victorian centre for climate change adaptation research

Technical Report

Decision principles for the selection and placement of Green Infrastructure

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A report for the Victorian Centre for Climate Change Adaptation Research (VCCCAR) under the project: Responding to the urban heat island: Optimising the implementation of green infrastructure.

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List of abbreviations

CCD	Census Collector District
GOS	Green Open Spaces
LGA	Local Government Area
SVF	Sky View Factor
UGI	Urban Green Infrastructure
UHI	Urban Heat Island
VGS	Vertical Greening System
WSUD	Water Sensitive Urban Design

Executive Summary

Using green infrastructure to moderate high urban temperatures is increasingly a focus of city governments around the world. This is motivated by the negative health consequences of high urban temperatures as well as the threat of increasing frequencies of heatwave events under climate change predictions. Green infrastructure is an attractive method of mitigation because of the diverse additional benefits beyond temperature reductions it delivers to the community. There is as yet little guidance on how to effectively implement green infrastructure for the hot, dry summer conditions experienced in southeastern Australia.

This report presents a series of guiding principles for land managers at the Local Government Area level in Greater Melbourne for making decisions on how to most effectively implement green infrastructure to cool urban areas during summer daytime conditions. The decision principles are based on a review and synthesis of relevant sections of the green infrastructure literature and literature from urban climatology as well as novel data presented in Coutts and Harris (2012) A multi-scale assessment of urban heating in Melbourne during an extreme heat event and policy approaches for adaptation.

The mitigation target is urban surface temperatures during the day. Surface temperatures influence human thermal comfort through mean radiant temperatures. They are a useful mitigation target compared to air temperatures because they fluctuate in a similar pattern but at a different magnitude than air temperatures, and can be compared accurately between different areas as they are not as subject to additional factors such as wind. The framework is focused on cooling of public spaces rather than cooling the interior of buildings and the overall goal is to maximise green cover.

The key steps to develop a green infrastructure implementation plan for cooling urban public spaces are: identification of priority neighbourhoods within an LGA; improving the health and resilience of existing green infrastructure to heat and drought by integrating water sensitive urban design; selecting priority streets within priority neighbourhoods; and appropriate selection of green infrastructure elements for streets with different orientation, width and building height.

The main green infrastructure elements identified and discussed in this document are green open spaces, street trees, vertical greening and green roofs. The evidence for the extent and type of cooling provided by these different vegetation elements is presented and discussed. Green open spaces provide cooling at a wide scale and potentially provide oases for local residents to escape hot conditions. Street trees are an excellent method for cooling urban areas at local scales, and at city-wide scales if a wider strategy is adopted. Trees provide shade and evapotranspirative cooling and remain green for longer under stressful drought conditions than, for example, grass. Green roofs and vertical greening systems provide insulation to buildings as well as evapotranspirative cooling. There are a number of horticultural challenges associated with their use under hot, dry conditions. All of the vegetation types discussed provide greater cooling services with adequate water availability during hot periods.

A diversity of green infrastructure types will be most effective in accomplishing a cooling outcome while maximising the additional benefits of greenery. Green open spaces are critical in meeting the overall goal of maximising green cover in urban spaces. In urban streetscapes, in the first instance ‘overhead’ vegetation canopy cover should be increased to provide shade and evapotranspirative cooling. Secondarily, surface vegetation cover such as green roofs and green walls should be implemented, which provide transpirative cooling and shade surfaces but do not provide shading to people.

1. Introduction

Urban development replaces natural surfaces and vegetation with the dry, hard impervious surfaces and structures of roads, footpaths, roofs and buildings. On sunny days, these hard, exposed surfaces accumulate and store solar heat energy and eventually become a source of heat themselves. When it rains, the impervious surfaces are designed to drain water rapidly into gutters and stormwater pipes leaving little moisture in the urban built environment which leads to reduced evapotranspirative cooling. In addition, the geometry of high density cities traps heat at night. Urban areas are also warmed from anthropogenic sources of heat, for example air conditioners and vehicle engines (Oke et al., 1991; Oke, 1981). The combination of these factors commonly leads to warmer air temperatures in urban areas than in the surrounding rural areas, a phenomenon termed the 'Urban Heat Island effect' (UHI) which is evident in many cities around the world (Oke et al., 1991; Oke, 1982).

The urban heat island effect exposes urban populations to longer and more intense periods of heat stress, particularly during heat wave events. Heat waves and other extreme heat events can lead to increased rates of mortality and morbidity in the urban population (Corburn, 2009; Gosling et al., 2009; Kovats & Hajat, 2008; O'Neill & Ebi, 2009) and models predict increasing frequency and intensity of heat waves under future climate change scenarios (Meehl & Tebaldi, 2004). Large areas of Melbourne are planned for densification or new developments, which will increase the number of people subject to high urban temperatures (Coutts et al., 2008). While low temperatures can also cause human health problems (Gosling et al., 2009; O'Neill & Ebi, 2009) heat waves are generally more detrimental (O'Neill & Ebi, 2009) and in Australia heat waves have been the greatest source of weather-related deaths (Loughnan et al., 2013).

The consequences of heat waves are not evenly distributed across urban populations (Gosling et al., 2009; Kovats & Hajat, 2008; O'Neill & Ebi, 2009). People's vulnerability to extreme heat events is affected both by their exposure to high temperatures as well as their adaptive capacity, e.g. their access to air conditioned spaces (Chow et al., 2012). Increased urban temperatures disproportionately affect the elderly, the very young, people with pre-existing medical conditions, people living alone, people living in particular house types and people of low socio-economic status (Kovats & Hajat, 2008; O'Neill et al., 2009). Reducing the intensity of heat waves and people's exposure to extreme heat in urban areas is therefore a social justice as well as a health and environmental issue.

The increasing frequency of heat waves is a problem in urban areas of Victoria as it is in cities around the world (Department of Human Services, 2009; Queensland University of Technology, 2010). There are a number of ways of addressing the urban heat island and deleterious interactions with heat wave events, and a suite of methods are likely to be necessary to do so effectively (Emmanuel, 2005; Shaw et al., 2007; Silva et al., 2010). These include modifying the surface properties of building materials to reduce heat absorption, for example by painting them white or light colours (Stone Jr. & Rodgers, 2001). Similarly, solar sensitive design of urban streets (orientation, linearity, width etc) is important to provide areas that minimise negative health effects on residents and pedestrians (Kovats & Hajat, 2008). Providing access to air-conditioning is an obvious way of providing refuge from hot urban air temperatures (Chow et al., 2012; Cutter et al., 2000; Huang et al., 2011). Finally, increasing vegetation in the urban landscape is an effective mitigation strategy providing solar reflectance, absorbance (shade) and evapo-transpiration benefits (Rizwan et al., 2008).

This report focuses on adapting urban communities to increased temperatures through the use of urban green infrastructure (UGI). UGI implementation is a particularly attractive climate change adaptation approach as unlike air-conditioning it can reduce urban air and surface temperatures without significantly increasing energy use and greenhouse gas emissions. It can be retrofitted to the existing urban built form, whereas modifications in urban geometry, design and planning are usually restricted to new developments. Furthermore, UGI provides many additional benefits which other low-tech engineered adaptation strategies; such as high albedo reflective surfaces, do not provide. For example, greener, vegetated cities provide both human health and environmental co-benefits that engineered solutions cannot and these should be recognised and prioritised.

1.1 Definition and importance of urban green infrastructure

Urban Green Infrastructure is defined as 'the network of natural and designed vegetation that provides a wide range of environmental and quality of life benefits for urban communities'. It includes remnant vegetation, parks, gardens and golf courses, urban agriculture, street trees as well as newer vegetated technologies such as green roofs and green walls, biofilters and raingardens.

Increasing the total proportion of UGI in our cities has been repeatedly shown to reduce urban surface air and surface temperatures (Bowler et al., 2010; Finnigan et al., 1994; Gallo et al., 1993; Hamdi, 2008; Su et al., 2012; Walz & Hwang, 2007), reducing both the maximum temperature and temperature variation (Jenerette et al., 2007; Luvall & Holbo, 1989; Whitford et al., 2001). For a substantial reduction in the urban heat island, addition of green infrastructure across the whole city will be required (Wong & Chen, 2010). For example, measurements during an extreme heat event on 24-26 Feb 2012 in Melbourne suggested that a 10% increase in vegetation cover reduced daytime land surface temperature by approximately 1°C under these conditions (Figure 1) (Coutts & Harris, 2012). But even small increases in urban vegetation cover can lead to reductions in city-wide temperatures (Sailor, 1998).

UGI is regarded as an effective means to minimise heat accumulation in the urban environment through shading hot surfaces, increasing evapotranspirative cooling and modifying wind patterns (McPherson, 1994; Oke et al., 1989; Taha, 1997). UGI also delivers multiple additional benefits to the urban environment, including recreation (Bolund & Hunhammar, 1999), aesthetic benefits (McPherson et al., 2005), stress relief and wellbeing (Lottrup et al., 2013), increased property values (Pandit et al., 2013), biodiversity habitat (Benedict & McMahon, 2002), noise attenuation (Van Renterghem & Botteldooren, 2009), stormwater capture and retention (Coutts et al., 2013a; Czemiel Berndtsson, 2010; DeNardo et al., 2005), and removal of air-borne pollutants (Escobedo et al., 2011). Furthermore, providing vegetation to shade people and surfaces from high solar radiation is also effective at reducing exposure to UV, which can be damaging to people's health (Lemus-Deschamps et al., 2009). Many of these ecosystem services interact in ways that are not yet fully understood. For example, people who are in a good 'frame of mind' from experiencing a pleasant, green vista are less likely to experience temperature discomfort as compared to people experiencing the same measured temperatures in a landscape without vegetation. (Hutchison & Taylor, 1983).

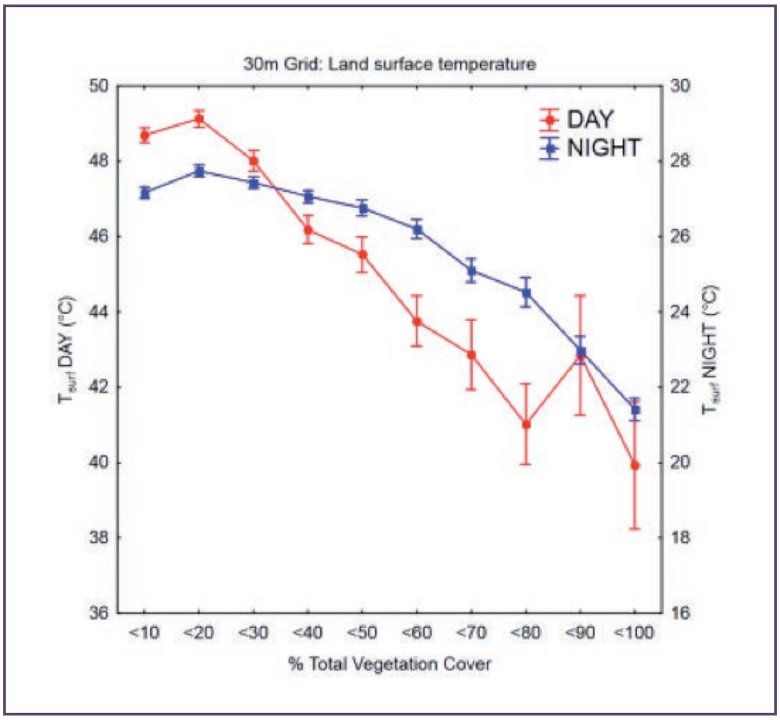

Figure 1: Relationship between per cent total vegetation cover and land surface temperature for both day (left axis) and night (right axis). Vegetation cover is binned into 10% categories. Error bars denote 95% confidence level (Figure 17 from Coutts & Harris, 2012).

UGI implementation needs to be actively undertaken. Private and public green spaces are being lost in Victoria (Victorian Environmental Assessment Council, 2011; Victorian Local Sustainability Advisory Committee, 2011) as they are around the world (Nowak & Greenfield, 2012), so it is critical that planning agencies develop strategies to minimise future loss and to replace what has already been lost. More and more cities have plans for green infrastructure implementation, but their motivation is seldom to provide urban cooling (Bosomworth et al., 2012).

1.2 Scope of this document

We have reviewed and synthesised UGI research into a set of decision steps that aim to provide solutions for cooling urban areas using UGI in Greater Melbourne. The decision approach is flexible and could be adapted to other cities with Mediterranean climates where adaptation to and refuge from hot, dry summers is a key priority. We have highlighted at the end of the document some of the key areas where future research would be beneficial for improving these recommendations. This document provides the scientific evidence to support the Green Infrastructure Implementation Guide. Together they form part of the broader VCCCAR project *Responding to the urban heat island: optimising the implementation of green infrastructure.*

This document cannot replace the role of landscape architects or urban designers who are critical in integrating the competing demands of urban space by designing areas that are useful and attractive. Planning for green infrastructure implementation is also likely to be undertaken in conjunction with environmental and civil engineers. We consider that the information provided here will provide a valuable addition to the suite of tools used by urban landscape management professionals (landscape architects, urban planners, engineers).

2. Introduction to the framework

2.1 Context for the guidelines – where, when and who?

We have integrated existing and new data to provide a general framework for how to retrofit a Melbourne neighbourhood to reduce surface temperatures. Melbourne (37° 49’ S; 144° 58’ E) is situated on the southern coast of south-eastern Australia. It is currently home to over four million people (Australian Bureau of Statistics, 2011a) and is projected to grow to 6.5 million people by 2051 (Department of Planning and Community Development, 2012a).

The focus of this document is on mitigating hot temperatures during summer. Melbourne has a Mediterranean-type climate, with warm, dry summers and cool, wet winters, with an average maximum rainfall in October of 66.2 mm, and an average minimum of 47.3 mm in January (Australian Government Bureau of Meteorology, 2013). In February, the average minimum temperature is 14.6°C and maximum is 25.8°C (Australian Government Bureau of Meteorology, 2013). The maximum solar angle (summer solstice) is 75.6° (Time and Date, 2013). Summer is the period of greatest climatic extremes in Melbourne and is when there are the most climate-related health problems, as heat waves claim more human lives than very cold days in Australia (Nicholls et al., 2008). Internationally, mitigating hot, dry conditions is not always the primary focus, as cold winters may be a more important climate stressor, and in humid areas, mitigation strategies will have a greater emphasis on maximising air flow (Emmanuel, 2005; Erell, 2008; Givoni, 1998, 2010).

