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Literature Review

Responding to the Urban Heat Island: A Review of the Potential of Green Infrastructure

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Abstract

In Australian cities, infill development and urban sprawl are leading to the loss of vegetation and the ecosystem services that plants provide. As warming associated with urban development and climate change intensifies, vulnerable social groups will be at greater risk of heat-related morbidity and mortality. There is an urgent need to address this problem without increasing emissions of greenhouse gases. The strategic development of urban green infrastructure can help achieve this goal. This report reviews the Australian and international scientific and technical literature quantifying the cooling and energy-saving benefits of three types of green infrastructure: shade trees; green roofs; and vertical greening systems (VGS) (green walls and facades). International research demonstrates that green infrastructure can reduce surface and ambient temperatures at the micro-scale. However, there is limited research using experimental methods and validated modelling to determine the magnitude of cooling and energy-saving benefits that may be achieved at local-to city-wide scales, particularly for green roofs and VGS. The greatest thermal benefits are achieved in climates with hot, dry summers, particularly if water is available to maintain canopy health and evapotranspiration. Despite this, green infrastructure is not well established in Australia. There is a pressing need for experimental research quantifying the effects of specific plant traits, vegetation health, water availability and soil/substrate composition on the thermal performance of shade trees, green roofs and vertical greening systems. Research to determine the extent, location and mix of green infrastructure required to produce optimal cooling and energy-savings at neighbourhood and city-wide scales, in the diverse climates and ecosystems of Australian cities is also required.

Contents

List of acronyms

HTC	Human thermal comfort
LAI	Leaf area index
LCA	Life cycle analysis
PET	Physiologically equivalent temperature
UBL	Urban boundary layer
UCL	Urban canopy layer
UHI	Urban heat island
VGS	Vertical greening systems
VPD	Vapour pressure deficit

1. Introduction

1.1 Population growth and urban climate warming

Australia is one of the most highly urbanised nations in the world, with an estimated 75 – 82% of the population living in urban areas (Australian Bureau of Statistics (ABS) 2006). Since 2001, greater Melbourne has absorbed 80% of Victoria's total population increase and has continued to grow steadily (ABS 2010; Victorian Local Sustainability Advisory Committee (VLSAC) 2011). ABS projections indicate that by 2056, the population of Melbourne will have swelled to between 6 and 8 million inhabitants, depending on fertility and immigration rates (ABS 2008). In 2008, the Brumby Labor Government published *Melbourne 2030: Planning for Sustainable Growth*, which estimated that in the years to 2030, an additional 600,000 new dwellings would be needed to accommodate Melbourne's burgeoning population, with 284,000 of these to be constructed in outer Melbourne's new growth areas, and almost 316,000 to be built closer to the central business district (CBD), in established areas (Victorian Department of Planning & Community Development 2008).

If this growth were to occur without fundamentally addressing the climate impacts of intensified urban development and global warming, Melbourne will become a much hotter, less liveable city. In comparison to rural areas where built infrastructure is minimal, cities and their suburbs can exhibit significantly warmer air and surface temperatures. Commonly known as the 'urban heat island' (UHI) effect, this phenomenon is particularly apparent on summer nights (Cleugh & Oke 1986), under synoptic high pressure systems, still conditions and low wind speed (Oke 1988). In general, inner urban areas can be 3.5 – 4.5 °C warmer than surrounding rural areas, and it is anticipated that warming associated with the UHI effect will continue to rise by approximately 1°C per decade, over and above that caused by global warming (Voogt 2002). International research indicates that localised temperature increases associated with the UHI effect already exceed those predicted by climate change models over coming decades (Grimm *et al* 2008; McCarthy *et al* 2010). Urban dwellers are increasingly having to cope with the mutually compounding effects of both UHI and climate change. Indeed, Grimm *et al* (2008, p. 758) suggest that the magnitude and effects of UHI 'may represent harbingers of future climates'.

1.2 Urban development and the loss of vegetation

Vegetation cools microclimates by shading heat-absorbing materials, increasing the albedo[1] (or reflectivity) of surfaces, providing evapotranspirative cooling and altering wind patterns (Oke 1989; McPherson 1994; Taha 1997). However, as land is urbanised, large areas of vegetation are typically replaced by materials of high thermal conductivity, high heat storage capacity and low albedo values, such as terracotta tiles, bricks, bitumen and concrete. These materials absorb and store large quantities of solar radiation during the day, and then release it as 'sensible' heat at night (Arnfield 2003). Densely developed urban areas have a distinctive geometry, and are often referred to as 'urban canyons' (Nunez & Oke 1976, p. 122). These canyons have a large three-dimensional surface area with limited sky view, diminishing long-wave radiative loss to the atmosphere and surface cooling (Oke 1988; Stone & Rodgers 2001) (Figure 1).

[1] Albedo value can be defined as the ratio of reflected to incoming shortwave radiation (Tsang & Jim 2011). Materials such as asphalt have a low albedo value compared to that of vegetation.

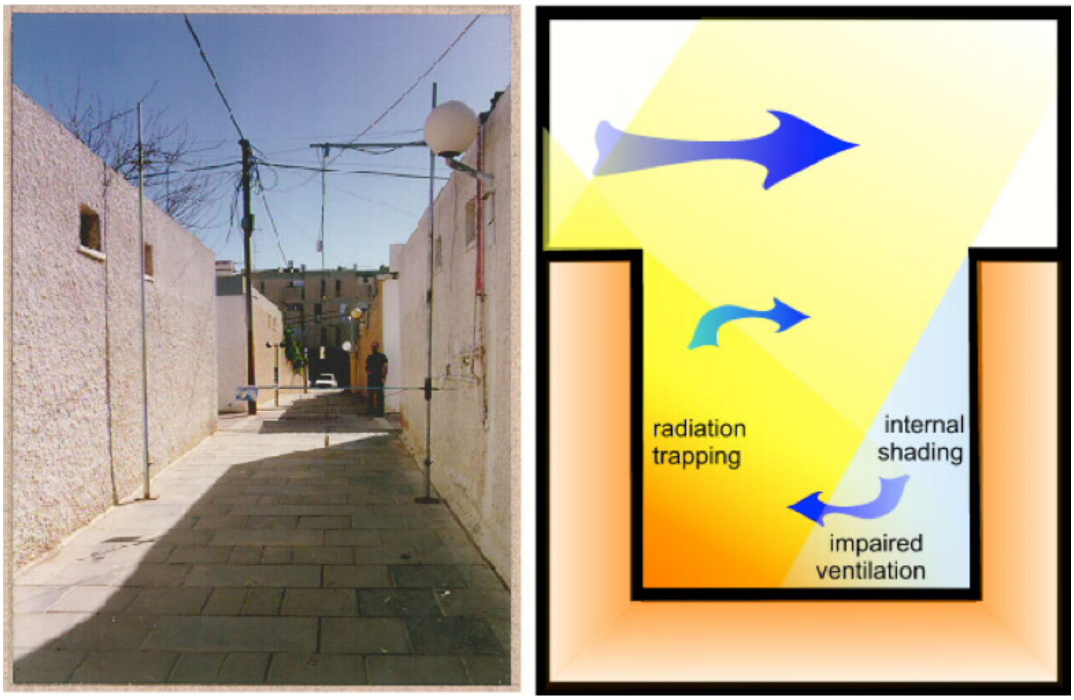


Figure 1: A small scale urban canyon (source Pearlmutter 1998)

As vegetation is replaced by impervious surfaces, water infiltration rates decrease dramatically, resulting in the drier soil conditions common in urban environments (Walsh et al 2004; 2005). Drier surfaces mean that less incoming solar energy is used to drive plant transpiration and soil evaporation, leaving more of this energy to warm urban surfaces (Coutts et al 2007; Oke 1988).

Vegetation is not only lost in the process of urbanisation on city fringes. A recent study on the state of Melbourne's urban forest found that although city councils are generally planting more trees on public land than they are removing, anecdotal evidence suggests that infill development (or 'densification') on private land in Melbourne's long-established inner suburbs has resulted in the removal of large, mature trees and their replacement with small-scale vegetation. An analysis of satellite and aerial imagery in the report indicates that between 2000 and 2009, North Melbourne's tree presence declined by 55% on private land, compared to 18% on public land. By way of contrast, in the middle- to outer-suburb of Broadmeadows during the same period, tree presence declined by only 4% on private land and increased by 38% on public land, due to active tree planting by Hume City Council (VLSAC 2011). These findings are consistent with a study of urban densification gradients in Sheffield, UK, which found that the density of detached housing had a 'positive impact' on tree cover up to a certain threshold, beyond which the quality and quantity of tree cover declined (Davies et al 2008). The loss of large shade trees in Melbourne's inner suburbs is a cause for concern, because this is where localised climate warming associated with UHI effects is most intense.

1.3 The human health impacts of the UHI and heatwaves

In Australia, heat waves claim more human lives than any other natural hazard (Nicholls et al 2008). As urban climates become hotter, heat waves will become more frequent and intense (Alexander & Arblaster 2009). The elevated night-time temperatures associated with the UHI make it more difficult for many city-dwellers to recover from any heat stress they may have experienced during the day (Loughnan et al 2009; Martiello & Giacchi 2010). Higher day and night time temperatures will place vulnerable population groups across all social strata and geographical locations at greater risk of heat-related disease and death – particularly the very young, the frail elderly and those with a pre-existing physical or mentally illness (McMichael et al 2006; Turner et al 2003; Victorian Department of Human Services 2009). These groups often have limited thermoregulatory capacity due to their age and/or medication regime and may not have control over their physical environment, be aware of symptoms of heat stress, or be able to adopt protective behaviours (Loughnan et al 2009).

Several studies have demonstrated that UHI 'hotspots' are not evenly distributed, often resulting in socially disadvantaged groups experiencing greater urban heat exposure (Huang et al 2011; Heynen et al 2003; Loughlan et al 2009; Tomlinson et al 2011). A study by Harlan et al (2006) in Phoenix, U.S., found that disadvantaged socioeconomic groups and ethnic minorities tended to be concentrated in densely populated neighbourhoods with little vegetation and no open space. Consequently, these populations had a much greater exposure to heat stress than more affluent groups. Loughnan et al (2009) found that increased heat-related mortality and morbidity were evident in areas of Melbourne with 1) the highest proportions of aged care facilities (eastern and south-eastern suburbs); 2) households in which English was not the main language spoken (north-west and south-east); 3) socially isolated elderly people; 4) single detached housing; and 5) elderly or very young residents.

The predominance of these variables in explaining the spatial distribution of heat-related vulnerability is largely consistent with international research. A review of 113 European and North American studies of the health effects of heatwaves similarly pointed to the over-representation in heatwave mortality rates of the bed-ridden or hospitalised, recipients of aged pensions or benefits, the socially isolated and those confined to their homes on a daily basis. Socioeconomic factors contributing to heat stress vulnerability included ethnicity, poverty, unemployment and heavy physical labour (Martiello & Giacchi 2010). Studies of the European heatwave of 2003 and the Chicago heatwave of 1995 found that those living on the upper floors of multi-storey residential buildings were at greater risk of heat-related mortality (Semenza et al 1999; Vandentorren et al 2006). Although the UHI effect is greatest in Melbourne's CBD and compact inner suburbs (Torok 2001), some of the city's population groups most vulnerable to increased temperatures live in low-rise suburbs in the north-west and outer south-east (Loughnan et al 2009).

The impact of urban climate warming on the mentally ill should not be overlooked. A study conducted in Adelaide observed that hospital admissions for mental and behavioural disorders rose once ambient temperatures exceeded 26.7 °C. During heatwaves, admissions for these disorders increased by 7.3% compared with control periods. Admissions for senility among the elderly increased more than twofold (Hansen *et al* 2008). Elsewhere, it has been demonstrated that having a pre-existing psychiatric illness more than triples the likelihood of mortality during a heatwave (Bouchama et al 2007).

Mapping the relationship between urban surface temperatures and social groups vulnerable to heat-related morbidity and mortality can enable governments to identify 'hot spots' for priority heat prevention and intervention (Huang et al 2011). In the wake of recent heat waves in Europe, North America and Australia, policy-makers have developed heat wave plans to protect vulnerable populations (see for example, *Heatwave plan for Victoria: protecting health and reducing harm from heatwaves* (Victorian Department of Health 2009); the European Union's guidance for public health policy-makers, *Heat-health action plans* (Matthias et al 2008) and the United Kingdom's *Heatwave plan for England: protecting health and reducing harm from extreme heat and heatwaves* (UK Department of Health 2010)). Plans such as these do not directly address the causes of urban warming, but seek to better protect vulnerable populations through heat alert systems, public health campaigns aimed at improving understanding of heat-related illnesses, vulnerability registers, the provision of cooling centres and additional domiciliary services for the frail aged (Martiello & Giacchi 2010).

