotic vegetation. The laboratory based experiment found that the increase in stress was more pronounced amongst the exotics. These findings are important as they outline the need for further research into vegetation used in green city plans before implementation to avoid the loss of thousands if not millions of dollars.
CHAPTER 5: FINAL DISCUSSION AND CONCLUSION

The UHI is expected to continue playing a dominant role in an ever growing urban landscape with the possible socio-economic, environmental and health related impacts directing a lot of focus on mitigation of UHIs. Vegetation strategies have been found to be the most effective in terms of cost, convenience and mitigation (Brack 2002; Payton et al. 2008; A. H. Rosenfeld et al. 1995; Memon et al. 2008; AH Rosenfeld et al. 1998). Vegetation strategies are now used worldwide to try and reduce UHIs. While there is a lot of research on the benefits of these strategies, there is very little research done on whether the type of vegetation plays an important role.

My research was aimed at improving the understanding of whether tree type is a crucial element in mitigating the UHI. Specifically, I was interested in whether exotic trees were better than native trees. Chapter 2 investigated the relationship between extreme temperature events (ETE) and plant stress levels over an urban gradient at a landscape scale. I found that while remotely sensed satellite data could pull out the differences among vegetation along an urban gradient, it could not detect heat stress within the vegetation after hot days. It was difficult to investigate these due to Landsat images being unavailable at appropriate times, which may have meant that heat stress may have been present but not captured due to the temporal mismatch of images and ETE. However, with the lack of heat stress being recorded in the vegetation, I concluded that there might be other factors, such as water and plant condition that could buffer against the onset of stress and local in-situ experiments could help determine how street trees would relate to heat events.

To that end, in chapter 3, I determined whether street trees do help in the mitigation of urban heat islands and whether this mitigation differed between native and exotic vegetation. Using IR imaging, I found that native and exotic vegetation, both exhibited an ameliorating effect against the UHI which varied across season. In addition, I found that the ameliorating effect was better under native than exotic street trees, despite the broad leaves and big canopies of exotic vegetation. This suggests that some aspect of the tree other than shade also played an important role in determining the ameliorating effect. For example, the density of the canopy could trap hot air under it which could then aid in the retention of heat on surfaces under the tree. To investigate this further, stress levels of native and exotic trees were compared.
(Chapter 4) in a field- and lab-based experiment. In the field, I was able to significantly identify that both native and exotic trees exhibited different stress levels in response to increased temperature. Interestingly I found a reduction in stress for the natives over the summer which was not expected. Native trees studied in the field; *M. azedarach, M quinquenervia* and *T. laurina*, appeared to prefer the hotter climate in summer when compared to the cooler climate during spring. This result was mirrored in the lab-based experiment using a set of different native species; *A. smithii, C. citrinus* and *E. teretroncis*. These species did not show any significant increase in stress at the highest temperatures and this resulted in no diurnal recovery as the trees were not pushed to their thermal tolerance at 35°C. In contrast, exotic trees did show significant difference between day and night stress levels with stress levels decreasing during the night. This suggests that during the day, the exotic plants studied experienced stress which caused some elastic stress effects in the leaf in response to heat stress from which the plant recovered during the night when the heat was reduced.

My research outlines the importance of vegetation type in green city plans. For Australia, there are clear benefits to planting native vegetation from a biodiversity and economic perspective. Native species cope better with hot days and provide a greater ameliorating effect. Globally, millions of dollars are spent annually in implementing and maintaining green plans. These costs are normally offset by the economic benefits of the trees. A study in Canberra on the economic value of trees estimated that the value of reduced electricity usage and pollution reduction in the city due to the trees would amount to US$20-$67 million between 2008 and 2012. However, these benefits depend on the tree surviving and thriving in an urban environment. This study (Chapter 2) has outlined that vegetation and urban gradients can be monitored through remotely-based satellites. This can help in the planning of cities as well as the allocation of green funds in already developed cities. Planning of cities should also take into account that different species of trees have different benefits and drawbacks. For example, while trees with broad leaves such as *Liquidambar spp.* and *Platanus spp.* are extremely effective at shading, their broad leaves allow very little air flow which would be disadvantageous in a narrow street as it would limit the airflow, thus increasing the temperature of the street.

Lastly, future climate scenarios should be taken into account, with extreme temperature events becoming more frequent and intense, climatic stress could play an important role in
the survival of urban trees. My research points out that heat plays an integral role in the stress of urban trees. Millions of dollars could be lost due to trees dying after being pushed outside their thermal tolerance range.

5.1 Future research directions

This thesis outlines the need for continued research to improve the overall understanding of urban vegetation and the relationship it has with urban heating. Given the moderate climate experienced during this study, it would be important to repeat aspects of this study during years when water availability was greater and temperatures higher. The lower than average temperatures restricted the amount of heat stress the trees experienced and the increased precipitation over the two seasons limited the number of days the sample could be carried out.

Future research could also establish physiological estimates of plant stress to complement the spectral information gathered in this study. Proteomics or gene expression techniques would be useful to try and determine physiological stress as this would allow for better resolution in determining what part of the plant is affected by heat stress and by how much. Another method such as chlorophyll fluorometry could give insight into how the photosystems are functioning and how heat stress affects these systems. Both these techniques also provide a proxy against which the remotely sensed data could be compared for different species providing a ground truth for the remotely sensed data. In addition, this would allow for quantitative comparison among different species. However, I also emphasise the importance of developing and using remotely-sensed data. With better understanding and higher correlation between spectral changes and stresses, remotely sensed data could be used to map real-time changes in plant stress over large spatial scales, which would allow for both management and better understanding of the interaction between urban forests and our ever growing urban environment.
REFERENCES


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