This document will consider the thermal environment of public open spaces rather than private domains. Public spaces are managed by local governments, whereas private spaces and buildings are primarily the responsibility of the property owners, making integration of UGI more complicated (Pandit et al., 2013). While the use of UGI to reduce temperatures in public open spaces will also provide flow-on temperature reductions to private spaces and building interiors, there are specific recommendations and different considerations for cooling of buildings and energy reduction at different times of day that are beyond the scope of this document (Akbari et al., 1992; Erell, 2008; Givoni, 1998; Oke et al., 1989; Parker, 1983). Related to this, we also focus on the mitigation of day-time temperatures. The selection, arrangement, location and management of UGI would be different if night-time cooling was the primary objective (White et al., 2012).

This document provides recommendations for retrofitting existing urban areas with UGI, and is not as useful for new suburban developments. However, the principles discussed could guide discussions of UGI in new developments. Greenfield developments have greater potential to incorporate a diverse range of climate sensitive strategies, including designing and orienting streets and buildings to moderate climatic conditions and reducing temperatures (Emmanuel, 2005; Givoni, 1998; Golany, 1983); approaches that are impracticable in existing urban street networks (Gill et al., 2007). Within the scope of retrofitting, we assume there will be possibilities for some modification to the existing urban fabric. For example by modifying existing footpaths, walkways and nature strips, or parking spaces. It is also important to consider not just the present function of a street, but also the possibility that its function might change over time and that UGI may help facilitate this (Kleerekoper et al., 2012).

Although we have attempted to draw generalisations from the literature on what types of UGI will be suitable in different circumstances, appropriate UGI selection will remain context-specific, both in terms of the local climate and soils, as well as the cultural and community values of urban citizens (Bowler et al., 2010; Pataki et al., 2011a).

2.2 Mitigation target

Human thermal comfort

Human thermal comfort (HTC) is related to a person's thermal balance with the surrounding environment. It is a subjective sensation but is based on the physiological conditions of the body (Givoni, 2010). People's perception of HTC is influenced by four microclimatic conditions: air temperature, relative humidity, air movement and mean radiant temperature. Mean radiant temperature is the most important meteorological parameter affecting the human energy balance during daytime summer weather conditions (Matzarakis et al., 2007). Mean radiant temperature represents the total influence of solar and terrestrial radiant heat loading on the human body. Solar radiation has also been shown to be one of the key factors in determining HTC under hot conditions (Brown & Gillespie, 1990; Emmanuel, 2005; Shashua-Bar et al., 2011) and highlights the importance of shading. Surface temperatures are related to radiant temperatures. High surface temperatures increase (terrestrial) radiant heat loading, and are driven by surface albedo, surface materials and surface heat storage. Increasing vegetation cover shades reduces heat transfer into urban surfaces, reducing their surface temperature. Surface temperature mitigation through green infrastructure implementation will therefore play an important role in improving HTC.

Scale of mitigation

Human thermal comfort is affected by conditions in the 'urban canopy layer' (UCL), which is the volume of air from the ground surface to approximately roof-level or tree-top height (Arnfield, 2003; Oke, 2009) (Figure 2). The UCL encompasses two scales of climate: 1) the micro-scale, and 2) the local-scale. The micro-scale refers to the climate of individual elements in the city, for example plants and buildings (from 0-100 m) (Oke, 2009). The local-scale covers areas of 100-10,000 m, approximately equivalent to a suburb, and the green spaces comprised within (Grimmond & Oke, 2002). Beyond the UCL is the 'urban boundary layer' (UBL), which refers to the atmospheric conditions arising from the meso-scale climate (10,000 m + horizontal distance) and is affected by regional climate processes such as topography and rainfall. The UBL refers to climate processes of the whole city or region (Arnfield, 2003; Grimmond & Oke, 2002; Oke, 1988b).

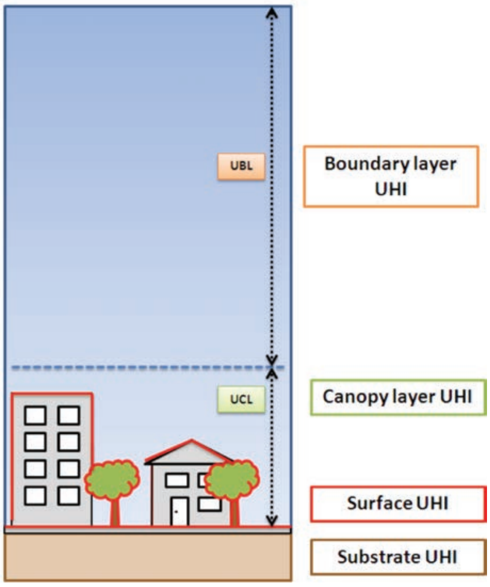

Figure 2: Types of urban heat islands - adapted from Oke (2009)

The climate at each of these scales is driven by different energetic relationships, which become more complex at larger scales (Oke, 2009). The climate in the UCL, which primarily determines human thermal comfort, is driven by micro-scale, site-specific characteristics and processes (Arnfield, 2003; Oke, 1988a). We therefore focus on manipulation of the urban landscape at the micro-scale (local or neighbourhood scale). This is an appropriate level for planning UGI implementation as it corresponds largely with the scale of urban planning and design by local government and other planning authorities (Growth Areas Authority, 2009; The Council of Mayors, 2011). While it is well-established that more vegetation within a city will reduce temperatures at a meso-scale (see references in Section 1.1), there is currently insufficient data at the micro-scale to propose an implementation strategy for green infrastructure at this scale (but see Section 3.4).

Surface temperatures

Figure 3: Example daytime thermal image of a street environment. Yellow are hotter surfaces, purple are cooler (Photo: A. Coutts).

We aim to mitigate high surface temperatures that form the 'surface urban heat island'. It differs from the more commonly cited 'air temperature' UHI, which is a phenomenon usually associated with increased air temperature in urban areas compared to the surrounding landscape, on calm, clear nights (Oke et al., 1991; Oke, 1982). In fact, there are a number of ways in which urban heat islands can manifest, that depend on both scale and whether air or surface temperatures are measured (Harris & Coutts, 2011). The surface UHI has different properties from the air temperature UHI, most notably that temperatures peak during the day rather than at night (Roth et al., 1989). Human thermal comfort is closely related to air temperature (see Section 2.2.1) but is also influenced by surface temperature (Emmanuel, 2005). Surface temperature is an appropriate mitigation target for a number of reasons:

A. Surface temperatures can be compared more accurately between areas than air temperatures because they are not influenced as much by localised wind patterns and wind speed (Brown & Gillespie, 1990; Stone Jr. & Rodgers, 2001)

B. Increased surface temperatures are a key contributor to increased air temperatures and high urban temperatures (Ali-Toudert & Mayer, 2006)

C. Stored and re-radiated heat from dark impervious surfaces with high heat capacity such as asphalt and concrete make an important contribution to the urban heat island (Rizwan et al., 2008)

D. Changes in surface temperatures generally follow the same pattern as changes in air temperature, but the range and rate of change in surface temperatures are of a greater magnitude (Figure 4). Sometimes the relationship between air and surface temperatures is predictable, but not always (Coutts & Harris, 2012; Eliasson, 1992; Jenerette et al., 2007; Roth et al., 1989; Saaroni et al., 2000) particularly under windy conditions (Nichol, 1996)

E. It is possible to make use of remotely sensed surface temperature data at high spatial resolutions to produce a continuous map of the surface urban heat island

F. Approaches to reducing surface temperatures during the day will reduce daytime heat storage, which means less energy is available for release at night, helping to mitigate increased urban temperatures at night in the canopy layer.

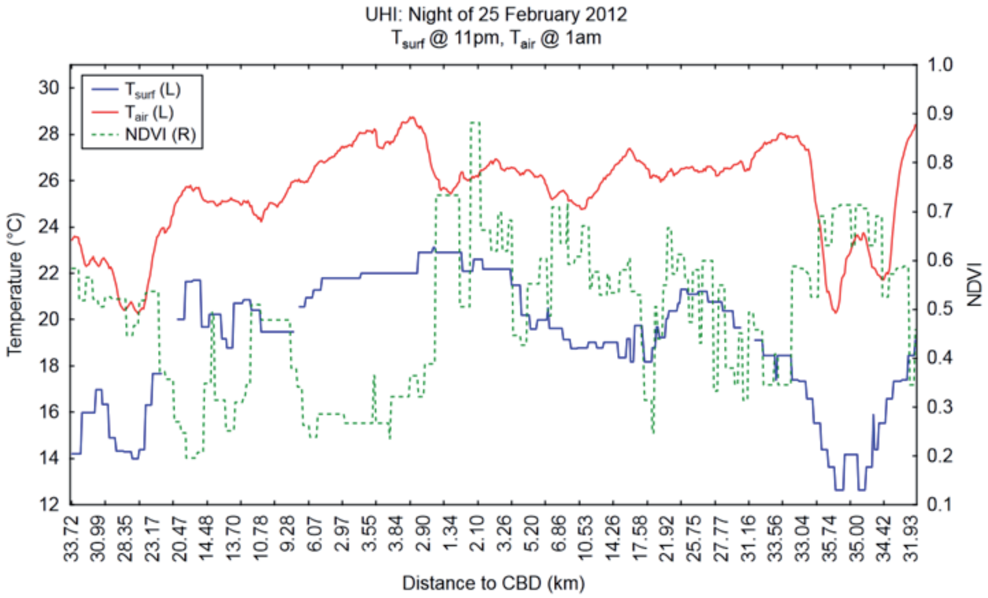

Figure 4: West-East surface and air temperature UHI transects conducted on the night of 25 February 2012, Melbourne, Australia. The air temperature transect is corrected to 1am. The MODIS surface temperature data corresponds to 1:05am (Sunday morning). NDVI values indicate fraction of vegetation cover. CBD was taken as 37° 48’ 51.0906”, 144° 57’ 47.2782” (intersection of Swanson St and Bourke St, Melbourne) (Figure 13 from Coutts & Harris, 2012).

Surface temperatures are an excellent target for mitigation by green infrastructure because one of the key drivers of increases in surface temperatures is solar exposure (Arnfield, 1990), which green infrastructure can reduce through shading or surface coverage. The albedo and moisture of urban surfaces are important determinants of surface temperature increases in response to solar exposure (Erell, 2008). By replacing or covering urban surfaces with UGI, both the albedo and the water availability of surfaces will change, reducing surface temperatures.

It should be noted that most of the research referred to in this report was done under clear, calm conditions on hot days in the middle of summer. The extent of UGI cooling will not be as great under cool or warm days, with cloud and greater wind speeds. A degrees centigrade reduction in surface temperature is therefore not included in this document as it could be misleading, the emphasis is on whether a temperature reduction was observed and what factors maximised the reduction. Two related reports from this VCCCAR project provide indications of the air and surface temperature benefits provided by UGI as measured in different studies (Coutts & Harris, 2012; Hunter Block et al., 2012).

2.3 Other considerations

This document does not cover details of how to deal with infrastructure ownership and cooperation from private land owners. Some of these issues are dealt with in a related report from this VCCCAR project (Bosomworth et al., 2012) but are beyond the scope of this document. The details of engineering restrictions for different types of UGI are also beyond the scope of this document but installation guidelines and requirements for green roofs and green walls will be addressed in the ‘Growing Green Guide’ for the City of Melbourne, available in the second half of 2013 (Inner Melbourne Action Plan).

Cooling using increased albedo and shading structures

UGI is just one approach to mitigate excess urban heat and in reality a mix of approaches are needed for effective climate change adaptation in urban areas, including surface material selection and street design (Akbari et al., 1992; Emmanuel, 2005; Rosenfeld et al., 1995). Cooling using paint to increase surface albedo or artificial structures to provide shade are two common alternative strategies to reduce temperatures in public spaces; although they do not have the wide range of benefits provided by UGI (Tzoulas et al., 2007). Painting buildings in light colours has become a popular strategy for mitigating urban heat (e.g. Carlos & James, 2012) and has the potential to reduce temperatures at a meso-scale (Akbari et al., 2012). Using light-coloured buildings to minimise heat gain is not a new concept, and is based on historical design concepts from the Mediterranean and north Africa (Golany, 1983). Light colours increase the albedo, or reflectance, of surfaces, thereby reducing solar absorption and material heat accumulation and consequently reducing urban temperatures (Rosenfeld et al., 1995; Rosenfeld et al., 1998; Scherba et al., 2011). Converting a black roof to a white roof can sometimes reduce surface temperatures by as much as the addition of a green roof substrate (Scherba et al., 2011; Taha et al., 1988). Other studies have found that the cooling effects of light surface colours are not as great as using UGI under hot conditions (Rosenzweig et al., 2006b; Saiz et al., 2006). However, there is greater opportunity to re-paint buildings and roofs and it can be relatively cost-effective and therefore has a clear role in urban cooling strategies (Rosenzweig et al., 2006b). For a discussion of some relevant issues in Australia, see The University of Melbourne’s report *Cool roofs: City of Melbourne research report* (2011). In deep, narrow canyons where growing UGI may not be a viable option, changing the albedo of surfaces may provide a useful alternative, although the issues of glare must always be considered for pedestrians and road users.

A variety of artificial shade structures are also used in urban areas, including awnings attached to buildings, removable umbrellas and shade sails. These solutions can be beneficial where there are space restrictions on green infrastructure implementation, but in some hot climate cases they can actually lead to higher air temperatures due to restricted air movement (Shashua-Bar et al., 2009), and provide less air temperature reduction than UGI (Shashua-Bar et al., 2011).

2.4 Canyons

The urban 'canyon' is a standard measure of the street environment used by urban climatologists (Arnfield, 1990). It is the area of the street (plus footpath, front gardens etc) bounded by two buildings and is often conceptualised in cross-section. This is a useful unit of study and planning because it ties in well with the urban climatology literature and because the geometry and orientation of street canyons is very important in understanding solar exposure and surface temperatures in urban areas (Arnfield, 1990; Bourbia & Awbi, 2004a, 2004b). The structure of street canyons are diverse and sometimes complex (Ali-Toudert & Mayer, 2007) but research is normally undertaken on simple, standardised scenarios to draw out general principles.