1.4 Air space cooling and human health

In the United States and Europe, air-conditioning has been identified as the most important protective factor against heat-related mortality and morbidity (Bouchama et al 2007; Martiello & Giacchi 2010). However, reliance on air-conditioning alone is problematic. Once considered a luxury, energy consumption associated with air-conditioner use has been growing rapidly in Australia, with two-thirds of homes using some form of cooling (air conditioners or evaporative coolers) in 2008, up from 59% in 2005 and 35% in 1999. During the same period, the intensity of cooler use also rose, with the proportion of households using their coolers for three to six months per year rising from 26% in 2002 to 33% in 2008, and those using their cooler for one to three months per year increasing from 35% to 40% (ABS 2010).

The likelihood of power failures increases on very hot days, as people turn on their air-conditioners and energy consumption increases (Rosenzweig et al 2006a; Priyadarsini 2009). During the Victorian heat wave of 2009 (26 January – 1 February), twenty-five per cent of hospitals experienced problems with their air-conditioning systems, public transport systems were severely disrupted, and on Friday 30 January, 500,000 people were left without power for several hours (O'Keefe 2009; Victorian Department of Human Services 2009). Moreover, anthropogenic heat generation associated with air-conditioning systems create positive feedbacks, increasing external ambient temperatures. For example, Ohashi et al (2007) found that air-conditioners in the Tokyo CBD increased external air temperatures by as much as 1-2 °C. While air-conditioners cool the air within the buildings, the risk of heat-related mortality and morbidity is not diminished outside buildings, particularly for those who work outdoors, who rely on public transport, or who are homeless.

1.5 Green infrastructure for UHI and climate change adaptation

Green infrastructure, the "interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations" (Benedict & McMahon 2002, p. 12), has the potential to conserve and maintain climate-regulating ecosystem services. These ecosystem services include the carbon cycle (photosynthesis, respiration and growth), nutrient cycles (for example, exchanges of nitrogen between soil and atmosphere) and water balance (plant transpiration, interception of rain and runoff) (Pataki et al 2011).

Green infrastructure can re-establish – at least to some extent – the ecosystem services of shading and evapotranspirative cooling, improving thermal comfort both within and around buildings and reducing energy demands for summer cooling (Del Barrio 1998; Sailor 2008; Sailor et al 2008). It can achieve this without significantly increasing greenhouse gas emissions, which on a per capita basis are large in Australia, due to the heavy dependence on brown coal for electricity production. Green infrastructure also offers a range of other benefits, including the provision of accessible green spaces 'close to home' for those living in densely populated areas (Alexandri & Jones 2008); improved human health (Tzoulas et al 2007); stormwater capture and retention (Buccola & Spolek 2011; Rowe 2011); the creation of habitats for other species (Solecki & Rosenzweig 2004; Lundholm & Richardson 2010); noise attenuation (Van Renterghem & Bottledooren 2009); and the trapping of air-borne pollutants (McPherson et al 1997; Morani et al 2010; Escobedo et al 2011).

A growing number of cities around the world are developing strategic and integrated green infrastructure strategies to cool urban climates. In Germany, several cities including Stuttgart, Bremen, Dresden, Nurnberg and Berlin are preparing, or have developed, strategies for climate change adaptation and mitigation (Baumueller & Baumueller 2011). One of the key objectives of Stuttgart's strategy is to facilitate the nocturnal movement of cool air through urban areas by expanding open space and increasing vegetation cover. No large-scale constructions are permitted in areas critical for maintaining air-flow, the felling of large trees is prohibited, restrictions have been placed on the laying of impervious surfaces and financial incentives and regulatory measures have facilitated the expansion of green roofs. As a result, 39% of the city's surface area is protected by nature conservation orders (Kazmierczak & Carter 2010). In the United Kingdom, the Liverpool City Council's (2012) green infrastructure strategy seeks to 'manage UHI effect particularly as it affects vulnerable communities' (Liverpool City Council 2012). In South Australia, the *Adelaide green city sector agreement* (Adelaide City Council and the Department of Premier & Cabinet, Government of South Australia, 2010), has been established to encourage, among other things, the 'greening' of buildings and additional plantings in the city's streetscapes to provide shade, cooling and greater connectivity with the city's extensive parklands.

1.6 Green infrastructure for Australian cities

The intensity and rapid pace of urban development places green infrastructure at risk in cities all over the world. For this reason, there is a pressing need to quantify and value the ecosystem services provided by green infrastructure (McPherson et al 1997). This report reviews the Australian and international scientific and technical literature in relation to three types of green infrastructure: shade trees; green roofs; and vertical greening systems (green walls and facades). It focuses on research quantifying the cooling and energy-saving benefits of each type of green infrastructure at micro-, local, and city-wide scales, and thus the potential of green infrastructure to mitigate the effects of urban development and climate change in medium- to high-density areas of Australian cities. Knowledge gaps, priority areas for further research and issues associated with selecting green infrastructure systems for certain scenarios will be discussed.

One of the key organising concepts in this review is spatial scale. In urban climatology, there are three nested scales within and between which energy fluxes are studied:

- the micro-scale, which refers to surface energy balances of individual elements, such as plants, buildings and gardens and streets (from 0-100 metres);
- the local- or neighbourhood-scale, which refers to contiguous private gardens, streetscapes, local public parks and suburbs, covering horizontal areas of 100 – 10,000 metres (Grimmond & Oke 2002); and
- the meso-scale, which refers to city-wide and regional climate processes, occurring across horizontal areas exceeding 10,000 metres, and encompassing the entire city-wide network of parks, street trees, reserves, green wedges and private gardens (Arnfield 2003; Grimmond & Oke 2002; Oke 1988).

This report will evaluate the available research for each type of green infrastructure, at each of these three spatial scales. It will identify the scale at which studies have been conducted and highlight those types for which there is need for further research.

In addition to the spatial scales delineated above, urban climatologists identify two distinct urban atmospheric layers: the 'urban canopy layer' (UCL) and the 'urban boundary layer' (UBL) (Oke 1988; 2009) (Figure 2). City-dwellers live within the UCL – that is to say, the volume of air extending from a depth below ground surface at which energy exchanges are insignificant to approximately roof level. Containing buildings, vegetation and other surface elements that create friction or 'roughness', the UCL determines the ambient climate around buildings and vegetation, and thus, human thermal comfort (Arnfield 2003; Oke 1988; Oke 2009). Airflow and energy exchanges within the UCL are largely determined by microscale, site-specific characteristics and processes (Arnfield 2003; Oke 1988).

Operating at meso-scale, the 'urban boundary layer' (UBL) lies immediately above the UCL. It extends 'from the top of the UCL, to a height where urban surface influences are no longer perceptible' (Oke 1988, p. 474-475). The UBL is influenced by regional climate processes, such as topography and rainfall.

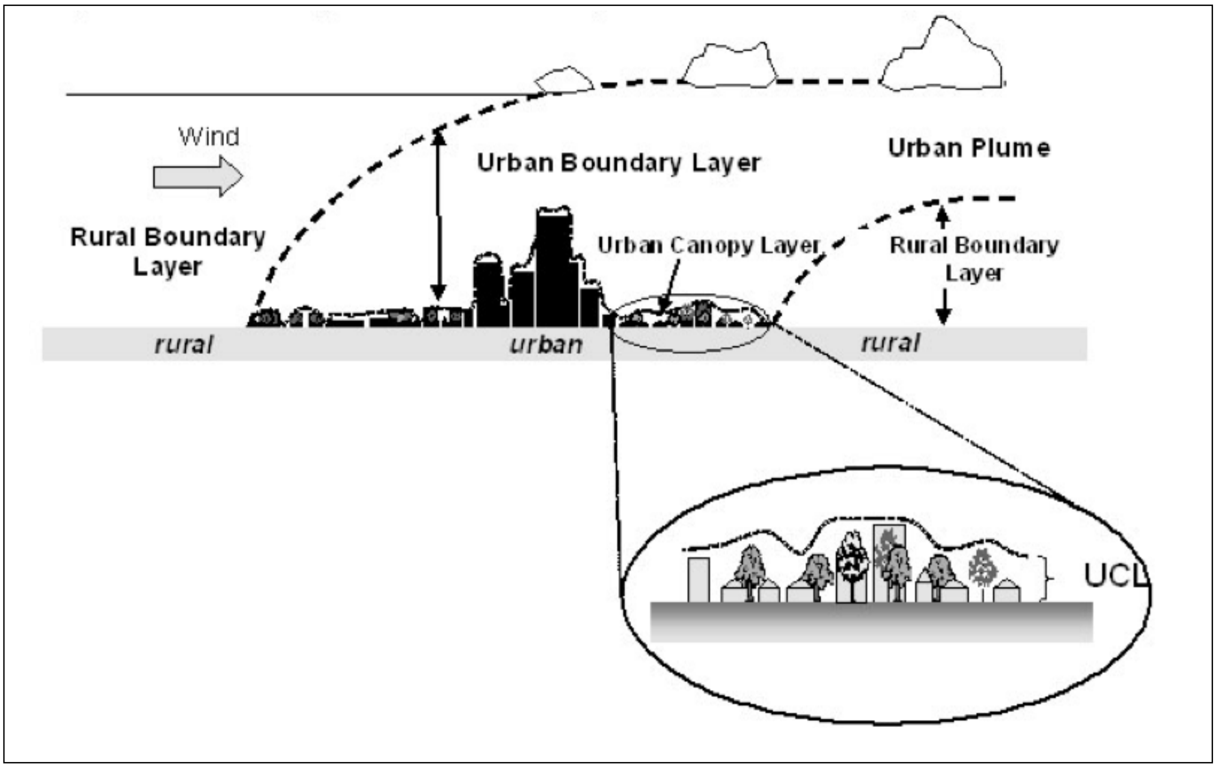


Figure 1: Components of the urban atmosphere (source: Voogt 2004)

It is at the micro- and local-scales within the UCL (homes, workplaces, city blocks, streetscapes and local parks) that people experience the thermal effects of UHI and climate change. Consequently, it is at this scale that the potential benefits of green infrastructure will be felt. It is also at this scale that the effectiveness of green infrastructure can be most directly measured. Because of the wide variety of environmental niches found in urban areas, many of the studies reviewed use observational research methods that do not permit comparisons to be made between studies. This highlights the need for controlled experimental research, rather than reliance on observational methods alone. Modelling methods are most commonly used in research investigating the meso-scale effects of green infrastructure. Where a modelling approach is adopted, the assumptions underlying the model should be clearly delineated and the model itself validated by fieldwork (Oke 1989).

2. Trees

2.1 The urban tree population

In response to climate change and urban development, government agencies and local communities in Australia, North America, Europe and Asia are moving to increase urban tree cover thereby increasing the ecosystem services provided by urban vegetation (for example, the City of Melbourne's draft *Urban Forest Strategy 2012-2032*, which proposes to mitigate urban warming by increasing tree canopy cover from 22% to 40% by 2040; the 'Million Trees' initiatives developed by the City of Los Angeles and New York City; and the City of Toronto's study of its urban tree population, *Every tree counts: a portrait of Toronto's urban forest).*

One of the key ecosystems services provided by trees is the provision of shade and cooling. Considerable efforts have been made in the preceding twenty to thirty years to quantify the cooling and energy-saving benefits of trees and shrubs (see for example, Heisler 1986; Akbari et al 2001, 2002; Grimmond et al 1996; McPherson & Simpson, 2003; McPherson et al 2005). It has been suggested that increasing tree canopy cover and total green space is one of the most cost-effective strategies for cooling buildings and local neighbourhoods (Akbari et al 1988).

Urban areas can be a relatively hostile environment for trees, due to high impervious cover, low soil moisture, soil compaction, nutrient and trace element deficiencies and toxicities, lack of rooting volume, frequent soil disturbance and air/water pollutants (Craul 1985; McCarthy & Pataki 2010; Peters et al 2010). Urban tree canopies are often subjected to low vapour pressure deficits, anthropogenic heat sources, air turbulence or conversely restricted air movement, vandalism and heavy pruning. Urban trees may also be exposed to high wind speeds in inner-city canyons and higher ambient air temperatures than adjacent rural areas. The capacity of a tree to dissipate the high heat loads and evaporative demands typically encountered in built-up urban areas depends on its own morphological and physiological features, water availability and wind strength (Oke 1989). Not all tree species provide the same degree of cooling, nor do they possess the same capacities for heat and drought tolerance (Leuzinger et al 2010; Specht & Specht 2002).