The key properties of the urban canyon (Figure 5) are:

- **Building height (H)**. This is the height of the buildings on one side of the street. In the simplified canyon scenario buildings are the same height on both sides of the street.
- **Canyon width (W)**. The distance between the front of the buildings on either side of the street.
- **Height to width ratio (H:W)**. Canyons with high H:W are tall and narrow, and with low H:W they are short and wide. Consistent relationships can be developed based on H:W that are not possible using the H and W measures separately. The H:W is calculated by dividing the canyon height by its width.
- **Sky view factor (SVF)**. SVF is the amount of sky visible from the ground. This will be reduced if H:W is high (tall, narrow canyon) or if there is a lot of street trees in the canyon. SVF affects how much heat can be released into the atmosphere, particularly overnight.
- **Length of the canyon**. This is the length of the street along one block.

The canyon geometry in many instances influences the climate of the canyon in a predictable way. This is particularly true for surface temperatures.

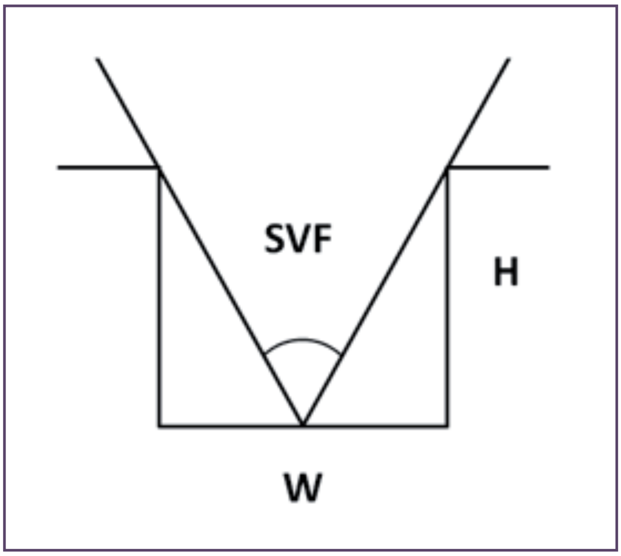

Figure 5: Diagram of a street canyon in cross-section, showing the building height (H), canyon width (W) and the sky view factor (SVF).

3. Decision framework

We have established a hierarchical series of steps to aid the selection of sites for daytime surface temperature mitigation using UGI and the most appropriate UGI for use in those areas (Figure 6). The first step (A) is to identify priority neighbourhoods within the local government area. This is undertaken using information about the demographic and socioeconomic structure of the population. Once priority areas have been selected, existing UGI should be identified and maintained. UGI is more effective and resilient when irrigated, and this can be a low-cost solution to optimising the use of existing resources. The influence of effective irrigation on cooling efficiency of GI is assessed (B) and this is discussed further in Section 3.2. For the implementation of new UGI, particular streets within the area need to be selected (C). Finally, appropriate green infrastructure can be selected for the type of street (D). This document focuses on day-time cooling of surface temperatures. Spronken-Smith and Oke (1998) summarise the key controls over surface temperatures “the presence or absence of shade, the surface albedo and the state of water availability are the most apparent controls during day-time. These properties govern the receipt of solar radiation, its absorption and the role of evaporative cooling.” Once areas have been selected for adaptation (Steps A and C), the focus turns to water availability (Step B), and the selection of UGI to maximise shade, evapotranspiration and increase surface albedo in areas that receive greatest solar radiation (Step D).

The priority hierarchy operates at two main scales. Steps A and B are approached at the local or neighbourhood scale, considering broad patterns of vulnerability and exposure to heat risk. Step C is also at this scale, but requires consideration of individual streets within a neighbourhood area. Finally, the implementation recommendations (Step D) occur between the micro and local-scales, focussing on characteristics of the street. Integrating these two scales for GI planning for cooling is rarely done.

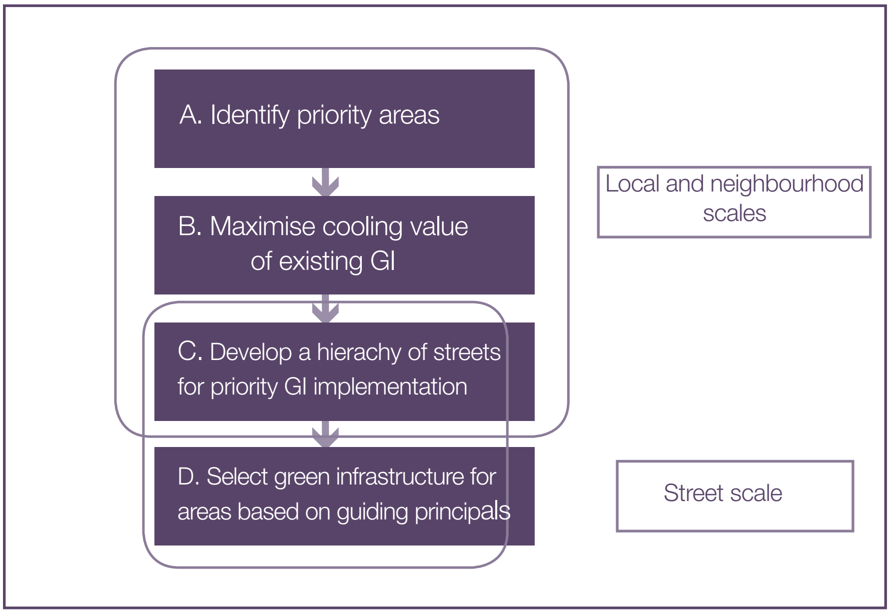

Figure 6: Workflow for selection of most appropriate green infrastructure for cooling surface temperatures contributing to high daytime urban surface temperatures. Details of each step are in the text.

3.1 Section A: Identify priority neighbourhoods

The first step is to select priority areas for the mitigation of high daytime urban temperatures. It is necessary to prioritise investment in UGI to maximise the benefits to the vulnerable sections of the community in the most cost-effective way. Whether a heat-health outcome (e.g. morbidity or mortality) occurs or not is dependent on a person's 'exposure' to high temperatures, and their underlying 'vulnerability'. Areas where both exposure AND vulnerability are high should be prioritised for UGI implementation (Figure 7). To assess exposure and vulnerability, information about 1) temperature patterns during extreme heat events, as well as information about 2) the socio-demographic characteristics of the neighbourhood population is required.

Assessing exposure and identifying areas of high activity

Assessing exposure requires the identification and quantification of hotspots within the urban landscape. It is difficult to collect *air temperature* data across a large spatial area and requires expensive and laborious observations. An alternative approach is the use of **remote sensing** to provide a snapshot in time across a large spatial area of **land surface temperature** as a proxy for air temperature. Determining which neighbourhoods have relatively warmer surface temperatures can be done effectively using satellite or airborne thermal remote sensing. Given the focus on reducing land surface temperatures for improving human thermal comfort, remote sensing of surface temperatures is a good approach.

Various satellite remote data products are available for free from the NASA website including Landsat ETM+ (Enhanced Thematic Mapper), which is freely available on the USGS website[1] and ASTER at resolutions of 60 m (resampled to 30 m) and 90 m, respectively. These spatial resolutions are suitable for identifying hot-spots across a local council or neighbourhood area. These hotspots can then be prioritised for UGI intervention.

Higher resolution airborne thermal remote sensing data (1-5m) can be obtained via aircraft mapping, however the expense of these measurements, data capture and processing issues, and the long data processing times make satellite remote sensing a more cost-effective option. A detailed discussion of these issues can be found in Harris and Coutts (2011) an associated report from this VCCCAR research project. Further information on the use of Landsat and other remote sensing data is available in Coutts and Harris (2012) and Tomlinson *et al.* (2011).

Loughnan *et al.* (2009; 2013) analysed MODIS data (1 km resolution) to assess patterns of heat throughout Melbourne, and provide a useful broad-scale assessment of the magnitude and temporal pattern of excess urban heat in different Local Government Area (LGAs) of Melbourne. These data are at the meso-scale, but identify areas in Melbourne most in need of mitigation during extreme heat events. Location-specific information about temperatures is important because risks to the population of heat waves depend in part on the local climate (Gosling et al., 2009; Kovats & Hajat, 2008; Meehl & Tebaldi, 2004; O'Neill & Ebi, 2009).

At the local and neighbourhood scales (within an LGA) not only is it important to identify areas of high temperature, but to identify areas within these neighbourhoods where people will be active and exposed during the day. Areas with many pedestrians should be identified and prioritised (White et al., 2012). These include shopping strips, public transport interchanges, the location of aged care facilities, pedestrian thoroughfares, schools and the streets around them, areas close to kindergartens, and areas close to disadvantaged populations, for example areas of social housing.

Remotely derived assessments of spatial surface temperature patterns combined with information about areas of high pedestrian activity will determine where people within LGAs are likely to be exposed to the highest temperatures during a heat wave event (Figure 7). Remotely sensed data can also be used to indicate which neighbourhoods have low overall vegetation cover (existing UGI). While a program of increased UGI will be beneficial to reducing overall temperatures within an area, appropriate placement of UGI elements will assist in reducing heat stress for those most vulnerable within the population. In Section 3.4, appropriate spatial arrangements of UGI to reduce heat-related stress to the population at street level are discussed.

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[1] http://pubs.usgs.gov/fs/2010/3026/

Assessing vulnerability

Certain population and demographic groups are disproportionately affected by heat stress during extreme heat-wave events. Ascertaining where these groups are, who they are, and what temperature is considered a risk has become a major research area (e.g. Cutter et al., 2000; Huang et al., 2011; Jenerette et al., 2011; Jenerette et al., 2007; O'Neill et al., 2009). For Melbourne, Loughnan et al. (2009; 2013) have developed methods and produced analyses for broad patterns of vulnerability to heat stress. Loughnan et al. (2009) identified five key indicators of vulnerability; areas with large numbers of aged care facilities, areas with families speaking a language other than English at home, areas where elderly people live alone, suburban areas (in contrast to high-density inner suburbs), and areas with a high proportion of elderly and very young (>65 years,<4 years) citizens.

Areas with high densities of vulnerable populations should be identified when selecting priority neighbourhoods for UGI implementation (Figure 7) but this needs to be done at a finer scale than Loughnan et al.'s (2009) analysis which was done at the LGA level and so cannot indicate which neighbourhoods within an LGA are most vulnerable to heat stress. To understand the patterns of vulnerability within LGA's, similar analyses should be undertaken at the 'census collector district' (CCD) level. O'Neill et al. (2009) demonstrate this in an American context. The information is mostly drawn from ABS Census Data which is freely available. An online assessment tool using this approach at the CCD level has recently been released (www.mappingvulnerabilityindex.com). For alternative methods of collecting and visualising data to determine which areas possess more vulnerable sections of society, see Appendix 1.

Finally, in planning for greening to reduce risks associated with extreme heat events, it is important to consider population projections as well as the current population structure. This is important as Victoria's population structure is projected to change over the current period of forecasting (up to 2051), with the number of Victorians aged 85 years and older expected to almost quadruple (Department of Planning and Community Development, 2012a). Information about expected population growth to 2026 is available from the Department of Planning and Community Development website (2012a). Refer to Appendix 1 for sources of relevant data.

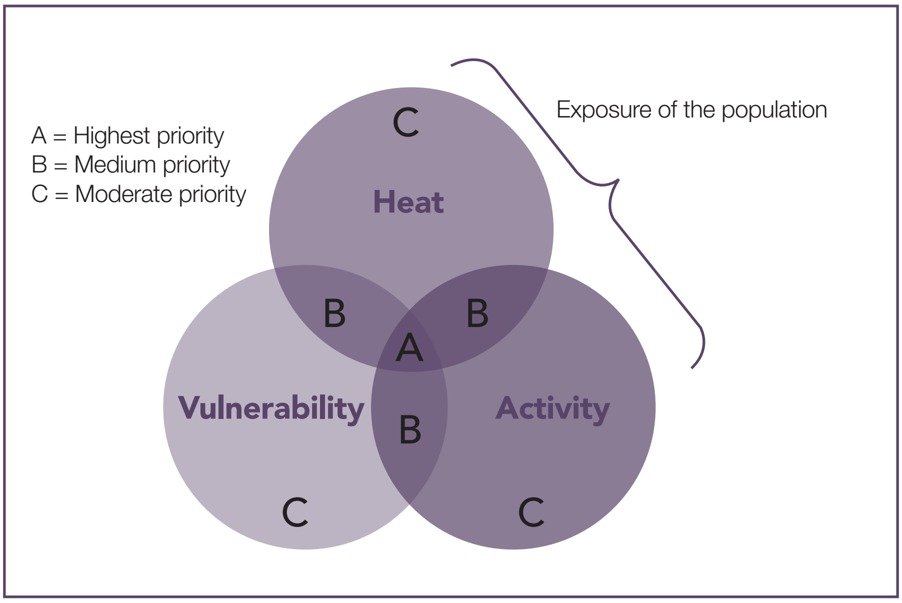

Figure 7: Venn diagram representing factors required to identify areas of high (A), medium (B) and moderate (C) priority for UGI implementation for surface temperature heat mitigation. The key factors are daytime surface temperatures (Heat) and areas of high activity (Activity), which combined indicate areas of high exposure. In addition, areas with high concentrations of vulnerable population groups (Vulnerability) should be identified.

3.2 Section B: Maximise the cooling value of existing UGI

An important first step in mitigating high urban temperatures is to maximise the effectiveness of existing UGI by providing adequate water during periods of dry weather.

Water availability is important as it can assist plants to retain their leaves and physiological function during hot conditions and thereby continue to transpire and provide shade. Evapotranspirative cooling is an important contributor to vegetation enhancing human thermal comfort (see Section 2.2.1). Plants can only continue to transpire if their stomata open and remain open during daylight hours. Under hot and dry conditions some plants will close their stomata, meaning they no longer provide this important function of transpirative cooling during periods when it is most required. The likelihood of stomatal closure depends on the sensitivity of that species to increases in vapour pressure deficit[2]. Furthermore, when plants close their stomata, surface leaf temperatures increase, further contributing to heat gain in the urban environment (Leuzinger et al., 2010). Finally, water is required for plants to grow and survive so sufficient water availability contributes to the long-term survival and retention of established urban UGI, such as mature street trees and turf grassed areas.

In warmer climates like Melbourne's, transpirative cooling by trees can be negligible or non-existent during the hottest hours of the day (late-morning to mid-afternoon), as leaf stomata of most species often close to prevent extreme water loss and plant water stress (Gullo & Salleo, 1988). Urban vegetation is often under water stress because of the large area of impermeable surfaces, which prevent rainfall infiltration, leading to drier soil conditions in urban environments as compared to rural and natural ecosystems (Walsh et al., 2005). Consequently, supplementary irrigation in cities in hot, dry climates is particularly important to alleviate stressful urban soil water conditions and thereby maintain and maximise the cooling benefits that existing UGI can provide.

Water can be supplied to UGI through both irrigation (particularly from sustainable sources) and water sensitive urban design (WSUD). There is a great deal of evidence suggesting that irrigated vegetation will reduce temperatures more effectively than unirrigated vegetation (e.g. Bass et al., 2003; Bonan, 2000; Liu & Bass, 2005). For example, a study in Melbourne found that surface temperatures of unirrigated grass was between 3.6°C and 5.2°C hotter than watered grass (Coutts & Harris, 2012). Grass surfaces are less important than tree canopies in providing human thermal comfort benefits in most urban settings (Ng et al., 2012; Shashua-Bar et al., 2006; Shashua-Bar et al., 2011), but grassed areas can be important in reducing overall air temperatures (Rosenzweig et al., 2006b). However, without any supplementary irrigation, grass will experience water stress more rapidly than trees (Gill et al., 2007) and will 'die-back' much earlier than urban trees. Existing and new UGI should also be integrated to make sure that plants are watered sufficiently to provide cooling benefits, for the reasons discussed here. This issue will be dealt with further in Section 3.4.

A lack of plant water use information makes it difficult to determine the amount of water required to maintain and maximise the performance of different UGI elements. Trees are the best-studied form of UGI, yet there is still very little information available on the water requirements for urban and suburban trees (McCarthy & Pataki, 2010; Pataki et al., 2011b; Peters & McFadden, 2010). Recent research has shown that water use and transpiration rates of street trees varies greatly depending upon the species (McCarthy & Pataki, 2010; Pataki et al., 2011b) and that providing supplementary water provides a more positive cooling effect in areas with little vegetation cover compared to areas with higher vegetation cover (Gober et al., 2009). Until information on plant water use requirements is available, an approach that maximises water availability during drought periods would be prudent, especially for street trees and areas where cooling is particularly important. Water availability for priority UGI elements must be considered, including rainfall input, stormwater capture and redistribution or traditional irrigation using potable or non-potable sources. Water availability needs to be assessed particularly for times of high temperatures and low rainfall.

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[2] Vapour pressure deficit is the difference (or deficit) between the amount of moisture in the air and the amount of moisture the air is able to hold when saturated. Air with a high VPD holds very little moisture.

There is an urgent need for species-specific data on the water use, ecophysiology, thermoregulation and microclimate cooling benefits of different types of UGI in urban settings to inform irrigation requirements.

Water restrictions have become a common response to reduced water availability in Victoria, yet by reducing irrigation to UGI, the ecosystem services provided are reduced; cooling benefits are diminished locally and city-wide, leading to reduced human thermal comfort benefits and increasing energy demands for building space cooling (Coutts et al., 2013a; Gill et al., 2008). Water use on UGI should therefore not be considered ‘wasteful’, but rather regarded as ‘investment’ in ensuring the long-term provision of quantifiable benefits of environmental, social and cultural value (Cleugh et al., 2005). To ensure continuous water supply, areas of key UGI could be made exempt from restrictions allowing use of potable water for irrigation, or alternative water supplies could be established, for example through sewage recycled water systems, grey water or stormwater capture, storage and redistribution (Hunter Block et al., 2012). The role of continued irrigation for urban vegetation to maintain cooling function remains a knowledge gap and critical research issue (Hunter Block et al., 2012).

Direct irrigation will not be the only solution to maintain UGI so it provides cooling benefits. The selection of drought and heat tolerant plant species will also be important in reaching a balance between providing adequate leaf area to shade people and surfaces, and being able to tolerate hot summer conditions in situations where supplementary irrigation is problematic. Where irrigation is not available it will be particularly important to select species that minimise water use while maximising cooling services (Gill et al., 2008). Related issues will be discussed further in Section 3.4.

3.3 Section C. Identify a hierarchy of streets for priority UGI implementation

Prioritising car parks and intersections

This document focuses on UGI implementation in streets because of the large area of the urban landscape in the public domain that they cover. However, we recognise that other urban spaces that are not shaded and covered with impermeable surfaces may also be prioritised. Areas that experience particularly high surface temperatures during the day are **open-air car parks** (Coutts & Harris, 2012). Furthermore, they have high rates of pedestrian use and access. Significant temperature reductions have been achieved in car parks in other countries through UGI implementation, and have even been the focus of UGI implementation policy in some cities (McPherson, 2001; Onishi et al., 2010).

Figure 8: An example of a wide intersection in inner-Melbourne planted with trees and low shrubs (Photo: N. Williams)

Intersections are another location that could benefit from greening. Some intersections are large, open areas of asphalt that heat up significantly during the day from solar exposure as well as vehicle fugitive heat emissions. They can be 1.5 °C to 3.0 °C hotter than other sections of road during daylight hours (Chudnovsky et al., 2004; Saaroni et al., 2000). In roundabout intersections, UGI can be established to increase albedo and provide both shade and evapotranspirative cooling.

Prioritising urban streets

Once priority neighbourhoods have been determined based on urban heat and demographic patterns (Section 3.1), priority streets within those areas need to be identified. Areas with canyon geometries that result in high solar exposure present the best opportunity to improve people's thermal comfort (Section 2.2.1) and are therefore key targets for mitigation.

Selection of appropriate UGI should be based on two key features of prioritised streets:

- Street 'canyon' height and width
- Street 'canyon' orientation

Green infrastructure is important in reducing heat accumulation as much as it is in actively cooling areas (Oke et al., 1989). Therefore, identifying and prioritising streets that heat up the most is the main strategy recommended and explained here. The street width and building height will determine the openness of the street to solar radiation and therefore heat stress in the canyon. The canyon orientation has a further influence on solar exposure, as east-west canyons receive more hours of direct solar radiation than equivalent north-south orientated canyons (Ali-Toudert & Mayer, 2007) (Refer to Section 2.4 for definitions and Section 2.2.1 for a discussion of the influence on pedestrians). Figure 9 shows the amount of sun reaching the floor of street canyons with different geometries at the summer solstice. It demonstrates that UGI will provide less benefit in street canyons with a high degree of self-shading.

Providing sufficient solar access to city-dwellers has been an important consideration in past urban planning (Ali-Toudert & Mayer, 2007; Knowles, 1981), but in hot, dry summers the trade-off is that this can lead to very high temperatures. Street orientation and canyon H:W ratio are particularly important for determining the patterns of surface temperature in a street canyon (Ali-Toudert & Mayer, 2007). Variations to canyon morphology, for example including building overhangs that shade footpaths, can play a role in mitigating canyon climates, but they have a minor role to play compared to orientation and H:W ratio (Ali-Toudert & Mayer, 2007).

Canyon height:width (H:W) ratio

The canyon H:W ratio determines the amount of shade cast by buildings across the canyon floor (e.g. Figure 9). Many studies have shown that wide, open canyons (low H:W ratios) experience higher temperatures during the day due to high solar exposure compared to deep, narrow canyons (high H:W ratios) where shade from buildings is present (Johansson, 2006; Swaid & Hoffman, 1990). This means that we need to be strategic about the placement of UGI in urban canyons to minimise solar exposure and maximise reductions in surface temperature. Here, we present recommendations for UGI implementation based on canyon geometry and the amount of existing shade from buildings. These recommendations are developed for the height of summer (summer solstice) for Melbourne (Figure 9) when the sun is at its highest point in the sky. At other times of the year the sun is lower in the sky and the degree of shading will change.

Another way of thinking about the canyon geometry is to consider the sky view factor (SVF). While the canyon geometry focuses on building height and the distances between buildings, SVF also takes into account other obstructions, such as trees and awnings, and therefore provides a better measure of true solar radiation exposure and long-wave radiation cooling (loss) potential (Coutts & Harris, 2012). Surface temperature is very dependent on SVF because of its relationship with the amount of solar radiation that can reach the canyon surfaces (Bourbia & Awbi, 2004a). At night, there is a linear, negative relationship between SVF and surface temperature which has been demonstrated in a large number of cities around the world and is due to an inverse relationship between SVF and long-wave radiation loss (Bärring et al., 1985; Eliasson, 1990-91; Oke et al., 1991; Oke, 1981; Unger, 2004).

Sky view factor and street geometry are related, and where there are no additional shade providing objects, the effects on surface temperature are the same (Bärring et al., 1985; Bourbia & Awbi, 2004a; Hamdi, 2008). Where trees and other vegetation contribute to further reducing the SVF, the relationship to surface temperature reduction becomes more complex.

Figure 10 summarises all the information presented in Section 3.3, below, and recommends street types for priority implementation of UGI. The recommendations are based on common street geometries in Melbourne. Recognising that local councils and related land managers may have limited resources for public UGI, this table provides guidance on where the biggest potential gains are for urban cooling. All areas would benefit from different forms of UGI intervention, but if a decision must be made, Figure 10 presents a hierarchy for investment.

Wide canyons with tall or short buildings (H:W ≤ 1) receive more sunlight (high solar radiation) during the day because they are less self-shaded by buildings that form the canyon walls (Coutts & Harris, 2012) (Figure 9). They can become very hot during the day, but because the surfaces are open to the sky they can also cool quickly at night. A number of studies have recommended that a street canyon H:W ratio of between 0.5, and 1.0 would be effective geometries at a Melbourne latitude (30°-40°) as they would provide some shading during the day, but retain the potential for heat to dissipate at night (Bourbia & Awbi, 2004b; Mills, 1997; Oke, 1988a), although how practical this is depends on available space (McPherson, 1994). Bourbia and Awbi (2004b) are more generous for streets with a north-south orientation, suggesting that H:W ratios between 1.0 and 2.0 are optimal to balance daytime shading and night time heat loss. Wide canyons can therefore be regarded as priority street types for temperature mitigation using UGI (Figure 10).

Narrow canyons with short buildings (H:W = 1-2) are less well-shaded during the day and can heat up depending on their orientation.

Narrow canyons with tall buildings (H:W ≥ 2) are generally well-shaded during the day because direct solar radiation cannot reach very far down the walls or onto the ground surface (Santamouris & Papanikolaou, 1999) (Figure 9). At night, however, the tall buildings and narrow streets can trap heat and restrict surfaces from cooling down quickly through long-wave radiation loss (Coutts & Harris, 2012; McPherson, 1994; Offerle et al., 2007). This type of canyon structure is where the classic night-time urban heat island is most evident. Deep, narrow street canyons are a lower priority for UGI implementation to provide daytime cooling benefits because of the greater degree of inherent self-shading and cooling during daylight hours (Pearlmutter et al., 1999) (Figure 10).

Canyon orientation

Streets oriented East-West become particularly hot during the day as they receive almost continuous, direct solar radiation (Ali-Toudert & Mayer, 2006). East-west streets are therefore a high priority for mitigation using UGI (Figure 9; Figure 10). If the H:W ratio is low (e.g. 0.5), the east-west oriented street will receive direct solar radiation for 8 hours of the day. The number of direct solar radiation hours will be reduced as the H:W ratio increases (Bourbia & Awbi, 2004a). As a result, there is little temperature variation in the street through the day due to the continuous solar exposure (Bourbia & Awbi, 2004b).

Streets oriented North-South will experience the majority of their sun exposure in the middle of the day (Bourbia & Awbi, 2004a). The actual amount of time the street remains exposed to solar radiation is also related to the canyon's H:W ratio. One study (at 33°N) determined that streets with a H:W ratio of 4.0 would receive direct solar radiation between 10 am and 2 pm in summer, and that as the H:W ratio reduced, the number of hours of solar exposure would increase (Bourbia & Awbi, 2004a). North-south oriented streets are most affected by self-shading (Bourbia & Awbi, 2004b). There will be a lot of temperature variation across the north-south oriented canyon, and across the day, with different sections of the canyon heating up and cooling down at different times. Note that there is a different relationship between shading and H:W ratio in summer compared to winter because of the different solar angle (Bourbia & Awbi, 2004b).

Both the east and west-facing building walls of a north-south oriented canyon can experience the highest temperatures of any surface in a canyon during the day, but they do so for only a short period of time (Bonan, 2000). Time of day is very important for the patterns of temperature increase in north-south oriented canyons: east-facing walls heat up in the morning, west-facing walls heat up in the afternoon (Oke, 1982). As north-south canyons become deeper, they can be heavily shaded, receiving more than 40 per cent shading with H:W > 1.5 (Bourbia & Awbi, 2004b). For these reasons north-south oriented canyons are lower priority targets than east-west canyons, unless they are very wide (Figure 10).

The north-facing (south) side of the street will be the hottest in the southern hemisphere because the north facing walls will receive direct solar radiation throughout the day, while the south-facing walls will remain cooler (Bonan, 2000).

Streets on a diagonal: Surface temperature is highly dependent on the time of day and length of time it is warmed by solar radiation. The greater the street orientation deviates from north-south, the less self-shading from canyon buildings is possible (Bourbia & Awbi, 2004b). Even relatively small changes from north-south can result in greater temperature peaks (Johansson, 2006; Nichol, 1996).

Section C summary

- All wide streets with low building heights are a priority for UGI implementation because of the high solar radiation exposure. East-west oriented streets are the main priority for UGI cooling, especially if they are wide (H:W < 1) (Ali-Toudert & Mayer, 2007; Bourbia & Awbi, 2004b; Coutts & Harris, 2012).
- North-south oriented streets must have lower building heights to benefit from UGI intervention (H:W <0.5) (Coutts & Harris, 2012).
- Streets with higher H:W ratios (taller, narrower street canyons) are lower priorities for UGI cooling because of the existing benefits of self-shading, which means day-time surface temperatures stay low and light availability is sub-optimal for plant growth.