The species composition of many urban forests is the product of pre-settlement ecosystems and the history of human land-use and cultural practices since (Pataki et al 2011a). Melbourne's urban forest comprises more than 1100 taxa, but is dominated by Australian natives (60%), with wattles (*Acacia* spp.), gums or eucalypts (*Eucalyptus* spp.), paperbarks (*Melaleuca* spp.), bottlebrushes (*Callistemon* spp.) and Queensland brush box (*Lophostemon confertus*) representing 43% of the total urban forest population (Frank et al 2006). The city centre and inner suburbs are dominated by deciduous broadleaf trees (*Ulmus* spp., *Platinus* spp., *Fraxinus* spp.) common in European cities, whereas central and outer suburbs are dominated by these native Australian species interspersed by a smaller proportion of exotics (Fairman et al 2011).

The morphological and physiological characteristics of urban trees differ from those of natural and managed forest trees of the same species. Urban trees tend to be more open-grown and isolated compared to forest trees of the same species (Peper & McPherson 2003). Nowak (1994) found that the above ground biomass of open-grown trees was 20% less than forest-grown trees of the same species and diameter. Similarly, Peters et al (2010) found that equations developed to predict leaf area in forest-grown trees overestimated measurements for the same species in the urban environment by 26%. Compared to natural forest ecosystems, data on the structure, morphology and ecophysiology of urban trees and the urban forest is relatively scarce, as is empirical evidence for the important ecosystem services that urban trees and other green spaces provide.

2.2 How trees modify urban microclimates

The distinctive thermal, aerodynamic, morphological and physiological characteristics of trees and other vegetation can be used to moderate urban microclimates[2] by providing 1) shade, 2) evapotranspiration and 3) altering the movement of air (Oke 1989).

2.2.1 Shading

Trees intercept incoming solar radiation, shading surrounding heat-absorbing materials. In this way, they reduce surface and ambient temperatures and heat gain to buildings and other infrastructure. Trees also intercept diffuse radiation reflected from the sky and surfaces such as glass, cement and roofs, altering the exchange of heat in urban systems (Akbari 2002; Shahidan et al 2010). Outside a building, it is not simply air temperature, but also radiation exchange that determines human thermal comfort. A vegetation canopy can aid human thermal comfort outside a building by direct shade but also by reducing solar radiation reflected from ground and building surfaces (Shashua-Bar et al 2011). The quality of shade provided by a tree is determined by factors such as placement, canopy height and architecture, and leaf size and structure (Brown & Gillespie 1995; Kotzen 2003).

The amount of solar radiation that a plant canopy actually intercepts is determined by morphological characteristics, such as clumping or continuity within the canopy, the size, type and angle of leaves, the depth or density of the canopy layer(s). A plant canopy intercepts and dissipates solar radiation via reflection, absorption and transmittance (Specht & Specht 2002). Reflection is the bouncing or scattering of some of the solar radiation back into the atmosphere, and is greatly influenced by leaf structures, leaf epidermal characteristics, and leaf angle. Absorption of radiation by a foliar canopy is principally determined by the chlorophyll and water content of its leaves. The absorbed radiation may be dissipated as heat or consumed through photosynthetic electron pathways. Transmissivity is a dimensionless ratio indicating the proportion of total solar radiation transmitted through a canopy layer to the surface or objects below. Commonly, a simple Beer's law approach is used to describe the amount or proportion of solar radiation passing through a horizontal, homogeneous canopy layer (Hardy et al 2004).

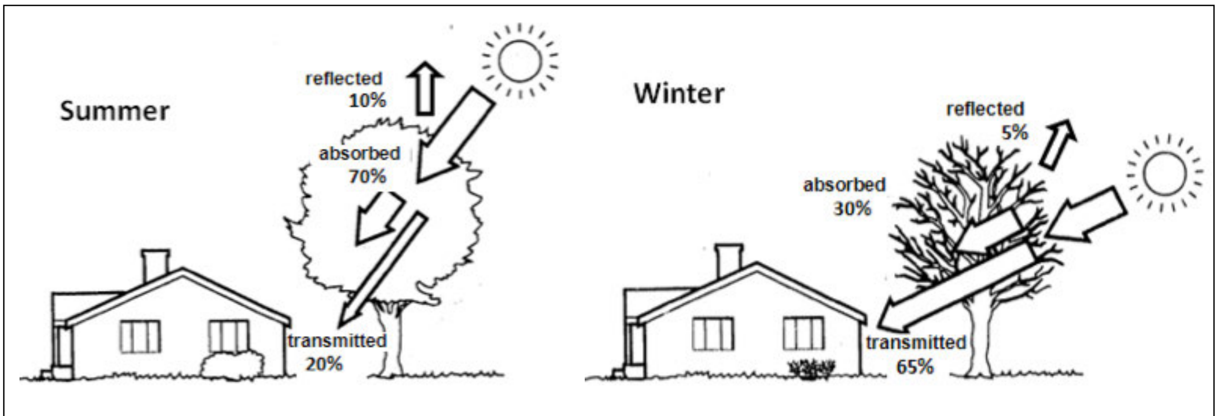


Figure 2: General proportions of summer and winter solar radiation that is reflected, absorbed and transmitted through a deciduous tree canopy. Note that an evergreen tree canopy in winter would be similar to those presented above for summer. Based upon Heisler et al (1988) and Brown and Gillespie (1995).

Studies have identified several tree attributes that influence the quality of shade provided, including, leaf area, high branching density, multiple canopy layers, canopy transmissivity, canopy size and projection and canopy ventilation (which enables convective heat loss). Canopy branch architecture can contribute significantly to the overall canopy transmittance.

[2] 'Microclimate' has been defined as '[t]he condition of solar and terrestrial radiation, wind, air temperature, humidity, and precipitation in an outdoor space' (Brown & Gillespie 1995)

The contribution of trunk, branch and twig architecture to shading is often underestimated. For example, Heisler (1986) found that even when leafless, *Acer saccharum* reduced solar radiation level below by nearly 40%. Obviously, regardless of differences in branch architecture, a deciduous tree will provide very different patterns of seasonal shade provision and solar radiation reduction as compared to an evergreen species.

Leaf area

Leaf area is a key measure of shading potential by tree canopies and an important parameter in modelling the ecosystem services provided by individual trees and the urban forest. Leaf area index (LAI) is a dimensionless ratio parameter that is defined as (Kjelgren & Montague 1998; Ong 2003):

$$\frac{\text{the total 'single-sided' leaf area of a canopy (m2)}}{\text{the ground area (m2) directly under the crown 'dripline'}}$$

LAI will be high for a tree with multiple layers of foliage cover and thick, large leaves, and low for a tree that has few branches and sparse or clumped leaf cover and/or fine leaves.

A recent urban study of two contrasting tree forms provides an illustration of how reflection, absorption and transmissivity contribute to a net reduction in the solar radiation received beneath or behind a tree canopy. Shahidan et al (2010) quantified shade area, LAI and transmissivity to estimate solar radiation reductions. The tree species *Mesua ferrea* reduced incoming solar radiation by 93% with a canopy transmissivity of 5%, LAI value 6.1 (very high), whereas Hura crepitans trees reduced incoming solar radiation by 79% because of its much smaller LAI value of 1.5, but this was partially compensated for by the greater leaf emissivity (or reflection) value of 22%.

2.2.2 Evapotranspirative cooling

As stated, plants dissipate solar radiation that they intercept through reflection, absorption and transmittance (Specht & Specht 2002). The solar radiation absorbed by leaves is converted in part to heat whilst some contributes to photosynthetic energy pathways. In response to these absorbed heat loads, plants are able to cool their leaves through three mechanisms: conduction, convection and transpiration. Conduction is the passing of heat energy to the air mass in direct contact with the leaf, convection is the enhanced loss of heat energy to turbulent eddies of air (wind movement) that pass around the leaf. Transpiration is the conversion of water within the leaf to water vapour, which is then released to the atmosphere through the leaf stomata. Transpiration involves latent heat loss in the conversion of water to vapour, thus cooling the leaf and the surrounding local microclimate. Transpiration is only possible whilst leaf stomata are open to enable water vapour loss and the concurrent uptake of carbon dioxide for photosynthesis to occur in the leaves (Wong et al 2003; Kumar & Kaushik 2005). Without transpiration many leaves will 'overheat' on full-sun, summer days, leading to damage of photosynthetic and physiological apparatus and possibly leaf loss through abscission.

Evapotranspiration is the combined effects of i) evaporation from soil, vegetation and building surfaces and ii) transpiration of internal leaf water into water vapour (Specht & Specht 2002). These evapotranspiration processes all convert some of the sensible heat from received solar radiation into latent heat, or rather latent "cooling", as some of the heat is used up in the conversion of water from a liquid form to a vapour form (Taha 1997: 101).

2.2.3 Wind flow patterns

Vegetation can alter wind patterns and advection, on the one hand diminishing the 'windchill' factor of winter winds and the infiltration of cold air into buildings, but on the other, potentially obstructing cooling breezes in summer (Meier 1990/1; Akbari et al 1992). In general terms, it has been estimated that in a low-density suburban context increasing tree cover by 10% can decrease wind speeds experienced around buildings by up to 10-20% (Heisler 1988). However, the impact of trees on reducing windspeeds will decrease as urban density and building heights increase. Interestingly, even a leafless deciduous tree canopy in winter can reduce local wind speeds by 50-90% compared to that experienced in an open area (Heisler & Dewalle 1988).

Huang et al (1990) modelled the impact of reduced wind speeds upon building energy use in six US cities and the impacts reflect local climatic conditions. Reduced wind speeds resulted in lower building space heating costs, but in certain cities the cost of summer space cooling increased due to the restriction of beneficial cool breezes. Trees (and shrubs) can be used to direct or influence wind directions. Providing shelterbelts is an obvious example, but funnelling cool breezes towards a building is also possible (Akbari et al 1992).

2.2.4 Tree LAI and cooling potential

In urban areas, relationships between vegetation cover density and evapotranspiration rates are evident (Grimmond & Oke 1999), and several recent studies propose that LAI be used as an indicator of tree cooling of urban surface temperatures (Hardi & Jensen 2007; Ong 2003; Peters & McFadden 2010). LAI can 'provide a measure of the total amount of leaf surface area that can exchange heat, water, and CO2 with the atmosphere' (Peters & McFadden 2010). However, the use of LAI as an index of cooling potential raises several issues. Firstly, LAI is dynamic. It changes in response to the phenology of deciduous trees, but for all trees it can change in response to vapour pressure deficit (VPD) , soil water availability, seasonal temperature variation, stomatal conductance, incident light levels, soil nutrient availability and tree maturity (Whitehead & Beadle 2004). This obviously provides a strong link to the 'potential' transpiring surface, but presents the need for frequent or constant monitoring or quantification.

Secondly, although LAI indicates direct tree shade potential, it is an indirect indicator of potential evapotranspirative cooling, as these are a product of the interaction between VPD, air temperature, stomatal conductance, tree hydraulic status, soil water availability and wind speed. Thus, a tree species with high LAI and sensitive stomatal conductance (stomata close when VPD increases) may achieve the same annual transpiration and therefore evaporative cooling as another tree species with low LAI but stomatal conductance that is less sensitive to increasing VPD (Whitehead & Beadle 2004).

Thirdly, LAI cannot accommodate the many different and complex strategies that plants use to maintain hydraulic status and therefore transpiration processes under i) high heat loads, ii) high VPDs and iii) low soil water availability. Strategies used include: leaf structure (small leaves, hairy or silvery leaves, fewer stomata); leaf longevity; deep root systems; dormancy; leaf orientation; leaf senescence; stomatal control; and osmotic adjustment (Chaves et al 2002; Lo Gullo & Salleo 1988; McCarthy & Pataki 2010; Specht & Specht 2002; Werner et al 2001). Indices other than LAI, that are able to accommodate various morpho-anatomical and physiological features will best reflect the overall capacity of a species to either withstand dry conditions or conversely provide evapotranspirative cooling with adequate water supply (De Micco et al 2008).

2.2.5 Tree selection, water supply and extreme temperatures

There is an immediate opportunity to increase the species diversity (and therefore ecosystem resilience) of our urban forests. Trees in cities have radically shorter life-spans than those in natural and managed forest ecosystems (Akbari et al 1992). Whitlow et al (1992) noted that urban street trees in the north-eastern United States had an average life expectancy of approximately ten years, with up to half of those early tree deaths occurring in the first year after planting. As such, through council tree replacement and renewal it is quite conceivable that an urban council could change the species mix of the vast majority of trees planted on public managed land within a 20-year time frame.

In climates with hot, dry summers, the selection of trees on the basis of high LAI alone could lead to increased tree mortality rates in the absence of sufficient water supply, as high LAI generally correlates with drought vulnerability (Whitehead & Beadle 2004). In selecting trees for high water use and therefore cooling of urban environments, the specification of high LAI alone will not be sufficient. Water availability must be considered, through rainfall input, stormwater capture and redistribution or traditional irrigation, so as to enable those potential transpiration rates to occur at times when they are most beneficial; that is to say, during extended periods of high summer temperatures and VPD.