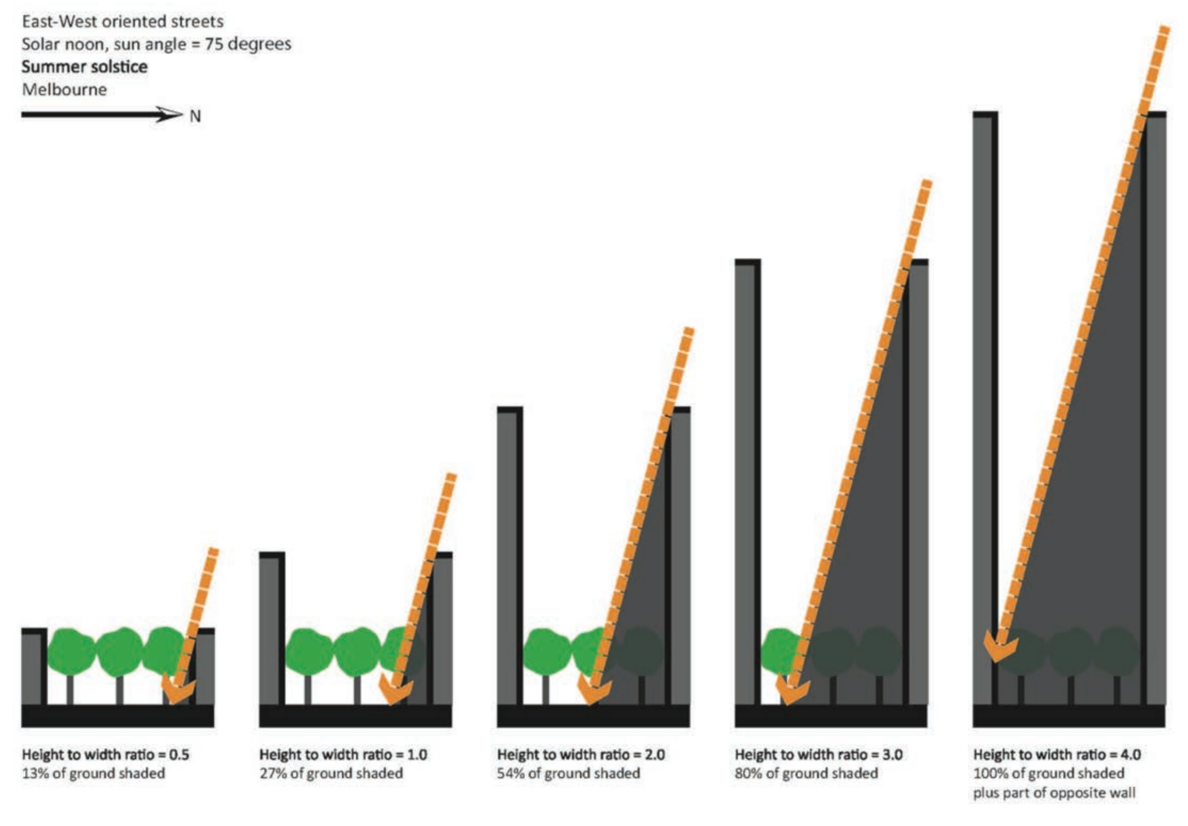
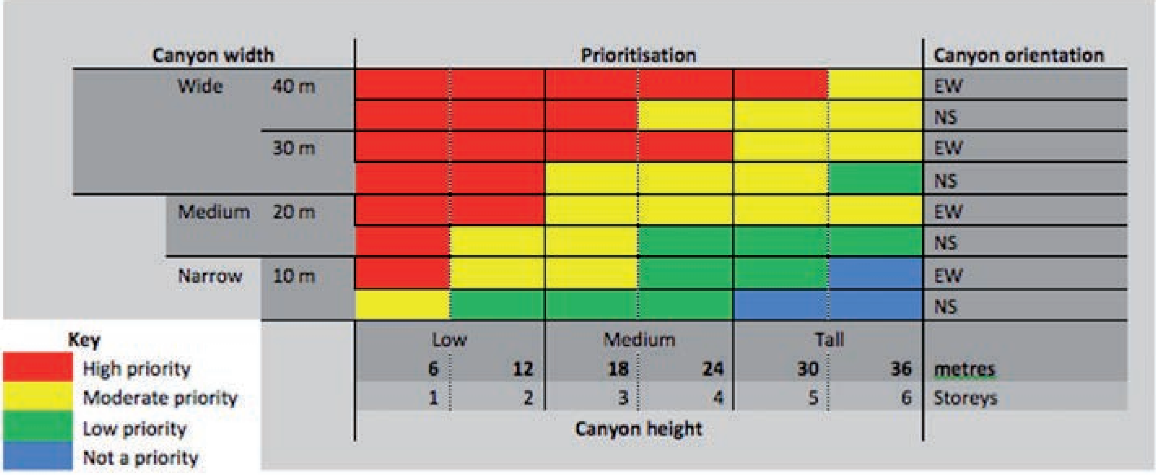


Figure 9: Examples of the different amounts of sun reaching the floor of E-W oriented canyons at noon at the peak of summer, which influences what UGI is suitable.



Canyon width		Prioritisation						Canyon orientation
Wide	40 m	🟥	🟥	🟥	🟥	🟥	🟨	EW
		🟥	🟥	🟥	🟨	🟨	🟨	NS
	30 m	🟥	🟥	🟥	🟥	🟨	🟨	EW
		🟥	🟥	🟨	🟨	🟨	🟩	NS
Medium	20 m	🟥	🟥	🟨	🟨	🟨	🟨	EW
		🟥	🟨	🟨	🟩	🟩	🟩	NS
Narrow	10 m	🟥	🟨	🟨	🟩	🟩	🟦	EW
		🟨	🟩	🟩	🟩	🟦	🟦	NS
		Low		Medium		Tall		
		6	12	18	24	30	36	metres
		1	2	3	4	5	6	Storeys
		Canyon height						

Key
- 🟥 High priority
- 🟨 Moderate priority
- 🟩 Low priority
- 🟦 Not a priority

Figure 10: Classification of streets in priority areas for UGI-based mitigation of daytime surface temperatures at the summer solstic based on the extent of self-shading by buildings. The assumption in this prioritisation is that there is no existing UGI in the street. Increased exposure and higher temperatures lead to reduced human thermal comfort, and therefore sites with high levels of solar exposure and resulting high temperatures are targets for mitigation.

3.4 Section D. Guiding principles for UGI selection

Once priority neighbourhoods have been identified (Section 3.1) and streets have been prioritised within these areas (Section 3.3), appropriate UGI can be selected for the conditions in each street. In order to maximise human thermal comfort, vegetation and other shading elements need to be appropriately combined with canyon orientation and dimensions (Ali-Toudert & Mayer, 2007). Here we provide guidelines on effective integration of these design features for the human thermal comfort of pedestrians and mitigation of excess urban heat at the local-scale. The guidelines for strategic placement and selection of UGI to reduce surface temperatures described here were determined based on temperature data collected from the peer-reviewed scientific literature, as well as a multi-scale thermal assessment of conditions in inner suburbs of Melbourne (Coutts & Harris, 2012).

UGI was defined in Section 1.1 as 'the network of natural and designed vegetation that provides a wide range of environmental and quality of life benefits for urban communities'. A wide range of UGI options are available. We focus here on five types: green open spaces which primarily emphasis public parks, but also includes golf courses, remnant areas and urban agriculture; street trees; green walls and green facades. Biofilters and raingardens are part of water sensitive design (WSUD) strategies which are referred to throughout this section. However if other UGI options such as vine-covered walkways are possible they can also be considered. The information here is based on the available evidence.

Locating UGI within prioritised streets

As described in Section 3.3, both the width and orientation of streets determine where UGI is most required for surface temperature reductions. In summary:

- **East-west oriented streets** receive direct solar radiation throughout the day, mainly on the north-facing side of the street, and therefore both sides of the street are a priority, with a particular emphasis on the south-side of the street;
- **North-south oriented streets** receive direct solar radiation in different places at different times throughout the day:
  - » in the morning the west side (east-facing);
  - » in the middle of the day the canyon floor;
  - » in the afternoon the east side (west-facing).

As such, the east side (west-facing) is the highest priority as solar radiation and background air temperatures are greatest in the afternoon. However, the level of this priority will depend in large part on the H:W ratio of these north-south oriented streets – as the H:W ration decreases (wider streets and lower buildings) increasing attention should be given to both sides of the street in equal measure.

Figure 11: Street trees lining a wide street with low buildings (Photo: E. White)

In both east-west and north-south orientations, as streets become wider and buildings shorter (reduced H:W ratio) there is more direct solar radiation exposure and surface conditions are likely to be hotter during the day. In east-west oriented streets with a low H:W ratio (H:W < 1 (Coutts & Harris, 2012); H:W < 0.5 (Bourbia & Awbi, 2004b)), large-canopied trees on both sides of the street should be selected, while east-west oriented streets with a H:W ratio > 1.0 means that UGI efforts should focus on the southern side of the street as approximately 25-30 per cent of the street will be self-shaded on the northern side (Coutts & Harris, 2012) (Figure 9). Because north-south oriented streets receive less direct solar radiation throughout the day they remain cooler and are generally of lower priority for UGI intervention (Section 3.3). Similarly to east-west streets, however, if a north-south street has a H:W ratio < 1.0, or particularly < 0.5, the canyon will be exposed to solar radiation for much of the day and shade trees located on both sides of the street should be selected (Coutts & Harris, 2012).

Although **narrow street canyons** with a H:W ratio > 2.0 are identified as a low priority for UGI cooling as they are often self-shaded (see Section 3.3), if the street experiences high pedestrian use they would still benefit from UGI installation on the canyon floor and lower walls in particular. Unlike the street floors, canyon walls remain warm at night (Coutts & Harris, 2012; Offerle et al., 2007) and so minimising their temperature gain will be beneficial.

The overall goal for urban temperature reduction using UGI is to maximise green cover. To meet this goal at a city-wide or local government level, green open spaces will be critical because of the significant contribution they make to UGI cover. Within street canyons, the goal is to maximise green cover particularly in highly solar exposed street. Within this, the primary goal is to maximise 'overhead' vegetation canopy cover. Overhead vegetation cover reduces canyon surface temperatures as well as providing shading and transpirative cooling. In most cases tree canopies are the optimal solution for providing overhead vegetation canopy cover because they shade large areas if appropriate canopy structures are selected and well maintained. In addition, they provide many other co-benefits such as aesthetic and cultural value or the absorption of particulate pollutants (Dobbs et al., 2011; McPherson et al., 2005). Trees should be prioritised unless space precludes their selection (Rosenzweig et al., 2006b; Spronken-Smith & Oke, 1999).

The secondary goal is to implement surface vegetation cover, which is vegetation that covers either ground or wall surfaces. This provides benefits in terms of reduction of surface temperatures and transpirative cooling, but no shading. GI options for surface vegetation cover include vertical greening systems, green roofs and grassed surfaces.

Surface vegetation cover is desirable in areas where tree installation is not possible, but a diversity of strategies should be explored to provide a diversity of ecosystem services. Surface vegetation cover provides additional benefits such as structural diversity, recreational space and increased permeability of urban surfaces. For example, if there is a particularly wide footpath in a street, there might be opportunities to turn half of this footpath into a treed nature strip or garden, which can provide effective shade and also changes the surface properties of the footpath, thereby further lowering surface temperatures. Planting of shrubs is not addressed separately in this document. In line with the overall goal to maximise vegetation cover in urban landscapes, planting of shrubs in streetside and nature-strip plantings, should be adopted where feasible. There is currently limited available evidence on optimal planting strategies to minimise temperature gain for shrub plantings, although there is strong evidence that increasing the overall cover of vegetation will assist in reducing urban heat accumulation (Section 3.4.4.3). Plant traits that have been identified as maximising cooling on green roofs are likely to apply to streetside plantings as well (Section 3.4.5). Street verge plantings can also be integrated with water sensitive urban design and biodiversity strategies. Street verge planting will be particularly beneficial in areas where increasing green cover is desirable, but planting trees is not practicable, for example where overhead powerlines compete for space. Options for greening in these scenarios are also addressed in sections 3.4.4, 3.4.6 and 3.4.7.

Figure 12: An example of footpath widening with vegetation added in inner Melbourne (Photo: N. Williams).

Selecting appropriate UGI elements

In the following sections we provide information about the surface temperature cooling provided by different GI elements, and the optimal selection of these for cooling purposes. Two of the key ecosystem services provided by UGI in relation to temperature mitigation are shading and evapotranspirative cooling (Pataki et al., 2011a). We discuss the role of different types of UGI in providing shade and also in changing the albedo of surfaces, which reduces heat absorption and also the radiant heat emitted from the surface (Appendix 2). Both are key priorities for reducing surface temperatures and contribute to improving human thermal comfort (Spronken-Smith & Oke, 1998).

The order of the UGI elements presented in this section is the order of priority given the goal of surface temperature reduction. In all cases there are caveats to whether a particular type of UGI can be implemented effectively (e.g. Figure 1), and therefore although more large green spaces may be desirable, they may not be feasible. In contrast, smaller UGI elements, e.g. green roofs, can potentially be implemented repeatedly to cover large areas. This further substantiates UGI strategies that make use of a variety of UGI elements and approaches.

Green open spaces

Green open spaces in urban areas are primarily grassed areas with a relatively sparse (or absent) overhead tree canopy, such as ornamental parks, sporting fields and golf courses. In some instances there are denser, more complex vegetation, such as remnant forest patches and botanic gardens (Victorian Environmental Assessment Council, 2011). Green open spaces are sometimes referred to as 'Park Cool Islands' in the urban heat mitigation literature. Green open spaces (GOS) provide a locally cooler climate than the surrounding built landscape. These GOS allow nearby residents to seek respite during heat wave events, as well as providing the diverse additional benefits of GOS's, including recreation, socialisation and spending time with nature (Benedict & McMahon, 2002; Bolund & Hunhammar, 1999; Tratalos et al., 2007; Tzoulas et al., 2007). As discussed in Section 1, increasing the per cent cover of green areas in a city leads to significant reductions in temperature at the meso-scale. As the largest form of UGI, green open spaces are therefore critical in maximising the per cent cover of green infrastructure at the city scale.

Effective cooling using green open spaces

Green open spaces (GOS) in urban areas have repeatedly been shown to have surface temperatures several degrees lower than those of the surrounding urban landscape, a temperature difference as large as the UHI difference between urban and rural areas (Upmanis & Chen, 1999). This has been shown in GOS in cities around the world in diverse climates, including in Stockholm, Sweden (Jansson et al., 2007), Sacramento, USA (Spronken-Smith et al., 2000), Vancouver, Canada (Spronken-Smith & Oke, 1998), and Melbourne, Australia (Coutts & Harris, 2012). Modelling at a meso-scale by Rosenzweig *et al.* (2006a) suggested that adding trees to GOS's had a small cooling benefit because the grass already provided significant cooling benefits at this scale. However, grass does not provide shade to pedestrians or GOS users, which is an important component of human thermal comfort in hot climates, therefore for local-scale benefits a combination of trees and grass in GOS is recommended (Table 1, Appendix 2).