Another critical issue that must be considered when selecting tree species for urban settings is vulnerability to extreme temperature events and/or extended drought. The selection of tree species and complete urban vegetation systems based upon drought tolerance and xerophytic characteristics is a justifiable alternative to the selection of high LAI trees with high water needs requiring supplementary irrigation (Gill et al 2008). This system (or approach) is apparent in Mediterranean and semi-arid cities and urban areas – and enables some limited evapotranspiration through hot summer periods whilst maintaining constant shade and solar radiation reduction benefits. The maintenance and infrastructure support requirements are greatly reduced and green cover may be maintained throughout the harshest of heatwaves, although the cooling benefits may be less than that for a broadleaf and irrigation supported tree canopy.

One way of increasing climate change resilience and maintaining ecosystem services is to create and sustain a high species diversity within the urban forest population, rather than relying on a small set of key species (Muller & Bornstein, 2010). For example, the City of Melbourne's draft *Urban Forest Strategy 2012-2032* (City of Melbourne 2011) recognises the futility of selecting tree species based upon cooling potential if their growth is poor or they die within a few years of planting because they lack the drought tolerance or avoidance mechanisms to persist in the harsh thermal and hydrological conditions common in urban centres. Furthermore, tree species that drop leaves (senescence) under high temperature conditions are not suitable for urban plantings in climates where ambient air temperatures can reach more than 35 °C, as UHI conditions will often push temperatures beyond critical leaf physiological thresholds. Once a tree has dropped all or some of its leaves, its ability to provide shade and evaporative cooling benefits is greatly reduced for the rest of that growing season or summer period – ie. the time when cooling benefits are most needed. In addition, all of the other ecosystem services provided by trees to city-dwellers, biodiversity and the environment are greatly compromised. For example, *Platanus X acerifolia* (London Plane) is a common urban tree in temperate and Mediterranean cities throughout the world, but it experiences leaf drop at high temperatures.

If soil moisture is not limiting, and leaf stomata are open, transpiration will increase in response to increasing VPD and/or increasing wind speeds, up to a maximum stomatal conductance rate for that tree species. The maximum transpiration rate is physically limited by the stomatal conductance limits of leaves for any given tree species. Under extended or intense VPD and/or high wind conditions, canopy transpiration will decrease and subsequently cease as stomata close to maintain plant water potential above critical levels. This mechanism prevents xylem cavitation, which can lead to plant death (Chen et al 2011; Whitehead & Beadle 2004; Hernandes-Santana et al 2008).

In warmer climates, such as Mediterranean or dry tropical, transpirative cooling by trees can be negligible or non-existent during the hottest hours of the day, usually between late-morning and mid-afternoon, as leaf stomata close to prevent extreme water stress (Lo Gullo & Salleo 1988). In such climates, supplementary water supply can be critical to maximising the rates and periods of transpiration cooling benefit. In addition, in all climates, transpirative cooling can be limited if either the air or water supplies are polluted; particulates are deposited on leaves thus blocking stomata; or air movement is restricted due to street canyon geometry (Oke 1989).

Observations of tree water status under actual street conditions are largely absent (Whitlow et al 1992). Very little is known about the water use of different tree species commonly used in urban and suburban ecosystems, particularly mature trees (Pataki et al 2011b; Peters et al 2010a; Whitlow et al 1992). In a sample of young street trees in Manhattan, Whitlow et al (1992) found evapotranspiration was driven by atmospheric demand (VPD) rather than by soil water deficits. In a sap flux study of three tree species in Royal Park, Melbourne, Misra and Sands (1992) observed that *Ulmus procera* and *Melaleuca styphelioides* had similar maximal rates of leaf level transpiration with increasing VPD, but stem sap flow in M. *styphelioides* was greater than U. *procera* at high VPDs. This suggests that for trees with comparable sapwood areas, M. *styphelioides* will extract more water from the soil and provide greater canopy transpiration than U. procera (Misra & Sands 1992). This does not mean that the cooling benefit of M. *styphelioides* is greater than U. *procera*, as the issues of direct canopy shade and canopy cover should also be considered.

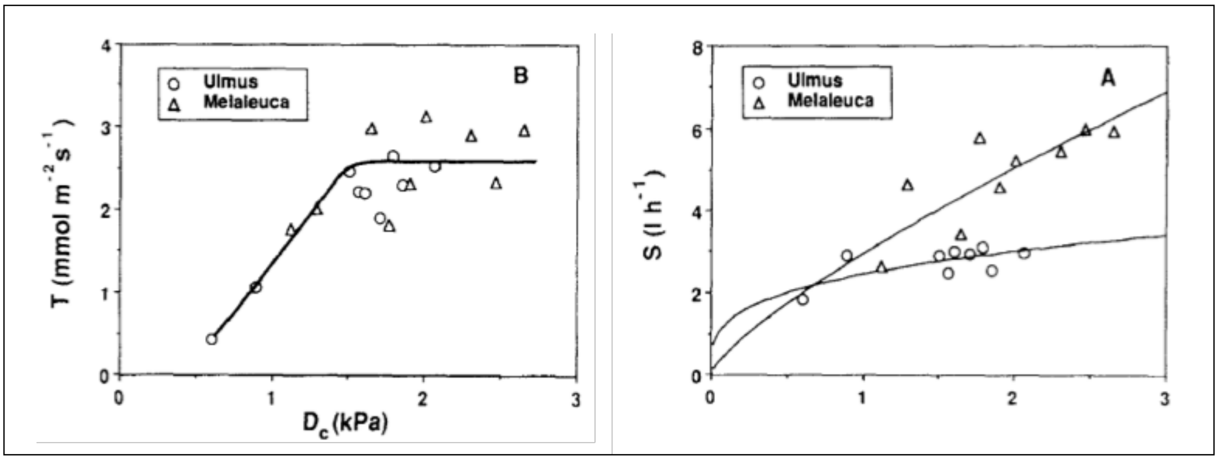


Figure 3: The relationship between leaf level transpiration (*T, left*) and stem sap flow (*S, right*) with increasing vapour pressure deficit (VPD) in *Ulmus procera* and *Melaleuca styphelioides* trees in Royal Park, Melbourne. Taken from Misra and Sands (1992).

Measuring sap flow in a sample of urban trees in street and gardens of Los Angeles, Pataki et al (2011b) similarly found that canopy transpiration increased with increasing VPD, but also observed that there were large differences in canopy transpiration on an area basis associated with tree species and tree density, even after accounting for variables such as tree size and sapwood depth. *Planatus* hybrids, *Ficus macrocarpa* and *Gleditsia triacanthos* showed high rates of whole tree transpiration. Australian species, *Brachychiton populneus*, *Brachychiton discolor* and *Eucalyptus grandis* exhibited lower whole tree transpiration rates, but not as low as those measured for *Jacaranda mimosifolia* and *Pinus canariensis*. There is an urgent need for this type of species-specific data on the water use, ecophysiology, thermoregulation and microclimate cooling benefits of trees in urban settings – i.e. a more quantitative and mechanical understanding of urban tree function (McCarthy & Pataki 2010).

2.3 Micro-scale effects of trees

2.3.1 Canopy shade for Human Thermal Comfort (HTC)

At the micro-scale, trees are able to provide an excellent means of reducing the thermal load received by building roofs, walls and impervious ground surfaces. This can greatly improve building thermal comfort levels and reduce energy used in, and greenhouse gases produced by air conditioning on warm/hot summer days. Similarly, trees can improve human thermal comfort along walkways where people may otherwise be exposed, and at critical positions in the urban landscape where people gather outside, such as bus/tram stops, children's playgrounds, inner-city plazas and car parks.

The microclimatic conditions that principally influence perceived human thermal comfort are:

- air temperature, which influence body temperature increase/decrease through conduction;
- relative humidity, which influences the body heat loss through sweating (evaporation);
- air movement, which influences both convective and evaporative heat loss from the body; and
- mean radiant temperature, which is the sum of radiative energy impacting the body from all directions. This includes direct solar radiation but also heat radiating from walls, cars and the ground.

The combined effect of these factors provides a fair indication of the microclimatic impacts upon human thermal comfort (Brown and Gillespie 1995). In hot, dry environments (such as city centres), evapotranspirative cooling provided by trees and green space can dramatically improve human thermal comfort if adequate irrigation is provided (Pearlmutter et al 2009; Shashua-Bar et al 2011). The ultimate thermal comfort of an individual is also greatly determined by other non-climatic factors such as his or her age, health, activity (walk, run), clothing layers, hydration, anxiety and mental state/attitude. Taking into account these factors, human thermal comfort is often quantified in terms of 'physiologically equivalent temperature' (PET), according to Hoppe (1999).

Brown and Gillespie (1990) used a micrometeorological model to estimate total radiation received by a person under the canopy of various tree species in Ontario, Canada, and this was converted to an index of Human Thermal Comfort (HTC). It was recognised that during times of high summer temperatures, winds were not effective in ameliorating HTC. At such times, a reduction in solar radiation load is critical and several 'heavy' canopy shade trees (*Platanus* X *acerifolia* (London Plane) and *Aesculus hippocastanum* (Horse Chestnut)) were able to provide this. However, the model indicated that in winter, the reduced solar radiation loads under the evergreen species had a negative impact on HTC, such that individuals would "prefer to be warmer".

There are very few experimental studies that have examined the relationship between the cooling benefit of different forms or combinations of urban vegetation and water supply/status. Shashua-Bar et al (2011) conducted such as study in the arid Negev desert, Israel, using two virtually identical courtyards and various combinations of above tree canopy or above shade mesh and under-canopy grass or paving. In these courtyards, air and surface temperatures, VPDs and solar radiation levels were very high. The study found that:

- shade mesh cover reduced air flow and was actually deleterious to HTC;
- the grass surface alone produced only a slight cooling benefit for the highest water consumption demand;
- tree canopy over grass created the most comfortable thermal environment, with ambient air temperatures up to 2.5 °C cooler than the bare courtyard; and
- tree canopy over paving offered the most water efficient scenario (in terms temperature reduction for litres of water used).

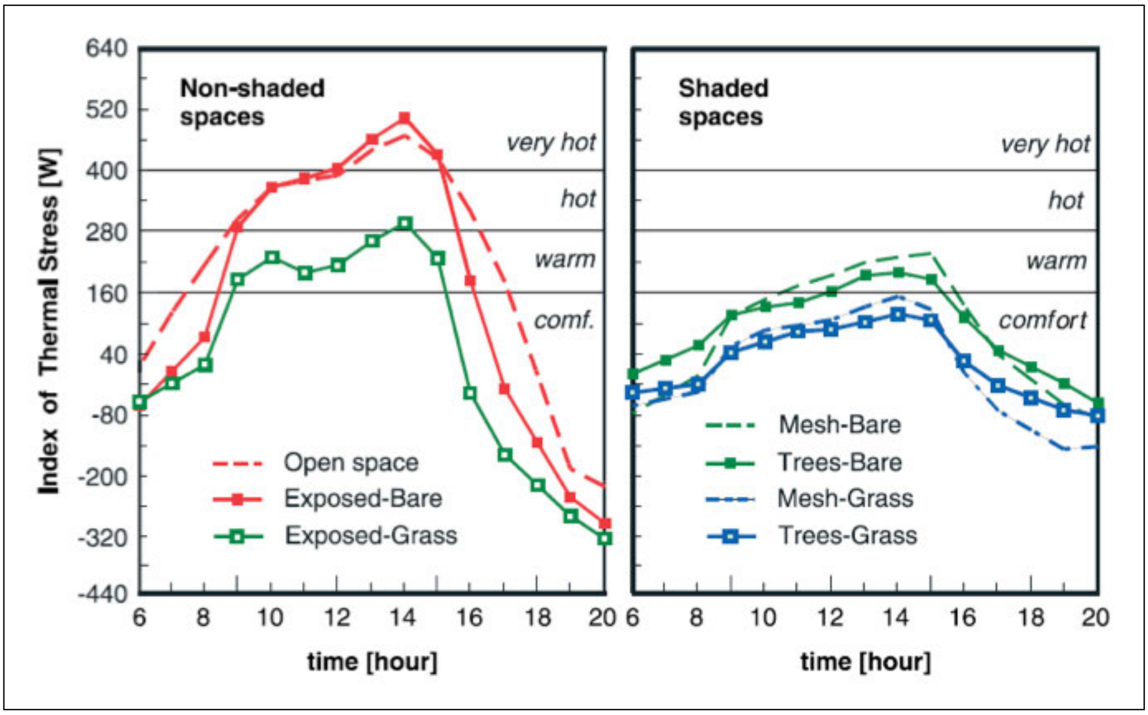


Figure 4: Normalised index of thermal stress during summer daylight hours for non-shaded courtyard spaces (left) and several vegetation and/or mesh shade combinations (right) in courtyard spaces in the hot, arid Negev desert, Israel. Source: Shashua-Bar et al (2011).