Table 1: Urban temperature mitigation provided by green open spaces.

UGI	Trees	
Shades canyon surfaces?	Yes, if grass rather than concrete used	
Shades people?	Yes, if treed	
Provides building insulation?	No	
Increases solar reflectivity?	Yes, when grassed	
Evapo-transpirative cooling?	When water is available to plants during hot, dry periods - Yes	No – if no water available
Priority locations	• *Wide streets with low buildings* – both sides of the street • *Wide streets with taller buildings* –sunny side of the street (south side of east-west streets, west side of north-south streets) • In GOS	

Although GOS can be notably cooler during the day in comparison to the urban landscape, they are not always cooler at night. In fact, the same conditions that favour cooler temperatures during the day (canopy cover from trees and wet surfaces) contribute to temperature retention at night, as both trees and moisture trap heat (Spronken-Smith & Oke, 1998, 1999) though GOS will still be cooler than surrounding urban landscapes dominated by impervious surfaces. The net benefit of the GOS for cooling is likely to be positive.

Not all GOS are equally effective in cooling, and there are a number of features that can increase their cooling effect:

- Adding scattered tree shade. Surface temperatures within a GOS will be variable, but shaded areas are consistently the coolest during the day (Jansson et al., 2007; Spronken-Smith & Oke, 1998). To minimise the retention of warm air under trees in GOS on very hot nights, scattered trees should be most effective, in comparison to a continuous overhead canopy (Dimoudi & Nikolopoulou, 2003; Spronken-Smith & Oke, 1999). In areas of high activity within GOS during the day – shading should be promoted.
- Increasing GOS size. Even small patches of greenery in urban areas will reduce local surface temperatures (Walz & Hwang, 2007) and their core can be as cool as the core of large GOS (Spronken-Smith & Oke, 1999). Yet urban GOS's never reach temperatures as low as those of their rural counterparts (Oke et al., 1989) and bigger GOS have larger areas of low surface temperatures. This is most likely due to hot air moving in from the surrounding urban landscape (Jansson et al., 2007; Shashua-Bar & Hoffman, 2000). The cores of GOS are always cooler than their edges (Chow et al., 2011), so the larger the GOS, the greater the area of cooling, although this relationship is not linear (Chang et al., 2007).
- Providing access to GOS. Given that the cooling effects of GOS are primarily felt within the GOS itself, it is important to provide easy access, local to GOS for as many people as possible so they can experience the cooling and other benefits, for example on foot or on a bike (Giles-Corti et al., 2005). Several studies have suggested that a number of small, accessible GOS may be more beneficial than a few very large GOS (Givoni, 1991; Shashua-Bar & Hoffman, 2000). This strategy would also be beneficial for WSUD implementation across an LGA. Establishing clear guidelines for optimal GOS sizes for urban cooling is still a work in progress (Chang et al., 2007).
- Irrigation. During the day, GOS with irrigated vegetation are notably cooler than the surrounding built landscape (Chow et al., 2011; Roth et al., 1989; Saito et al., 1990), wheras GOS with dry dead grass or bare soil can even be hotter than the surrounding urban landscape (Spronken-Smith & Oke, 1998). Irrigation is therefore important in maintaining and enhancing the cooling effects of GOS, as well as in contributing to the long-term health of the vegetation and attractiveness for amenity use. It will therefore be important to integrate stormwater harvesting into GOS management to ensure sufficient irrigation during hot weather, when cooling services are most important (Coutts et al., 2013a).
- Location upwind of particularly hot urban areas. The extent of cooling provided by GOS to the surrounding landscape is uncertain. The evidence to date suggests that the cooling effects of GOS are highly localised, especially for small, isolated GOS (Bowler et al., 2010; Dimoudi & Nikolopoulou, 2003). The cooling benefits that a GOS provides to the surrounding landscape is focussed on the downwind areas from that GOS (Chow et al., 2011; Dimoudi & Nikolopoulou, 2003; Spronken-Smith & Oke, 1998). In study of parks in Vancouver and Sacramento by Spronken-Smith and Oke (1998), it was found that the downwind influence of the park was restricted to about one park width.Consequently, urban planners should aim to establish GOS upwind of particularly hot areas or those with vulnerable populations (see Section 3.1) (Coutts & Harris, 2012; Hunter Block et al., 2012). More work is required to determine the optimal size, arrangement and vegetation composition of GOS for cooling.

For more information about the cooling potential of grass and trees refer to sections 3.4.7and 3.4.4, respectively.

Opportunities for new GOS's

Finding and acquiring space for GOS's when retrofitting an urban area can be challenging. Some solutions to this may be to maximise the cooling properties of currently unused lots where plants are already growing. If there are wider-scale changes being made to a local area there may be opportunities to create dead ends on quiet streets and to convert these to small GOS, for example.

Green open spaces – summary

- GOS can provide thermal respite from hot urban areas
- Current research is not adequate to suggest clear design guidelines in terms of size and composition of the GOS for urban cooling
- In general, GOS should be upwind of hot areas or areas with vulnerable populations
- The cooling potential of GOS during the day will be maximised if irrigated

Trees

Effective cooling using trees

Trees have distinctively different thermal properties from buildings, which make them suitable for urban cooling (Finnigan et al., 1994; Oke et al., 1989). Of the individual UGI elements (not GOS which are a larger unit) discussed here, trees are the best providers of urban temperature reduction at a local scale (Rosenzweig et al., 2006b) (Table 2, Appendix 2) and have been shown to be particularly effective at reducing surface temperatures in hot, daytime conditions in Melbourne (Coutts & Harris, 2012; White et al., 2012) and in other hot climates (Ali-Toudert & Mayer, 2007). Trees reduce surface temperatures by reflecting and absorbing solar radiation, thereby providing shade. Trees also cool themselves and the air around them at the micro-scale through canopy evapotranspiration.

Conditions in urban environments are often sub-optimal for tree growth and development and although street trees do cool their local environment, the magnitude of the degrees centigrade cooling may not be as great for non-urban trees (Oke et al., 1989) or trees in urban GOS (Leuzinger et al., 2010). Street trees also have shorter life spans than their non-urban counterparts (Hunter Block et al., 2012). One factor that contributes to reduced tree health in street environments is the surface these trees are grown over. Trees have been shown to be hotter and generally poorer in health when grown above concrete as compared to grass (Kjelgren & Montague, 1998). Trees under greater thermal stress from heat re-radiated from concrete or asphalt are more likely to close their stomata, therefore creating a ‘positive feedback’ that contributes to even hotter urban canyon conditions as canopy evapotranspirative cooling benefits are reduced or cease (Kjelgren & Montague, 1998).

Although trees are more stressed when growing over asphalt, when they are in good health urban trees grown over asphalt provide a greater overall urban cooling benefit at the meso-scale than urban trees grown over grass (Rosenzweig et al., 2006b).Trees will always provide some cooling benefit (Georgi & Dimitriou, 2010), but particular features can increase this thermal benefit.

The ability of trees to effectively cool surfaces through shading and evapotranspiration is dependent on how much water is available to their root systems (Finnigan et al., 1994; Pataki et al., 2011a; Pataki et al., 2011b). The water use requirements of street trees, which have different requirements from their forest counterparts, are not yet well understood and further research into critical amounts of water required for different species is an important area for future investigation (Hunter Block et al., 2012; McCarthy & Pataki, 2010; Pataki et al., 2011b). Watering trees is also important for evapotranspirative cooling benefits, which are less important than shade to surface temperature reductions, but does modify air temperature, contributing to neighbourhood-level cooling and human thermal comfort (Fahmy et al., 2010; Hunter Block et al., 2012). Ensuring trees have adequate water by integrating their installation with WSUD techniques could therefore be critical to maintaining canopy health and cooling functions (Coutts et al., 2013a).

Not all tree species possess the same capacity to tolerate extreme urban conditions, such as heat, drought, shade and winds (Leuzinger et al., 2010; Specht & Specht, 1999). Furthermore, urban areas are spatially heterogeneous and not all areas will be equally stressful for all species (McCarthy & Pataki, 2010). Appropriate tree selection for urban conditions will therefore be critical for successful survival of street trees to maintain cooling and other ecosystem services.

The extent of shade provided by trees is dependent on their woody architecture (trunk and branches) as well as their foliar canopy. Trees provide significant amounts of shade throughout the year from their trunk and branch architecture whether they are deciduous or evergreen (Hutchison & Taylor, 1983; Kotzen, 2003), and for this type of shading, broad, wide (i.e. high volume) trees are most effective (Kotzen, 2003). Trees with different branch architecture will provide different amounts of shade (Canton et al., 1994) and tree height, as well as volume, can be important in shade provision by the trunk depending on the shade target. Shorter trees provide more beneficial shade for people during summer conditions because the shade is cast more consistently in the immediate vicinity (White et al., 2012), although tall trees might be required if building shading is the priority (Tooke et al., 2011).

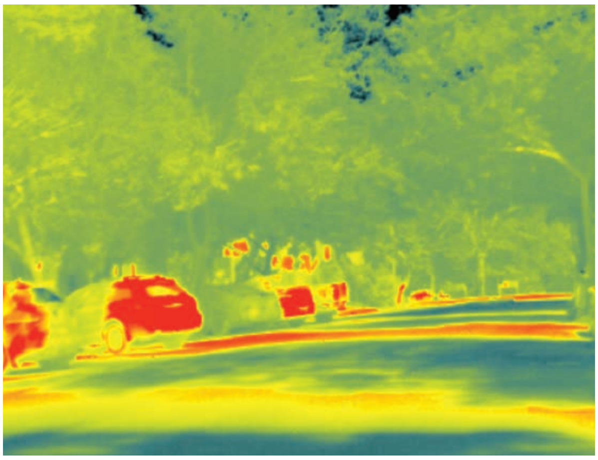


Figure 13: Treed street in inner-Melbourne at night. Blue indicates lower temperatures and red, higher temperatures (image taken using thermal camera. Photo: A. Coutts).

Tree foliar canopies are important for shade provision. The properties of canopies that provide the greatest amount of shade and surface temperature reduction below the canopy are foliage density and leaf area density (Lin & Lin, 2010; White et al., 2012), meaning that broadleaf trees provide more shade than needle-leaf trees (Leuzinger et al., 2010; White et al., 2012). The quality of shade provided by a tree is the result of a number of canopy properties (Meier, 1990/1), although canopy leaf area index (LAI) is a reasonably robust measure of shade quality provision (Hunter Block et al., 2012). LAI does not provide an adequate measure of tree evapotranspirative potential as this is the product of tree canopy properties, soil moisture availability and the local climate (Hunter Block et al., 2012). At the tree level, the amount of shade provided is related to the solar permeability (transmissivity) of the canopy, that is, the amount of solar radiation that the canopy lets through (Canton et al., 1994), and canopy density is important in determining the degree of permeability (Pataki et al., 2011a; Shashua-Bar et al., 2010).

There is an urgent need for studies on the cooling effectiveness of Australian trees in cities, although some data is available from studies overseas (e.g. Pataki et al., 2011b; Shashua-Bar et al., 2006). Melbourne's urban forest comprises more than 1,100 taxa, but is dominated by Australian natives (60 per cent) such as gums (*Eucalyptus* spp.), paperbarks (*Melaleuca* spp.), bottlebrushes (*Callistemon* spp.) and Queensland brush box (*Lophostemon confertus*) (Frank et al., 2006). As such, it is important that we improve our knowledge of Australian native tree physiological performance under harsh urban growth conditions. "Choosing the most appropriate tree species to promote cooling while also ensuring tolerance to current and future climate conditions will be critical, but there is very little data on tree physiological controls and responses in Australian urban environments" (Coutts et al., 2013a).

Although trees provide excellent cooling during the day, the properties that make them valuable as shade trees also mean they trap heat under their canopies at night (Spronken-Smith & Oke, 1999; White et al., 2012). The trade-off between day-time cooling and night-time heat retention in urban areas has not been adequately assessed. One study has shown that sites with little or no tree cover remained slightly warmer than shaded sites the next morning (Walz & Hwang, 2007). However, in Melbourne the net effect of having trees in a street was found to be positive (lower temperature) (White et al., 2012). In order to minimise heat trapped below canopies, trees in residential streets should NOT form a continuous canopy, which will allow hot air to escape in the spaces between trees. A mix of tree species with different canopy closure should be considered for the same reason. Tree diversity will also build resilience into the urban forest (Pauleit, 2003).

In order to maximise the cooling potential of trees for human thermal comfort of pedestrians, it is important to incorporate trees in an appropriate arrangement in relation to street orientation and street canyon properties (Ali-Toudert & Mayer, 2007; Shashua-Bar et al., 2010; White et al., 2012). The cooling effects of trees on human thermal comfort will be modified by being placed in a canyon (White et al., 2012). Trees have been found to be particularly beneficial in wide streets with low buildings (H:W < 0.8) if canopy coverage is > 40 per cent, so large-canopied trees would be beneficial (Coutts & Harris, 2012). In all wide streets, installing trees in the middle of the road (central reservation) will maintain lower road surface temperatures and contribute to neighbourhood-level temperature reductions (Coutts & Harris, 2012). As the H:W ratio of streets increases, i.e. as street canyons become narrower with taller buildings, trees should be prioritised on the side of the street with the greatest sun exposure. For east-west oriented streets this is the south side of the road. On north-south oriented streets this is the east side of the road although north-south streets are of lower overall priority because they self-shade and therefore receive less direct solar radiation (Coutts & Harris, 2012). It has been suggested that for street canyons with a H:W ratio > 3 alternative UGI solutions for cooling could be explored (See Section 3.4). If trees are still preferred then trees with a thin canopy could be useful in a deep canyon so that some daytime shade is provided, but heat release is facilitated at night (Shashua-Bar et al., 2010) Further research to validate and refine thresholds for the density and arrangement of trees for more effective street cooling is critical.


Figure 14: An example of trees planted in the median strip (Photo: N. Williams).

Table 2: Urban temperature mitigation by trees.