2.3.2 Trees for cooling/energy benefits in buildings

Shading, cooling and energy saving benefits can be optimised through proper selection and placement of vegetation relative to the building (Meier 1990/91; McPherson et al 1988). Heat is transferred into buildings through several mechanisms (Akbari et al 2002; Meier 1990/1):

- direct gain through windows;
- conduction through opaque wall and roof surfaces;
- infiltration; and
- latent heat transfer.

Although roof surfaces receive higher solar radiation loads than wall surfaces, walls are often a major source of heat transfer due to lower levels of insulation and the presence of windows (Heisler 1986). Consequently, trees should be placed with consideration not only of roof shade, but also wall and importantly window shade, especially during the summer months when solar radiation levels are high (McPherson et al 1996). The importance of enabling solar warming in cool winter months must also be considered, as cool winter wind reduction or displacement contributes to the net impact of the three microclimate factors (shade cooling, evapotranspirational cooling and wind reduction) over an annual period of seasonal change.

Trees and shrubs may be selected, located and managed to reduce energy consumption for cooling and heating of buildings, but the amount and type of energy savings associated with trees is highly site-specific (McPherson et al 1997). The amount of energy saved is influenced not only by climatic zone, building materials, aspect, surrounding built landscape and wind-flow, but also by vegetation type, size and water status. To make energy savings on building space cooling and heating, the best planting approach depends very much upon the climatic zone.

- In warm or hot climates, it is best to provide tree canopy shade to the roof and the north or western walls (southern hemisphere) (McPherson et al 1988; Simpson & McPherson 1996). Numerous studies conducted in hot climates have shown that the energy savings from summer cooling far outweigh the increased heating costs associated with winter shading of buildings (Heisler 1986). In Australian mainland cities (perhaps not Tasmania), energy consumption avoided in summer cooling is likely to outweigh that for winter warming.
- In cooler climates, such thermal load reductions and energy savings will be lesser, and counteracted by the concurrent reductions in thermal loads in winter that result in an increase in building space heating costs. In these cooler climates, especially those with strong winter wind conditions or exposed locations, trees should be planted in the path of prevailing winter wind directions, whilst allowing winter solar radiation to reach walls and windows on north or western walls (southern hemisphere).

In cooler winter months, the impacts of tree canopy cover may not all be positive from a building thermal regulation perspective as there is a 'conflict between the positive influence of shade and shelter and the negative impact of reduced solar access, plus the role of climate in generating different energy demands, accounts for the fact that estimates of energy savings of trees vary from 24% saving to a 25% increase in cost' (Oke 1989; Heisler 1986).

Heisler (1986) measured reductions in direct and diffuse solar irradiance from individual deciduous trees in the northern hemisphere, and used simple models to extrapolate solar irradiance reductions for a 'typical' house. Under clear sky conditions, a medium-sized Acer saccharum 'reduced irradiance in its shade on a south-facing wall (northern hemisphere) by about 80% when in leaf' (p. 337). Slightly smaller reductions were observed for *Platanus* X *acerifolia*. However, greatest reductions in solar radiation received were found for trees placed on the west side of the building. The planting of evergreen canopy trees on the southern side (northern hemisphere) results in greatest roof shading in winter with relatively little additional shading in summer. This can actually increase building energy consumption for heating during winter (Gomez-Munoz et al 2010; Heisler 1986).

For greatest cooling and energy saving of buildings, a tall, large canopy tree(s) on the north or western side (southern hemisphere) may be best to optimise winter to summer irradiation reduction (Heisler 1986). However, from a human thermal comfort perspective a smaller tree with a wide but dense canopy may be more appropriate to provide shading of the ground surface and the pedestrians beneath. More recently, Donovan and Butry (2009) estimated the effect of shade trees on the summertime electricity use of 460 single-family homes in Sacramento, California. They found that trees on the west and south side (northern hemisphere) reduced summer electricity use (-5.2%) for cooling, whereas trees on the north side of a house increased summer electricity use (+1.5%).

No studies have been found investigating the shade and cooling benefits provided by native species commonly planted in Australia's cities, such as *Lophostemon confertus, Corymbia maculata and Allocasuarina species*. Compared to exotic species, sclerophyllous Australian species generally have an open crown, pendulous, fine leaves (Specht & Specht 2002) and may offer more limited insolation reductions (Gies et al 2007). As such, it should be noted that crown density models developed for deciduous trees in cool temperate zones may not be applicable to many Australian native species, or to the growth conditions in south-eastern Australia, where frequent drought and relatively low nutrient soils may lead to slower growth and crown development.

2.3.3 Your neighbour's tree

Although a tree planted to provide cooling benefits to one building or property can benefit neighbouring properties, it can also have a negative impact on the thermal environment of those properties. At a neighbourhood scale, a tree planted on the northern aspect of one building to provide summer shade may well shade the southern side of an adjacent neighbouring building, thereby preventing the beneficial effects of winter solar insolation and warming. However, despite the reductions in beneficial solar warming on southern aspects during winter, the benefits of summer shading will often outstrip any additional costs of winter heating (Heisler 1986) in all but the coolest climates. This may not be of great consolation to the neighbour.

Shadow projections based on mathematical models are frequently used to evaluate the "quality" of shade provided by trees in and around buildings. However, while they accurately represent the extent of tree shadows, they do not reflect the true "quality" or complexity of the tree crown shade, such as 'the fraction of light that penetrates, reflects, or is absorbed by the plant' (Meier 1990/91). Not all micro- to local-scale studies rely strongly on modelling. For example, investigating solar radiation intercepted by trees in a low-rise residential neighbourhood using laser remote sensing technologies, Tooke et al (2011) observed a 38% reduction on average, with a strong correlation to tree height and volume.

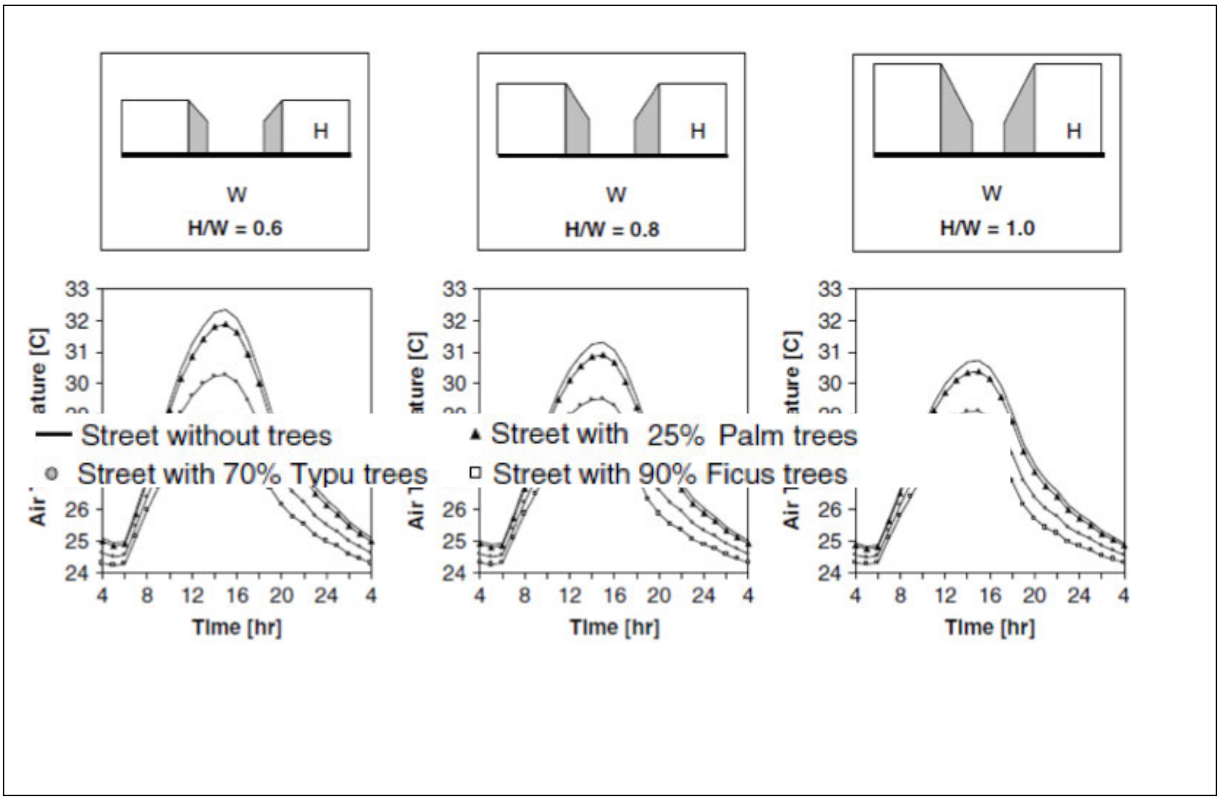
2.4 Local scale effects of trees

2.4.1 Street geometry and tree canopy cover

At the local scale, the beneficial effects discussed at the micro-scale can be aggregated. However, there are methodological issues associated with quantifying the cooling benefit of vegetation in a highly heterogeneous thermal environment and a combination of direct field measurement and urban system modelling may provide greatest insight (Oke 1989). The local scale (neighbourhood, streetscape, precinct) is the most likely scale at which climate change adaptation strategies will be implemented by local government authorities, focusing on streetscapes in suburbs with vulnerable populations, transport hubs, and built-up precincts dominated by commercial retail, business and office buildings.

In a network of urban streets, Shashua-bar et al (2010a) used the Green CTTC model to simulate radiation exchange to predict air temperatures within the UCL in Athens, Greece. The model was validated against direct temperature measures and predicted a cooling benefit of up to a 5 °C at midday, and an overall 3 °C daily cooling benefit. In a similar study in Tel Aviv, Israel, Shashua-Bar et al (2010b) noted that tree shade provided similar cooling benefits, equivalent to preventing 50% of the temperature increase from sunrise to midday under non-tree shaded street conditions. Contrary to the widely-held view that percentage canopy cover or leaf area should not be used as the sole index of cooling potential, in the Shashua-Bar et al (2010b) study, cooling benefit was most strongly related to percentage canopy cover. Species differences were less significant, although the three species measured (*Phoenix dactylifera*, *Ficus retusa* and *Tipuana tipu*) may not be very different in their water use strategies. Importantly, the modelling component of this study illustrated that the cooling benefit of any tree canopy cover will decrease proportionally as the street canyon becomes deeper (i.e. greater height to width ratio as in city centre streets). This is because the canyon walls increasingly shade the canyon itself, contributing to a reduced solar radiation load as the number of hours of direct solar exposure decrease. In another similar modelling study (ENVi-MET 3.0) investigating HTC within different urban canyon forms, with and without tree canopy shade, Ali-Toudert and Mayer (2007) observed that PET was greatest in east-west orientated streets, and consequently, it is in these streets that tree canopy shade had the greatest benefit for HTC.

Figure 5: The simulated diurnal air temperature pattern under Palm, Typu and Ficus trees at different percentage canopy covers in three urban street forms of increasing canyon depth (Tel Aviv, Israel). Taken from Shashua-Bar et al (2010b).



2.4.2 Trees in large green spaces

Parks can provide a cooling benefit to the people within them and to the adjacent built urban environment, particularly on calm, clear nights. Oke (1989) summarised the North American studies providing evidence for 'park cool islands' and noted that parks were from 1 to 3 °C cooler than the surrounding urban landscape, with the greatest 'zone of influence' extending downwind from the park. Other recent studies in parks and densely planted streetscapes have yielded similar results, with ambient air temperature differences of up to 3-4 °C observed at midday during summer (Chen & Wong 2006; Spronken-Smith & Oke 1998; Shashua-Bar & Hoffman 2000; Shashua-Bar et al 2010a; Potcher et al 2006). Modelling supports the observations that cooling benefits can extend beyond the boundaries of 'sizeable' parks, particularly in the downwind direction (Dimoudi & Nikolopoulou 2003). In contrast, a meta-analysis review of empirical evidence for park cooling by Bowler et al (2010) showed that the average park is only 0.94 °C cooler than surrounding areas during the day. This evidence for the cooling benefit of green space is based on a small number of observational studies and does not allow specific recommendations to be made on how best to integrate parks into an urban area.

The reason urban parks do not reach temperatures similar to green spaces in rural settings is probably that there is a continued supply of warm air from the built landscape around the park and from the air mass above, which thereby limits within-park cooling (Jansson et al 2007; Shashua-Bar & Hoffman 2000). It also appears that cooling benefits may be highly localised and rapidly diminish with increasing distance from the park's edge and in the case of small, isolated parks, the benefits may be insignificant (Bowler et al 2010). However, greatest benefits are always experienced downwind from any sizeable park (Spronken-Smith and Oke 1998). The modest nocturnal cooling provided by parks may nevertheless provide critical relief to social groups vulnerable to heat stress (Clarke & Bach 1971 in Oke 1989; Huang et al 2011). Urban planners should consider locating new aged care facilities, hospitals and public housing close to parks (downwind from prevailing summer wind direction), and ensure that urban development in general does not encroach upon existing parks. In addition, increasing the number of trees planted in and around public housing estates may reduce the cost of air-conditioning for space cooling for those who can least afford it (McPherson et al 1997).