UGI	Trees
Shades canyon surfaces?	Yes
Shades people?	Yes
Provides building insulation?	No, unless well-positioned
Increases solar reflectivity?	Yes
Evapo-transpirative cooling?	Yes
Priority locations	• *Wide streets with low buildings* – both sides of the street • *Wide streets with taller buildings* –sunny side of the street (south side of east-west streets, west side of north-south streets) • In GOS

Trees and WSUD

Urban landscapes are often described as deserts because of the large amounts of impermeable surfaces, meaning water is not kept in the landscape. Integrating UGI implementation with stormwater harvesting and WSUD provides opportunities to maintain water in the landscape and can contribute to urban cooling by helping to keep plants alive and functioning optimally (Coutts et al., 2013a). Currently tree pits and biofilters used in WSUD are too small to accommodate the roots of large trees that generally provide the best cooling services, or to store water over longer periods of time such as extended droughts, which is when the water is most required (Somes & Crosby, 2007). To ensure trees receive adequate space and water for their roots, other strategies need to be investigated. For example, permeable surfaces such as grass or permeable pavement would allow more water to filter down and reach tree roots (Volder et al., 2009). Alternatively water could be collected in above or belowground tanks for the purposes of watering the roots during hot, dry periods with timed release of water. This is particularly important as trees in urban areas can be particularly water-stressed due to low water access due to impermeable surface coverings (Oke et al., 1989).

Some practical considerations

Although trees are highly effective in mitigating high daytime urban temperatures through surface temperature cooling, there are some limitations to where trees can be planted (Jim, 1999). For example, an optimal solution for cooling wide urban canyons would be to plant trees down the middle of the road (Coutts & Harris, 2012). In many streets this is not an option due to requirements for car access. Furthermore, the centre of the road is often its highest point, making irrigation from runoff more difficult. If wide streets are to be resurfaced the opportunity to plant trees in the centre of the road and recamber its surface so that it drains to the middle should be considered.

There are opportunities in current street design for tree addition, for example car parking spots could be replaced by curb outstands for trees and other vegetation, for example small shrubs. Placing trees in curb outstands would allow shading not only of the street surface and footpath, but also cars, which become very hot and release hydrocarbons and other pollutants (McPherson, 2001) when they are exposed to the sun. Some Councils are starting to implement these sorts of programmes (City of Sydney, 2011).

Shrubs should cool the area around them through shading of surfaces and evapotranspiration, and have been shown to successfully reduce external wall temperatures (Parker, 1987). They can also be planted in small patches of bare ground where larger plants may not be an option and have other advantages over trees such as smaller root systems and no damaging limbs (Parker, 1987). An alternative form of shading that is particularly appropriate for pedestrian walkways is a vine-covered trellis over a path. Vine-covered archways provide overhead shading similar to a tree, but generally do not require as much space for roots. Shrubs and vines offer opportunities for greening where streets are narrow and urban greening competes with the needs of infrastructure, for example overhead powerlines or streetside bin collection. To maximise greening, strategies such as aerial bundling or undergrounding of powerlines would be optimal. Where this is not possible due to high costs, streetside shrub plantings may provide an alternative. Shrubs can contribute to overall reductions in heat accumulation but do not provide shading to pedestrians as trees do. Growing structures to support vines and other climbing plants (e.g. Figure 15) make overhead shading possible while controlling plant growth to avoid interference with existing infrastructure.

Figure 15: Pedestrian enjoying shade of a vine-covered walkway (Photo: J. Rayner)

Trees – summary

- Trees are an essential element in providing effective urban cooling at micro-, local- and meso-scales
- Maximise tree canopy cover. Dense canopies are best for daytime solar radiation reduction.
- Street tree arrangement affects cooling, wind flow and night time heat release.
- Trees grow best and cool best with supplementary irrigation or WSUD integration

Green roofs

There are two main types of green roofs – extensive roofs, which have thin substrates (2-20 cm) that can support a limited range of plants; and intensive roofs, which have a thick layer of soil, can support a wider range of plants and can function more like a rooftop park (Oberndorfer et al., 2007). Extensive roofs are much more common because they can readily be retrofitted to roofs, while the weight of intensive roofs means they require high weight-loading on a building and are therefore most often installed on purpose-built buildings (Castleton et al., 2010; Oberndorfer et al., 2007; Wilkinson & Reed, 2009).

Effective cooling using green roofs

During the day, roofs are some of the hottest surfaces in urban areas (Chudnovsky et al., 2004; Offerle et al., 2007), and in summer they can be almost 10°C hotter than roads (Leuzinger et al., 2010). High temperatures and large diurnal temperature fluctuations can reduce the life of bitumen and roof membranes. Green roofs reduce both temperature peaks and fluctuations (Liu & Bass, 2005). This effect is particularly pronounced in summer, when cooling is most beneficial (DeNardo et al., 2005). Furthermore, by adding rooftop gardens, heat transfer to the inside of the building is minimised, and there is increased absorption of solar radiation as well as increased evaporative cooling (Table 3, Appendix 2).

Figure 16: An extensive green roof of meadow grasses in Stuttgart, Germany (Photo: N. Williams).

Modelling studies have shown that green roofs can make a significant contribution to local- and meso-scale temperature mitigation (Bass et al., 2003; Gill et al., 2007; Hamdi, 2008; Liu & Bass, 2005; Rosenzweig et al., 2006b). This effect is likely to be greatest for roofs exposed to direct sunlight. Living roofs have been found to offer greater cooling per unit area than light surfaces, but less cooling per unit area than curbside planting of trees at the local scale (Rosenzweig et al., 2006b). As for most vegetation, the night-time surface temperatures under vegetation on a green roof are higher than the surrounding roof, but they are similar to day-time temperatures, equating to lower temperatures overall as well as low temperature fluctuation (Sonne, 2006).

The main role green roofs are likely to play in temperature mitigation is in building insulating, thereby reducing air conditioning loads, especially on buildings with high roof to wall ratios (Hunter Block et al., 2012). Modelling studies have suggested that green roofs will play a role in meso-scale cooling if they are implemented at a large scale, and that the cooling effect of irrigated green roofs is superior to the cheaper option of painting buildings with a high albedo paint (Rosenzweig et al., 2006b). Although green roofs are likely to provide cooling benefits at a neighbourhood scale, and they have a range of additional benefits such as aesthetic appeal and stormwater management, their influence on cooling at street level will be low unless the roof level is close to ground level (Erell, 2008; Ng et al., 2012). Therefore they have been recommended here primarily for large, low buildings and for areas with little room at ground level for urban greening (Table 3, Appendix 2).

Green roofs are an important component of WSUD themselves, as they capture water and slow its runoff from roofs (Czemiel Berndtsson, 2010). Like the other UGI types discussed, they also require water to be effective in providing cooling services. Adequate water availability is critical for plants on green roofs to meet their cooling potential by maintaining healthy plant foliage and evapotranspiration (Lazzarin et al., 2005; Liu & Bass, 2005; Scherba et al., 2011), especially as evapotranspirative cooling has been identified as critical in the effective thermal functioning of green roofs (Wolf & Lundholm, 2008). In a study comparing green and white roof treatments, Coutts *et al.* (2013b) determined that if urban heat mitigation is a key performance objective of a green roof, then irrigation is necessary for green roofs to provide a substantial daytime micro-climate benefit. Currently, irrigation is required to ensure plants on green roofs survive throughout hot periods in southern Australia when they are most useful in cooling (Williams et al., 2010a; Williams et al., 2010b). Compton & Whitlow (2006) successfully tested two species (*Spartina alternaflora* Loisel. and

Solidago canadensis L.) for their capacity to both rapidly take up stormwater and survive extended periods of drought. Similar research is underway using Australian plant species from rock outcrop habitats (Farrell et al., 2013) and this is an ongoing research agenda in Australia as well as overseas (Farrell et al., 2012).

Adding green roof substrate to a rooftop can lead to substantially reduced surface temperatures and temperatures at the roof membrane (Liu & Bass, 2005; Lundholm et al., 2010), but if the substrate is very dry, its surface temperatures can exceed those of the bare rooftop (Wong et al., 2007b). Substantial cooling of the surfaces is only possible with vegetation (Saiz et al., 2006; Wong et al., 2007a). Plants on green roofs reduce surface temperatures and provide cooling to the surrounding environment by shading the roof surface and through evapotranspiration (Saiz et al., 2006; Scherba et al., 2011; Wolf & Lundholm, 2008). There are particular properties of plants that enable them to perform especially well:

- The proportion of the roof covered by vegetation (Sailor, 2008; Wong et al., 2007b);
- Dense foliage (Niachou et al., 2001; Tan et al., 2003; Wong et al., 2002);
- Vegetation height – creeping shrubs are less effective than taller vegetation and tall forbs are particularly effective (Lundholm et al., 2010; Palomo Del Barrio, 1998);
- Greenness – dark green vegetation is more effective than red vegetation (Niachou et al., 2001);
- Some research indicates mixed-species plantings are more effective than monocultures (Lundholm et al., 2010);
- Complex vegetation structures (He & Jim, 2010);
- Large leaves / LAI (Lundholm et al., 2010; Palomo Del Barrio, 1998; Wong et al., 2003);
- Leaf angle – horizontal leaves are preferable (Palomo Del Barrio, 1998).

A problem with these findings is that extensive green roofs have very shallow substrates and are generally only capable of supporting mosses, small plants and groundcovers (Sailor, 2008). Achieving a balance between maximising the performance of green roof vegetation for cooling, while keeping plants alive in shallow soils with minimal irrigation is an ongoing area of research.

Table 3: Urban temperature mitigation provided by green roofs.

<table>
<tr><th>UGI</th><th colspan="2">Green Roofs</th></tr>
<tr><td>Shades canyon surfaces?</td><td colspan="2">Shades roof, not internal canyon surfaces. Depends on plant selection</td></tr>
<tr><td>Shades people?</td><td colspan="2">No - Only on certain intensive roofs</td></tr>
<tr><td>Provides building insulation?</td><td colspan="2">Yes - Plant and substrate selection are important</td></tr>
<tr><td>Increases solar reflectivity?</td><td colspan="2">Yes, if plants are healthy</td></tr>
<tr><td>Evapo-transpirative cooling?</td><td>When water is available to plants during hot, dry periods - Yes</td><td>No – if no water available</td></tr>
<tr><td>Priority locations</td><td colspan="2">• Sun-exposed roofs
• Poorly insulated buildings
• For street-level benefits: low, large building
• Dense areas with little room for ground-level greening</td></tr>
</table>

Some practical considerations

As discussed earlier, the type of green roof (extensive or intensive) that can be installed will depend on the structural properties of the roof. Where a green roof is not possible, for example if the roof is very sloped or has a very low weight loading, the use of a high albedo and emissivity roof coating might be necessary (Section 2.3.1). Wilkinson and Reed (2009) explain the roof properties required for green roof installation. Ideally roofs would be prioritised based on their albedo – darker colour roofs absorb more heat so should be the first targets for mitigation, as well as on the amount of direct solar radiation they receive. In reality, slope, weight-loading, cost and the willingness of private landowners to be involved will play a greater role. Because green roofs are generally installed on privately-owned building, strategies for incentivising green roofs will be required. Issues related to this for the Victorian context are discussed in Bosomworth et al. (2012).

Green roofs – summary

- Intensive roofs are more effective than extensive roofs for cooling but are harder to install
- Green roofs provide building insulation
- For street-level cooling, placement on large, low buildings is more advantageous
- Irrigation is required for extensive green roof plant health, survival and provision of cooling in southeastern Australia's hot, dry summers
- Optimal design of green roofs for southeastern Australia is an ongoing area of research

Vertical greening

There are two main categories of vertical greening: green facades and green (or living) walls. Green facades are climbing plants growing up a wall, either directly onto the wall surface or up a trellis or similar set slightly away from the wall. Green facades can be planted in the ground or in planter boxes at any height up a building. Green or living walls are made up of plants grown in modular panels or hydroponic felt curtains which are attached to the wall, and are a more expensive, resource intensive option.

Figure 17: A green facade of Virginia Creeper, in Weimar, Germany (Photo: N. Williams).

Effective cooling using vertical greening

Vertical greening systems (VGS) have roles in beautifying urban areas and some role in cooling. They are particularly beneficial where space at ground-level is at a premium (Wong & Chen, 2010) or where trees cannot be installed. Both green facades and green walls of different specifications are able to cool surfaces in comparison to bare walls (Wong et al., 2010). While walls facing different directions experience very different temperatures, VGS can equalise the diurnal variation in wall surface temperatures, and therefore the greatest thermal benefit they provide will be to walls that receive the most direct heat from the sun (Kontoleon & Eumorfopoulou, 2010). Walls that are already light colours should not be the first target of mitigation (Givoni, 1998). Because, unlike trees, VGS shade only the surface they cover they would be most beneficial on the south side (north facing) walls of tall, narrow, east-west oriented streets or on the east side (west facing) walls of north-south oriented streets (Coutts & Harris, 2012). These are the sides of the street with the most direct sunlight and minimal self-shading by buildings. In many urban areas there is limited ground area available for trees to be planted, and in these situations VGS could be particularly beneficial (Cheng et al., 2010) VGS should therefore be considered for walls in street canyons with high solar exposure, especially where there is high pedestrian access and where planting a tree is not possible. This includes both narrow streets where space is at a premium and wide streets where there are competing demands for space, such as tramlines or overhead powerlines (Table 4, Appendix 2).

At this stage, it is not possible to make generalisations about the cooling potential of VGS at the meso-scale. Although some modelling studies provide evidence of decreasing air temperatures with increasing vegetation cover of walls (e.g. Alexandri & Jones, 2008; Wong et al., 2009), they are rarely validated with experimental data and are based on assumptions about the extent of greening that are far removed from what is possible with current horticultural techniques (Hunter Block et al., 2012). Most likely, provided VGS are healthy and adequately irrigated, they, like other UGI, will provide cooling at multiple scales.