A common question from urban landscape planners is: 'are several small parks better at providing cooling than one large park?' Computer simulations by Hunjo and Takakura (1990) and Dimoudi and Nikolopoulou (2003) suggested that a series of small parks integrated throughout the urban built landscape provided more effective cooling to surrounding areas than a single large park. However, Bowler *et al* (2010) surmised that larger parks experienced the greatest within-park cooling during the day, and those with trees were coolest. This was further substantiated by Cao et al (2010), who investigated satellite measured land surface temperatures of ninety-two parks in Japan and similarly found that larger parks were cooler, and that a park had to be larger than two hectares before a significant temperature difference developed with the surrounding urban landscape. Park characteristics, such as the density and the distribution of trees, also influence the intensity of cooling provided.

The importance of trees within parks has also been indicated by Spronken-Smith and Oke (1998), who investigated several parks containing different vegetation forms in Vancouver and Sacramento. Parks with more tree canopy cover were coolest in the afternoon, whereas parks with less canopy cover achieved cooler night-time temperatures as a result of uninhibited long-wave radiation loss.

Another critical question often raised by urban landscape planners is: 'how are park cooling benefits affected by changes in irrigation practice?' Spronken-Smith et al (2000) observed that evapotranspiration in an irrigated park in Sacramento, California was three times that of the surrounding residential landscape. Reducing water available for park green space (or street tree) evapotranspiration, and the cooling benefits this provides, is an inadvertent consequence of policy-driven water restrictions at times of extended drought. These water restrictions reduce the ecosystem service function of green space and vegetation, diminishing the cooling benefits locally and city-wide, reducing human thermal comfort levels and increasing urban energy demands for building space cooling (Gill et al 2008; Larson et al 2009). The need to maintain water supply to urban trees and green spaces is evident. As Cleugh et al (2005, p. 2025) have observed, 'water used on urban gardens and parks is not a "waste" – it has quantifiable benefit that must be included in any policy about water use in urban areas'. Water supply can be maintained through exemptions from restrictions and the continued use of potable water for irrigation, or the use of alternative water supplies through sewage recycled water systems, grey water or storm water capture, storage and redistribution. The importance of continued irrigation to urban vegetation cooling remains a knowledge gap and critical research issue.

In summary, large parks with trees will achieve the greatest cooling benefits during the day; however, large parks with fewer trees will achieve and provide the greatest cooling benefits within the park and downwind at night. All parks will achieve greatest cooling benefits with an adequate supply of water to maintain tree canopy health and maximise evapotranspiration.

2.5 Meso-scale effects of trees

Cities have been described as 'deserts' because impervious surfaces dominate and catchments are engineered to rapidly remove rainfall received such that the ecosystem becomes and remains dry. At the same time, cities have been described as forests, because a 'forest' has been defined as land with less than 10% tree canopy cover (Rowntree 1984, in Oke 1989). Tree canopy cover in most North American cities is 20-40% overall, with less than 10% canopy cover in commercial or industrial areas, 15 to 40% in residential areas and 20 to 60% in green spaces (Oke 1989).

Urbanisation does not necessarily mean the loss of tree canopy cover in all situations; for example, in Chicago, USA tree cover has increased from an estimated 13% pre-European settlement, to nearly 20% today (McPherson et al 1997). In a more recent study of Phoenix, Arizona, it was noted that trees growing on low-density residential land and vegetated institutional lands (eg. parks, forests preserves, golf courses) accounted for 50% and 38% of the city's tree canopy area, respectively (Chow & Svoma 2011). Similarly, much of the urban development in Melbourne's western suburbs has occurred on what were once native grasslands. While municipal councils in these areas are putting considerable resources into planting trees on public land, it is uncertain as to whether the ecosystem services and cooling benefits these trees offer will offset the replacement of pervious surfaces with roads, paving and roofing (VLSAC, 2011). Both at a local- and meso-scale, the area of land allocated to urban parks and tree planting should be increased in all new developments so as to maintain evapotranspiration and provide storage areas for capturing stormwater (Grose 2009; Cleugh et al 2005).

At the city scale, the 'urban forest' comprises all of the trees and vegetation – including the soil, air and water that supports it – within an urban environment. It incorporates 'trees and vegetation in streets, parks, gardens, plazas, campuses, river and creek embankments, railway corridors, community gardens, green walls, balconies and green roofs' (City of Melbourne 2011).

Conceptualising the urban forest like this requires a shift from the local scale management of street and park trees to urban ecosystem management at the meso-scale (McPherson et al 1997). Increasing urban forest cover 'can modify fluxes of energy and water, thereby changing air temperatures, wind fields, and air pollution concentrations' (McPherson et al 1997). Trees can be viewed as flexible, adaptable and simple tools for environmental design (Oke 1989).

At the meso-scale, modelling studies are the most common method for investigating the role of vegetation in cooling the urban environment. Gill et al (2008) used an energy exchange model to estimate the impact of increasing (or reducing) the green cover in greater Manchester, UK. Their model indicated that a 10% increase in green cover would result in surface temperatures remaining at current levels for the next 70-80 years despite projected global warming conditions. Ng et al (2012) used an ENVI-met model to simulate 33 scenarios to cool the city of Hong Kong. The model predicted that to reduce urban near-surface air temperature by 1.0 °C, 33% of the urban area would have to develop tree canopy cover.

Rosenzweig et al (2006a) used the MM5 regional climate model in combination with observed meteorological, satellite, and GIS data to determine the impact of urban forestry, green roofs, and light surfaces on near-surface air temperature in New York City, USA. Nine combinations of 1) street trees, 2) park trees, 3) green roofs, 4) white roofs and 5) white road/sidewalks, were investigated city-wide and evaluated on their cost-effectiveness at reducing air temperature and demand for electrical energy for space cooling. Results showed that the most effective way of reducing air temperature was through a combined vegetation strategy (including street trees, park trees and green roofs). The model predicted that if all available space across the city were planted up, near-surface temperatures would drop by 0.4 °C. Notably the temperature impact of planting more trees in streets was considerably greater than planting more trees in parks. Furthermore on a 'value for money' basis, street tree planting and whitening roofs and ground surfaces were the most cost-effective means of reducing urban temperatures.

2.6 Environmental life cycle analyses of urban trees

Any investigation of the potential benefits of green infrastructure for cooling cities and reducing energy demands at micro-, local- and meso-scales must place these benefits in the context of their complete environmental life cycle impacts. There are challenging theoretical and technical difficulties in calculating the tangible and intangible environment costs of green infrastructure, both across the life cycle (in the case of trees, from nursery production to decomposition) and at scales ranging from micro to global. Moreover, life cycle analyses (LCA) necessarily rely on assumptions that may be invalid or difficult to substantiate. Despite these issues, LCAs arguably have value in encouraging researchers, designers, manufacturers and planners to place environmental sustainability at the centre of their decision-making processes.

There is a growing literature attempting to balance the direct (carbon sequestration) and indirect (reduction of greenhouse gas emissions associated with heating, ventilation and air-conditioning) environmental benefits of urban trees against their environmental costs (carbon emissions associated with their planting, maintenance, removal and decomposition) (see for example, Chen et al 2008; Escobedo et al 2010; Kaye et al 2004; McPherson et al 1997; McPherson & Simpson 2003). In general, studies suggest that the role of urban trees in reducing the use of air-conditioning is more significant than their carbon sequestration potential. Furthermore, a total life cycle approach to the management of urban trees is essential: a LCA by Nowak and Crane (2002) indicated that urban forest ecosystems will eventually become 'net emitters of carbon' unless long-term carbon storage can be achieved to offset carbon emissions associated with their management across the life cycle.

3. Green roofs

3.1 Types of green roofs

Although design varies considerably, green roofs are generally composed of four distinct layers: a base layer composed of waterproof membrane and root barrier; a drainage layer, which may include water-retention reservoirs or voids; a substrate layer usually separated from the drainage layer by geotextile fabric and the plant layer (Sailor 2008).

The interaction between substrate depth, local climate and availability of irrigation largely dictates the diversity of plant species that can be grown on a green roof. Extensive green roofs have shallow substrates ranging from 2-20 cm in depth (Oberndorfer et al 2007). This type of green roof is generally only capable of supporting mosses, small plants and groundcovers (Sailor 2008). Extensive green roofs function as a 'climatic skin' (Kohler et al 2002, p. 383) undergoing a continual, dynamic process of change that will influence their thermal performance and can make quantification difficult (Kohler 2008; Oberndorfer et al 2007). Imposing only an additional 70-170 kg/m2 to static loads (Oberndorfer et al 2007), extensive green roofs can be retrofitted to many existing buildings (Castleton et al 2010; Compton & Whitlow 2006; Feng et al 2010). They are also relatively inexpensive to install and require little maintenance. For these reasons, most green roofs in cities around the globe are of the extensive type. While these systems have functioned well without irrigation in temperate European and North American climates, it has proved more difficult to establish successful plantings in climates with hot, dry summers (Williams et al 2010a & b).

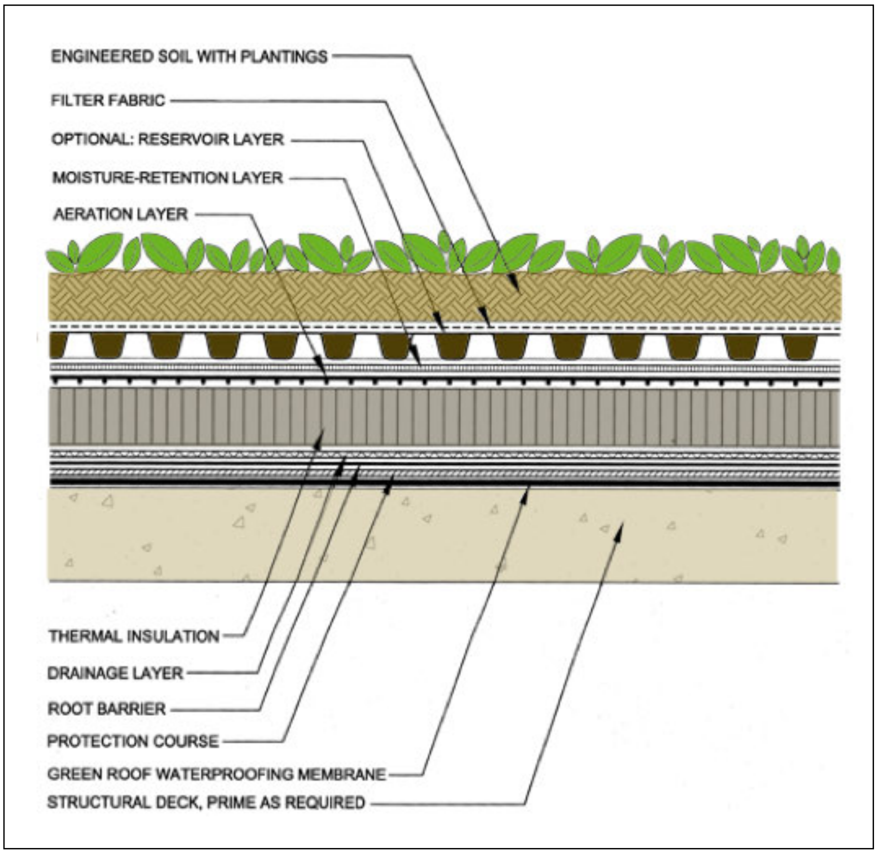


Figure 6: Typical extensive green roof construction (source: Eco Brooklyn Inc http://www.ecobrooklyn.com/extensive-green-roof/)

Intensive green roofs (or 'roof gardens') have much deeper substrates – from depths of 20 cm to more than one metre. Fewer intensive green roofs have been built because they are usually capital intensive, requiring highly engineered systems capable of supporting structural load capacities of 290-970 kg/m2 (Oberndorfer et al 2007; Wong et al 2007), as well as ongoing maintenance (Jim & Tsang 2011b). However, intensive green roofs allow the cultivation of a much wider diversity of plants (including large trees and shrubs), and unlike extensive ones, provide accessible recreational space to city dwellers (Oberndorfer et al 2007). This section of the review is largely restricted to the thermal benefits of extensive green roofs, as intensive green roofs, particularly those at grade or podium level, can be considered to have similar microclimate benefits to urban parks or gardens (which are reviewed in chapter 2).

3.2 Parameters influencing the cooling potential of green roofs

Like other forms of green infrastructure, green roofs cool urban microclimates by shading heat-absorbing materials, increasing albedo, and providing evapotranspirative cooling and convective shielding (Oke 1989; McPherson 1994; Taha 1997). As a consequence, they improve thermal comfort both within and around buildings and reduce energy demands for summer cooling and winter heating (Del Barrio 1998; Sailor 2008; Sailor et al 2008). However, the cooling provided by green roofs is a function of the contributions from the plant, substrate and drainage layer components and will vary according to their characteristics.

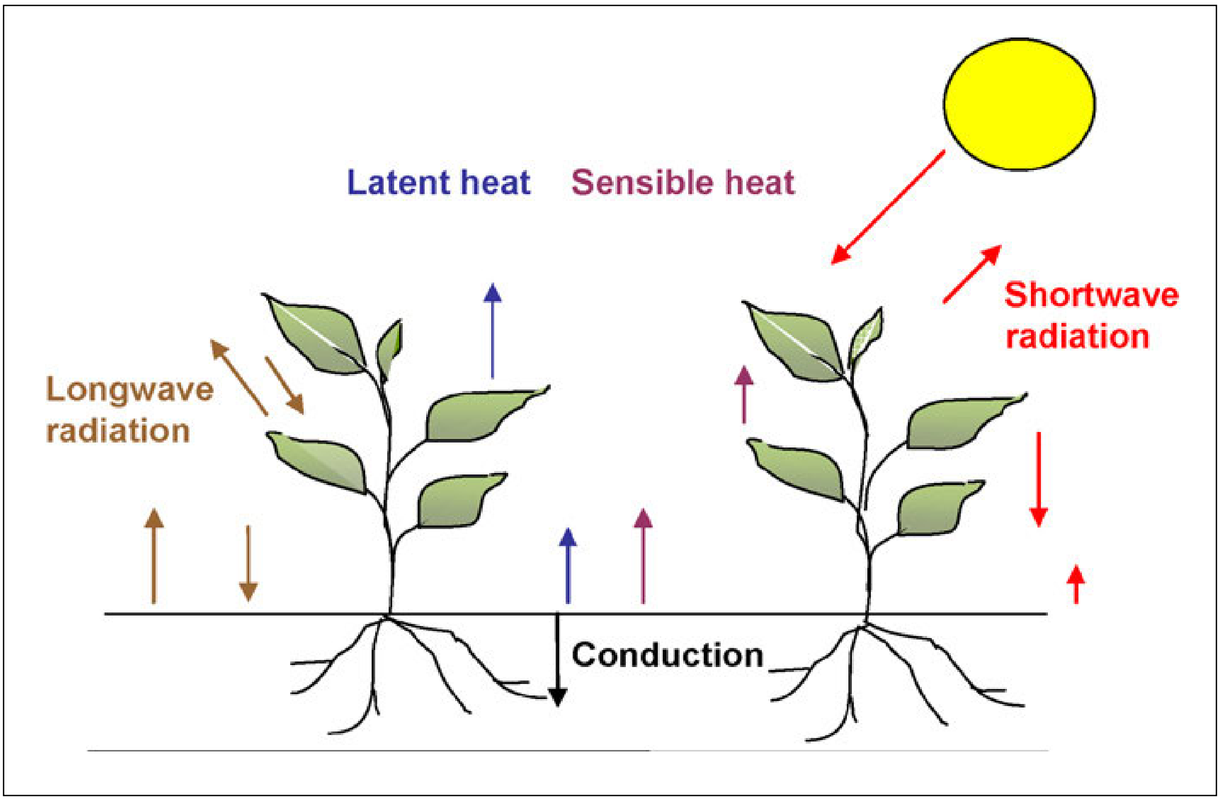


Figure 7: Simple depiction of the energy balance for a typical green roof (source: Sailor et al 2008)

3.2.1 Thermal properties of substrates

With the exception of traditional European sod roofs, green roof substrates are generally a constructed growth medium (Dvorak & Volder 2010). Typical inorganic components of green roof substrates include expanded slate, shale and clay; sand; volcanic materials such as perlite, pumice and scoria; recycled materials such as crushed bricks, concrete and fly ash; and/or synthetic materials such as urea-formaldehyde foam (Ampim et al 2010; Nektarios et al 2003; Tsiotsiopoulou et al 2003). Organic components include well-composted wood waste, livestock manure, grass clippings or sewage sludge and/or peat. There is much debate as to optimal components and proportions, but the inorganic fraction is generally greater than the organic. As it decomposes, organic matter shrinks in volume and produces a fine 'sludge' that can adversely affect green roof drainage. In addition, it may leach undesirable levels of nitrogen, phosphorus and metals into stormwater runoff. Consequently, organic matter usually comprises no more than 10-20% of the total substrate volume (Nagase & Dunnett 2011; Rowe et al 2006; Sailor et al 2008).

The particle size and mineral composition of a substrate determines its physical properties: bulk density (dry mass by unit volume), water holding capacity, air-filled porosity (the volumetric proportion of the substrate filled with air following free drainage) and saturated hydraulic conductivity (the rate at which water infiltrates through a saturated substrate) (Handreck & Black 2004; Raviv et al 2002). These physical properties in turn determine a substrate's thermal behaviour. (Tsiotsiopoulou *et al* 2003). However, there is limited information about the thermal properties of green roof substrates in the peer-reviewed scientific literature (Sailor et al 2008).

Moisture dependent thermal properties of substrates

Recognising that green roof substrates have very different thermal behaviour compared to natural soils, Sailor et al (2008) developed a database of thermal properties, which included thermal conductivity, specific heat capacity, short wave reflectivity, and long wave emissivity. Tests of eight different substrate samples at four different moisture levels indicated that these thermal properties vary in response to substrate composition and moisture levels. Thermal conductivity was higher for wet (0.31-0.62 W/m2 K) than for dry samples 0.25-0.34 W/(m2 K) (Figure 8). Specific heat capacity was also higher for wet (1085-1602 J/kg K) than for dry samples (830 to 1123 J/kg K). In general, saturated green roof substrates had '40% higher specific heat capacity and twice the thermal conductivity of their dry counterparts' (Sailor et al 2008, p. 1471). Surface albedos of wet and dry substrate samples were similar to values reported for natural soils, declining as moisture levels increased (ie. reflecting less incoming solar radiation as they became wetter). Thermal emissivities remained substantially the same for all samples and moisture levels. The authors stressed that the thermal conductivity and albedo of a green roof substrate are dynamic, changing 'substantially both seasonally and diurnally as a function of moisture status' (Sailor *et al,* p. 1250). Consequently, these cyclical variations make comparisons with conventional insulation materials (using R-values) inappropriate, as the R-value by definition, is a steady-state property of manufactured insulation materials (Tabares-Velasco & Srebric 2009; 2011). Moreover, the compaction of green roof substrates over several seasons can eventually result in a decline in thermal performance, with thermal conductivity of compacted moist substrates increasing by 30-40% compared to their uncompacted values (Sailor and Elagos 2011).

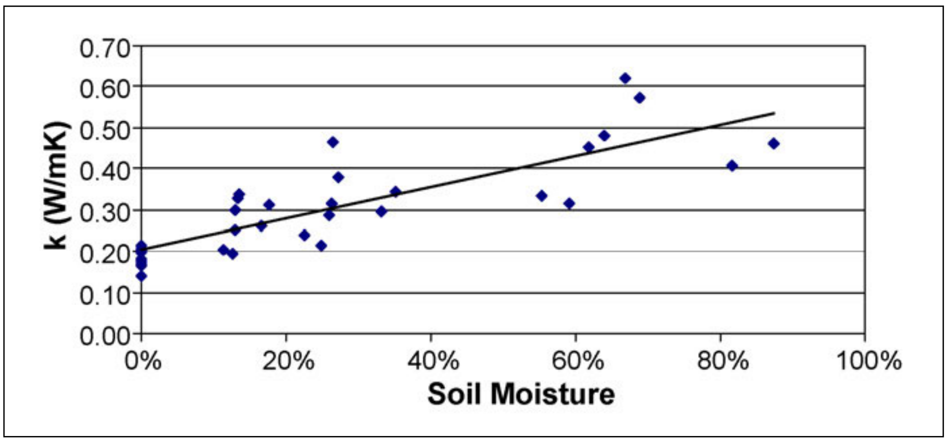


Figure 8: Soil thermal conductivity as a function of percentage moisture saturation (source: Sailor et al 2008)

Substrates can be designed to minimise diurnal and seasonal temperature fluctuations, which is particularly desirable during summer periods. Tsiotsiopoulou et al (2003) evaluated the thermal performance of four green roof substrates and their effects on the accumulated dry-weight biomass of *Lantana camara* over a fifteen-month period. The substrates were (i) a sandy loam; (ii) a sandy loam amended with 40% by volume urea formaldehyde resin foam, (iii) a sandy loam to which peat and perlite were added (50:30:20 v/v); and (iv) peat and urea-formaldehyde resin foam (foam) (60:40 v/v). They found that diurnal substrate temperature fluctuations were a function of substrate type, plant growth and seasonal changes.

Temperature fluctuations were greatest in the un-amended sandy loam substrate. Its relatively high bulk density and low air-filled porosity resulted in high values for specific heat capacity, thermal conductivity and thermal diffusivity. In other words, it rapidly absorbed heat during the day and dissipated it quickly at night, resulting in large temperature fluctuations. While stable substrate temperatures may be desirable for many plants, *L. camara* produced deeper roots and greater biomass in the sandy loam substrate, and exhibited low shoot to root ratios, enabling better anchorage. For the peat and foam substrate, the opposite occurred: its low bulk density and high air-filled porosity resulted in only small diurnal temperature fluctuations, and its high water holding content prevented wilting during hot, dry weather. In addition, the substrate was lightweight, making it attractive for green roof retrofits where structural load capacities are limited. Notwithstanding these benefits, the peat and foam substrate provided few plant nutrients and displayed high electrical conductivity (an indicator of excessive dissolved salts) that resulted in insufficient growth of shoots, and reduced root mass. The authors surmised that low values for root dry weight in the peat and foam substrate may have been due to the presence of melamine, a constituent of foam that has been associated with inhibition of photosynthesis and phytotoxicity.

These results demonstrate that there is no such thing as a ‘universal’ substrate suitable for all applications (Ampim et al 2010). To optimise thermal performance, substrates must be designed to suit local climatic conditions, water availability, the plants selected and available components. Moreover, thermal performance is not the only issue to be considered; some substrate components may have adverse environmental effects. Research is needed quantify the thermal properties of substrates used in Australia and to potentially develop substrates with low thermal conductivity composed from locally- and sustainably-sourced materials.

Substrate depth

Substrate depth largely determines the insulative properties, and thus the energy efficiency of a green roof (Lui & Minor 2005). In a modelling study investigating the volumetric heat capacity and thermal conductivity of a green roof substrate in humid continental Chicago compared to humid subtropical Houston, Sailor (2008) found that a substrate thickness of 200-300 mm reduced natural gas consumption for heating in winter, and electricity consumption for cooling in summer in both cities. The modelling found that of all parameters measured (substrate depth, LAI and irrigation), substrate depth had the most significant effect on reducing energy use for cooling and heating.

In Hong Kong, a substrate depth of only 100 mm was sufficient to diminish heat transfer into the building beneath (Jim & Tsang 2011). However, in the hot, arid climates, best thermal performance was achieved with thicker substrate layers: based on their work in the Negev Desert, Israel, Pearlmutter & Rosenfeld (2008) suggest that a substrate layer of 500-1000 mm (ie. an intensive green roof) could stabilise internal air temperatures to reflect seasonal rather than daily temperature cycles. In Australia, further research is needed to determine the minimum substrate depth needed to optimise thermal stabilisation and provide solar protection, as well as to sustain plant growth and ecosystem function during prolonged droughts and high summer temperatures (Williams et al 2010a). However, it is likely at least 150 mm would be required for plant survival (Williams et al 2010b).

3.2.2 Shading by plants

The major contribution of the plant canopy layer to the total cooling provided by a green roof derives from shading of the substrate surface. The properties that contribute most to the ability of plant canopy layer to reduce heat transfer through roof by shading are LAI, height, planting density, proportion of roof covered, and albedo (Sailor 2008).

Plants with a large LAI and horizontal leaf distribution maximise the shading effect (Del Barrio 1998). For an unvegetated surface with a LAI of 0, Wong et al (2003) recorded surface temperatures up to 57 °C, while under a densely foliaged *Raphis* palm with a high LAI, the maximum surface temperature was only 26.5 °C. Modelling by Sailor (2008) (using the EnergyPlus building energy simulation programme and validated using data gathered from a field study in Florida) indicated that compared to a control exposed roof, a green roof with a plant canopy with a relatively high LAI of 5 would experience both increased heating demand in winter and reduced electricity consumption in summer in both Chicago and Houston, but would nevertheless deliver net annual energy saving benefits in both climates.