The cooling potential of VGS at the micro-scale requires additional research, but generally speaking, VGS have been shown to reduce wall surface temperatures, and the magnitude of this reduction is greatest in summer (Hoyano, 1988; Pérez et al., 2011; Perini et al., 2011). VGS cool public spaces by intercepting solar radiation, thereby shading walls, and by providing evaporative cooling (Pérez et al., 2011). Reductions in air temperature have been observed up to 0.6 m away from VGS (Wong et al., 2010). Although plants generally provide a reduction in mean radiant temperature to pedestrians, in very hot conditions the surfaces of plants can reach temperatures as high as an exposed wall, reducing the otherwise beneficial effect of reduced albedo by plants (Oke et al., 1991; Wong et al., 2010). It is therefore important that VGS remain adequately watered (Table 4, Appendix 2). As observed for other forms of UGI, VGS trap some heat at night between the vegetation and the wall surface (Holm, 1989), but this is outweighed by the large cooling benefits over a 24 hour period (Parker, 1987; Wong & Chen, 2010). Similar to green roofs, VGS can reduce indoor temperatures through insulation (Cheng et al., 2010), reducing the transmittance of heat through walls (Hoyano, 1988) and reducing the effects of wind (Pérez et al., 2011) and therefore could lower energy consumption for cooling (Cheng et al., 2010; Perini et al., 2011) (Table 4, Appendix 2). Offerle et al. (2007) state that in dense areas, the majority of daytime atmospheric heating occurs from roofs, with heat release from walls dominating the night atmospheric heating. Implementing VGS could reduce the night-time warming influence of walls in dense canyons, without trapping heat like tree canopies can and so are effective in canyons of high H:W.

Similar to the other UGI elements discussed, keeping plants alive and healthy is critical to VGS providing effective cooling. Having an appropriate and sufficient volume of growing media with adequate water-holding capacity is very important but there has been little research in this area (Hunter Block et al., 2012). The characteristics of VGS plants that are particularly effective in providing cooling services are the percent cover of vegetation, leaf area and foliage density (Köhler, 2008; Wong et al., 2010; Wong et al., 2009). Although different species will provide different degrees of cooling with lower foliage density, as foliage density increases, differences between species are reduced (Holm, 1989; Ip et al., 2010). Some work has suggested that hedges might be a suitable alternative to green walls, and indeed may be more effective in cooling (Givoni, 1991) but their use is likely to be dictated by the available space. Hedges are likely to play a similar role to trees, but with a lower potential for shade provision as they do not have spreading canopies. Hedges or tall, thin trees may be suitable in areas where larger trees are not possible, but where there is more space available than required for a green wall.

Preliminary research from Singapore suggests that climbing plants on a trellis or similar structure set slightly away from the wall may be less effective than green wall systems in reducing surface temperatures (Wong et al., 2010), but the effectiveness of different systems may be improved through horticultural management (Rayner et al., 2010). At this stage there is not enough evidence to determine whether green walls or green facades are more effective at reducing surface temperatures, but appropriate plant selection for difficult urban conditions and a hot, dry climate is likely to play a key role in the cooling potential of any VGS (Hunter Block et al., 2012; Pérez et al., 2011).

Table 4: Urban temperature mitigation provided by vertical greening systems.

UGI	Green Roofs	
Shades canyon surfaces?	Shades roof, not internal canyon surfaces. Depends on plant selection	
Shades people?	No - Only on certain intensive roofs	
Provides building insulation?	Yes - Plant and substrate selection are important	
Increases solar reflectivity?	Yes, if plants are healthy	
Evapo-transpirative cooling?	When water is available to plants during hot, dry periods - Yes	No – if no water available
Priority locations	• Sun-exposed roofs • Poorly insulated buildings • For street-level benefits: low, large building • Dense areas with little room for ground-level greening	

Some practical considerations

Because VGS are often installed on privately-owned building, strategies providing incentives for their constructions may be required. Issues related to this in the Victorian context are discussed in Bosomworth *et al.* (2012). There are many horticultural issues that are still being resolved before VGS are amenable to widescale uptake (Wong & Chen, 2010). Currently there is insufficient practical information available on successful implementation of vertical greening in harsh urban environments, where conditions are often dry, shaded and windy (Hunter Block et al., 2012). This is a problem for modelling studies also, some of which have tried to extrapolate green wall coverage and cooling data to neighbourhoods using unrealistic assumptions about the ability to grow greenery over buildings (Hunter Block et al., 2012). More information about VGS installation and maintenance for Melbourne conditions will be available from the Growing Green Guide for Melbourne (to be released mid-2013) (Inner Melbourne Action Plan).

Vertical greening – summary

- VGS reduce surface temperatures
- VGS provide evapotranspirative cooling if provided with an adequate water supply
- VGS provide insulation and temperature reductions inside buildings
- Plant properties that maximise cooling benefits including canopy thickness and leaf size
- VGS should be considered for any sun-walls where tree installation is not possible
- There is a great lack of research in this area, and much more is required for widespread uptake

Ground cover

One of the key features of urban areas is large-scale changes to the ground surface properties, particularly increased cover of hard, impervious surfaces (Angel et al., 2005; Pauleit et al., 2005). This is a major area of potential modification for urban cooling (Asaeda & Ca, 2000). The properties of ground coverings in urban areas can contribute significantly to increases in surface temperature. While UGI addition is effective in contributing to reducing daytime urban temperatures, impervious surface cover will also have to be reduced for a more comprehensive solution (Myint et al., 2010). Increased permeability of surfaces will assist in integrating temperature reductions and WSUD by improving water availability to plants (Coutts et al., 2013a). Grass would perform this function, but there are also artificial alternatives available such as permeable paving (United States Environmental Protection Agency, 2008).

Road surfaces in particular occupy much surface area in cities and towns and because they are constantly exposed to direct solar radiation in most canyons they become particularly hot (Arnfield, 1990; Oke, 1982). Research in Melbourne has indicated that surface materials are likely to be more important than canyon properties in determining night-time road surface temperatures (Coutts & Harris, 2012).

Shading of impermeable surfaces by trees or buildings to maintain low surface temperatures has been found to be as effective as installing permeable surfaces including grass (Bourbia & Awbi, 2004b; Ca et al., 1998). However, providing tree shade is not always possible and does not increase the cover of permeable surfaces. To increase permeable surfaces grass or low-growing shrubs can be planted (also see sections 3.4.4 and 3.4.6). A study in Melbourne found that increasing the percentage of grass cover in an urban area was an effective way of reducing surface temperatures (Coutts & Harris, 2012). Grass has repeatedly been shown to be cooler than asphalt (Ca et al., 1998; Kawashima, 1990; Leuzinger et al., 2010; Nichol, 1996; Onishi et al., 2010), with temperature reductions up to 25°C (Kjelgren & Montague, 1998). The management of grass is important in maximising its effectiveness. The cooling provided by grass can be spatially and temporally variable, which is likely to be due to mowing (reduces cooling potential) and irrigation (Nichol, 1996). Grass needs to be irrigated to achieve maximum cooling potential especially in hot, dry conditions (Bonan, 2000; Coutts & Harris, 2012).

Artificial grass has increasingly been incorporated into the urban landscape. In a survey of land managers in Victoria this was found to be a popular management option (Bosomworth et al., 2012). This report does not support the use of artificial grass as an appropriate ground cover solution, especially not for the purposes of urban greening and urban cooling. Artificial grass can be as much as 35-60°C higher than natural turfgrass surface temperatures (Claudio, 2008; McNitt et al., 2007).

4. Future directions

A consistent message from this and other related research (Bowler et al., 2010; Hunter Block et al., 2012) is the lack of adequate information available to make some recommendations. Consequently, we have identified some key areas where further research would be valuable. Overall, appropriate replication of research in different climates is critical. Many studies are case studies, or compare different experimental units with no replication or with replication under different conditions, e.g. walls facing in different directions or on different buildings. Until data collection is more robust and standardised, making generalisations will be very difficult.

Implementing green infrastructure can be expensive. To reduce costs, we recommend that its installation be combined with ongoing maintenance and renewal works in an area. This will also aid in the effective integration of WSUD. For example if maintenance on underground gas pipes is required, the road may also be narrowed to create space for trees and water storage tanks could be installed. We have not undertaken a cost-benefit analysis for the green infrastructure solutions suggested because it was beyond the scope of this project. We instead focussed primarily on cooling. Further, much of the information required for a full cost-benefit analysis is not yet available. For example until further research is done on the water and maintenance requirements and life cycle of street tree species, there would be little value in a cost-benefit analysis. The options for greening at the ‘neighbourhood’ scale are many and varied and will depend on the values and vision of the relevant land management authorities, therefore a full economic assessment might be required.

4.1 What green infrastructure properties are most effective for cooling?

There are a number of questions that remain about the selection of UGI based on the properties of the vegetation. For trees, some important questions in the Australian context are:

- What cooling benefits do native street trees offer compared to broad-leaved exotic species?
- Which plant traits will increase tree survival rates under future climate change scenarios, particularly in our southern cities?
- What plant traits will maximise net cooling benefits at local- and meso-scales?
- What vegetation cover rates will maximise net cooling benefits at local- and meso-scales? How do these vary between species and genera?
- What irrigation rates and frequencies are required to optimise climate mitigation performance of native and exotic street trees?

Much remains to be learnt about appropriate plant selection for urban areas. This applies to trees in urban landscapes, but also to novel greening systems such as green roofs and vertical greening systems. Some important questions that remain to be answered include:

- What are the requirements of different plants under stressful urban environments?
- Which plant species can tolerate conditions in VGS and green roofs while maintaining their cooling function?
- What are the water requirements of different VGS plant species options?
- What irrigation rates and frequencies are required to optimise climate mitigation performance of VGS and green roof plants?

To optimally implement public green open spaces (GOS) in urban areas, the parameters of GOS most critical to cooling need to be determined. These include GOS size, the arrangement of trees and shrubs within the GOS and the location of the GOS in the city. Another area identified as important for future decisions about the cooling potential of different UGI options are the tradeoff between night-time cooling and day-time heating: what are the properties of trees that enable them to shade pedestrians during the day, but minimise heat-trapping at night? This question applies both to street trees and trees in GOS.

4.2 Ecosystem service tradeoffs

Quantifying the actual ecosystem services provided by different types of green infrastructure is critical to determining their financial benefits, and less tangible, ecosystem service benefits. This is not often explored experimentally, although there is some discussion of it in the literature (Bolund & Hunhammar, 1999; Coutts et al., 2013a; Pataki et al., 2011a; Tzoulas et al., 2007). Jenerette et al. (2011) provide a robust example of an analysis of water use and vegetation cooling potential in an arid zone.

4.3 Scaling-up

The majority of the studies we have drawn on for this document measured cooling effects of vegetation either at the micro-scale, or at the meso-scale. Understanding mitigation of high urban temperatures using green infrastructure at the local-scale remains difficult and not well studied. Some of the approaches used by urban climatologists working in urban canyons may be useful in approaching these problems (e.g. Hamdi, 2008; Mills, 1997). There are also a range of modelling tools available and in development to undertake this task, and concerted efforts to improve representations of vegetation in urban climate models (Grimmond et al., 2011).

More research is needed in understanding the interactions between different canyon geometries, tree locations and species selections to help establish connections between the spatial arrangement and properties of green infrastructure and the local-scale cooling provided. This is a complex problem, however, and ultimately a combination of field measurements and modelling is likely to be required (Oke et al., 1989). Once more information is available, it might be possible to develop a spatially explicit planning support tool similar to those used in conservation planning (Carsjens & Ligtenberg, 2007; Meyer & Grabaum, 2008; Pettit & Pullar, 1999; Pettit, 2005).

5. Conclusions

Higher temperatures in urban areas compared to rural areas are a problem for human health and wellbeing. The effects of already high urban temperatures will exacerbate the effects of climate change, which include increased frequency of heat wave events. This report used existing literature as well as new data from a component of the same project (Coutts and Harris (2012) *A multi-scale assessment of urban heating in Melbourne during an extreme heat event and policy approaches for adaptation*) to develop a systematic approach for urban land managers to optimise the selection and implementation of different UGI options.

The focus of this document is on daytime cooling of surface temperatures in public spaces. The scale of the decision process is at the Local Government Area (LGA), with smaller areas forming the target for action. A series of steps were recommended: identification of priority neighbourhoods within an LGA; consolidating the health of existing UGI by integrating water sensitive urban design; selecting priority streets within priority neighbourhoods; and appropriate selection of UGI elements for different street properties. The overall goal was to maximise green cover, which is accomplished most effectively using trees. We conclude that a mix of UGI strategies that relies heavily on increased tree planting will be most effective in cooling urban neighbourhoods and maximising the additional benefits provided by UGI.

There are many areas where additional research would greatly improve the recommendations that can be made, for example the optimal size of green open spaces for cooling. A consistent finding from this and related work from this project (Hunter Block et al. (2012) *Responding to the urban heat island: a review of the potential of green infrastructure*) is the need for adequate horticultural knowledge to support appropriate selection of plants. Without adequate research into appropriate plant selection, there is a risk that investment into UGI and green roofs and green walls in particular will produce sub-optimal outcomes. Further research into the water requirements of UGI under Australian conditions is also required.

The integration of information from urban climatology and green infrastructure research approaches is not often attempted and has provided an evidence-based set of decisions for UGI selection to reduce urban temperatures in an urbanising world. This document has identified areas of understanding and areas of future learning that could progress UGI implementation for urban cooling and provides a reference for urban land managers to assist in making complex decisions about UGI investment.

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8 Appendix 1: Sources of additional information on green infrastructure planning and implementation

8.1 Section A: Identify priority neighbourhoods

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9. Appendix 2: Cooling properties of urban green infrastructure options during summer

UGI	Shades canyon surfaces?	Shades people?	Provides building insulation?	Increases solar reflectivity?	Evapo-transpirative cooling?	Priority locations
Green open spaces	Yes, if grass rather than concrete used	Yes, if treed	No	Yes, when grassed	When water is available to plants during hot, dry periods - Yes No – if no water available	• High-density housing. • Upwind of vulnerable communities • Retrofit to dead-end streets
Trees	Yes	Yes	No, unless well-positioned	Yes	Yes	• Wide streets with low buildings – both sides of the street • Wide streets with taller buildings –sunny side of the street (south side of east-west streets, west side of north-south streets) • In GOS
Green roofs	Shades roof, not internal canyon surfaces. Depends on plant selection	No Only on certain intensive roofs	Yes Plant and substrate selection are important	Yes, if plants are healthy	When water is available to plants during hot, dry periods - Yes No – if no water available	• Sun-exposed roofs • Poorly insulated buildings • For street-level benefits: low, large building • Dense areas with little room for ground-level greening
Vertical greening systems	Yes	No	On walls adjacent to pedestrian footpaths - Yes On walls away from pedestrians, e.g. behind a fence - No	Yes	When water is available to plants during hot, dry periods - Yes No – if no water available	• Any canyon wall that receives direct sunlight • Narrow or wide canyons - in areas with pedestrians and where trees aren’t possible

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