Shading effects are strongly associated with vegetation structure, canopy transmittance and reflectance. He and Jim (2010) used a Bowen ratio energy balance model and a solar radiation shield effectiveness model to simulate solar radiation transmission in green roofs. Their modelling found that a complex vegetation structure incorporating many foliage layers (including shrubs) was most effective at shielding incoming radiation (shield effectiveness value (SEV) = 0.34), followed by groundcover comprising two layers (SEV=0.27) and grass (SEV=0.16). They concluded that the plant canopy layer has significant thermal storage capacity, forming a 'thermal buffer' against daily fluctuations in temperature and depressing air temperatures compared to the bare substrate. However, there is little research systematically comparing the thermal storage capacity of different plant life forms. This is perhaps because the thermal storage capacity of the vegetation is relatively small compared to that of the substrate layer (Tabares-Velasco et al 2011).

The shielding or shading effectiveness of green roof vegetation derives not only from its absorption and reflection of incoming and diffuse solar energy; it also traps a relatively still layer of air within its foliage and immediately above the substrate surface (He & Jim 2010), reducing temperature fluctuations. This may not always confer a thermal advantage; in trapping air within its foliage, the plant canopy can inhibit convective cooling in some circumstances (Pearlmutter & Rosenfeld 2008) del Barrio 1998). However, in the context of the green roof's total energy budget, this reduction in convective heat transfer appears to be negligible (Del Barrio 1998; Eumorphopoulou & Aravantinos 1998).

These studies indicate that cooling associated with plant shading can be optimised through the use of a range of plant forms (from grasses to shrubs) and dense plantings to ensure a high soil cover ratio (Fang et al 2008).

3.2.3 Evapotranspiration

Evapotranspirative cooling provided by the plant-soil system has been identified as 'a key determinant of the thermal functioning of green roof ecosystems' (Wolf & Lundholm 2008). It consumes latent heat, reducing heat flux through the roof and increasing relative humidity around and above the vegetation layer (Cheng et al 2010; Feng et al 2010; He & Jim 2010). Adequate substrate moisture is essential for both maintaining healthy foliage (and thus plant shading properties) and evapotranspiration (Tabares-Velasco & Srebric 2011; Wong et al 2007).

Water availability to plants can be optimised through substrate design, substrate depth (as detailed in section 3.2.1, above) and irrigation regime. With optimal water availability, the combined effects of shading, evapotranspiration and photosynthesis may prevent as much as 87% of solar radiation from reaching the roof surface (Wong et al 2003).

Plant selection for evapotranspiration

The conditions plants may experience on an urban rooftop can be exceedingly harsh and species with high evapotranspiration rates may be unable to survive. These conditions include exposure to dessicating winds, high insolation and temperature extremes, wide fluctuations in water availability (Dunnett & Kingsbury 2004; Wolf & Lundholm 2008) and lack of rooting volume (Lundholm 2006).

Plant characteristics or traits that confer the ability to survive on green roofs include: crassulacean acid metabolic (CAM) photosynthetic pathways; succulent leaves or other water storage adaptations; drought avoidance strategies (demonstrated by hemicryptophyte, cryptophyte and therophyte lifeforms); and sclerophylly (small, thick leaves to reduce surface area to volume ratio; sunken stomata; pendulous leaves;

silvery leaves to reflect solar radiation; leaves with a thick, waxy cuticle; and ground-hugging form (Specht & Specht 2002). Such traits are often 'negatively correlated with transpiration rate', and consequently, the plants most likely to survive on a green roof are also those least likely to provide the microclimatic cooling benefits of evapotranspiration (Compton & Whitlow 2006; Sailor 2008; Wolf & Lundholm et al 2008). In practice, this has resulted in the ubiquitous use of *Sedum* species in green roof plantings in both Europe and North America (Wolf & Lundholm et al 2008; Williams et al 2010a), and it is this genus that has been the subject of the most research (for example, Durhman et al 2004; Emilsson et al 2003; Monterusso et al 2005). Arguing that research should focus upon identifying a diversity of plants that tolerate the harsh conditions on green roofs while optimising evapotranspiration, Compton & Whitlow (2006) successfully tested two species (*Spartina alternaflora* and *Solidago canadensis*) for their capacity to both rapidly take up storm water equivalent to a two-year storm and survive extended periods of drought. Similar research is underway using Australian plant species from rock outcrop habitats (Farrell et al, unpublished data).

The transpiration rates of green roof plants can be highly sensitive to variations in solar intensity, wind speed and relative humidity (Jim & Tsang 2011). In the humid subtropical climate of Guangzhou, China, Feng et al (2010) calculated that for a green roof, 58.4% of incident solar radiation was absorbed through conversion of sensible into latent heat (evapotranspiration), 30.9% by long-wave radiative exchange and 9.5% by photosynthesis. By way of comparison, a study by Lazzarin et al (2005) found that during the summer in Vicenza, Italy (which has a maritime temperate climate), evapotranspiration consumed 25% of incident solar radiation on a wet green roof, but only 12 % on a dry green roof. These results indicate that irrigation is needed in hot, dry conditions to maximise the contribution of plants to the thermal performance of green roofs.

Researchers have also experimentally cultivated native plant species on green roofs to enhance biodiversity (Dunnett & Kingsbury 2004; Monterusso et al 2005; Wolf & Lundholm 2008). Results suggest that selecting plants with a diversity of species and life forms (forbs, grasses, succulents) not only benefits native flora and fauna, but also increases the cooling and stormwater retention capacities of green roofs (Wolf & Lundholm 2008; Lundholm et al 2010).

Irrigation

The moisture content of the substrate largely determines the magnitude of heat dissipated through evapotranspiration. High evapotranspiration rates (associated with saturated substrates and a plant canopy with high stomatal conductance) can effectively draw heat out of a building's interior, but conversely, the lower albedo and higher thermal conductance of wetter substrates may increase heat gain to the interior of the building (Castleton et al 2010; Sailor 2008; Wong et al 2003). The evidence suggests that evapotranspirative cooling may be optimised by: (i) designing lightweight substrates that maximise both air-filled porosity and water holding capacity; and (ii) maintaining moisture in these substrates (Del Barrio 1998).

Pearlmutter and Rosenfeld (2008) demonstrated that a 160 mm layer of irrigated substrate with the addition of shading via a layer of lightweight gravel or shade mesh sail, can transform a roof from 'one of the largest sources of heat gain in [a] building to its major cooling source' (p. 860). While evaporation from the exposed irrigated substrate produced a substantial cooling effect during the day and allowed for uninhibited evaporative cooling at night, it was not sufficient to prevent heat flux into the building's concrete roof, especially during the hottest afternoon hours. Only with the combination of irrigation and shading was a net cooling effect achieved. The gravel layer and shade mesh had different cooling effects. The gravel had a pronounced stabilising influence on interior surface temperatures, and reduced the evaporative demand by nearly 50% compared to the exposed irrigated substrate. The shade mesh maintained similar daytime peak temperatures to the gravel, but at night, substrate surface temperatures were 2 °C lower under shade mesh compared to those under gravel. Although this study did not compare the effects of shading via gravel/shade mesh to shading via a plant canopy, it demonstrates the importance of irrigating substrates, particularly in hot, dry climates. On a green roof, plant shading properties combined with irrigated substrate could potentially deliver a similar net cooling benefit, but further studies are needed to test this inference.

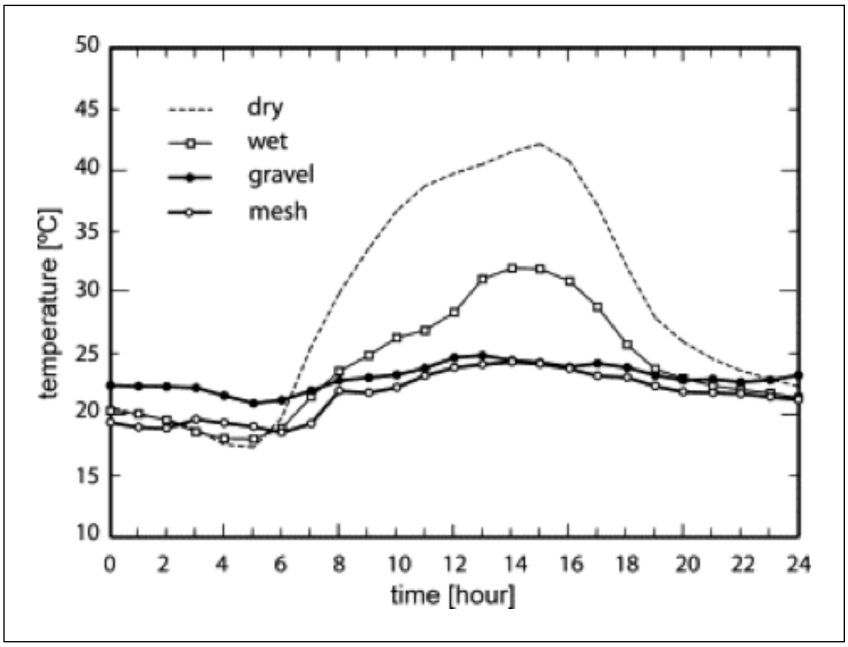


Figure 9: Normalised substrate surface temperatures for test cells with (i) dry substrate; (ii) wet substrate; (iii) substrate that was both saturated and shaded by gravel; or by (iv) shade mesh (source: Pealmutter & Rosenfeld 2008).

The drainage layer beneath the substrate can play an important role in maintaining moisture levels. A green roof with a 30 mm rockwool drainage layer and sub-irrigation maintained a continuous perched water table of 5 mm, resulting in a 2 °C reduction in internal room temperature (Niachou et al 2001).

In areas with limited water resources stormwater capture and grey water systems may be integrated into green roof design (Williams et al 2010a; Williams et al 2010b). Likewise green roof systems that incorporate water retention into the drainage layer may also increase the amount of water available for evapotranspiration and hence plant survival, but no research has been done to compare different proprietary systems.

3.3 Building scale cooling and energy savings

Observational studies in a wide range of climatic zones have pointed to the excellent thermal performance of green roofs, which can dramatically reduce dependence on air-conditioning to cool buildings. Measurements conducted on a low-rise commercial building in tropical Singapore found the heat transfer through an intensive green roof to be less than 10% of that recorded for a conventional control roof (Wong et al 2003). From early evening to sunrise, vegetation 'continuously cooled the ambient air', while the hard surfaces continued to emit heat as long-wave radiation. A maximum ambient air temperature difference was '4.2 °C, measured at 300 mm height, around 1800h' (Wong et al 2003). Onmura et al (2001) conducted field measurements of an extensive green roof during summer in humid-subtropical Osaka, Japan, and found a daily maximum surface temperature difference of 30 °C between the bare and 'greened' cement roof, when skies were clear. Daily heat flux through the green roof into the room below was approximately 50% lower than for the bare cement roof. In Ottawa (which has a humid continental climate), an extensive green roof with 150 mm of substrate reduced the maximum summertime temperature of a roof membrane from over 70 °C to 30 °C, and reduced temperature fluctuations of the membrane from 45 °C to 6 °C (Liu and Baskaran, 2003). Modelling of the thermal performance of a green roof with 90 mm of growing media and a bare roof in continental Mediterranean Madrid during summer suggests that the surface temperature of the former would be as much as 30 °C lower than the latter (Saiz et al 2006). This is consistent with studies in Singapore (Wong et al 2003) and Greece (Eumorphopoulou & Aravantinos 1998), which also recorded surface temperature difference of this magnitude.

Despite the abundance of observational studies, such as those described above, it is difficult to synthesise their results due to the lack of consistency between studies in parameters measured, differences in building construction, design and function, building aspect, external micro- and local-scale climates, whether internal fibre insulation has been installed, whether internal building temperatures are controlled by air-conditioning, heating and/or ventilation systems as well as green roof design itself (ie., plant species selected, substrate depth and composition, and base layer construction).

Most of the energy savings attributed to green roofs result from reduced energy demands for summer cooling rather than for winter heating (Getter & Rowe 2006; Saiz-Alcazar & Bass 2005). Spala et al (2008) simulated the thermal performance of a two-storey office building in Athens via mathematical modelling (TRNSYS), and found that the installation of a green roof reduced the cooling load by up to 58%. Chen and Williams (2009) reported on energy modelling conducted for a small experimental green roof installed on the Main Building at the University of Melbourne's Burnley campus. The model predicted that compared to a control room under a bare cement and bitumen roof, the air temperature in the test room under the green roof would be 1°C cooler in summer and 0.2 °C warmer in winter – results that accorded well with actual temperatures measured in these rooms. These temperature reductions gave rise to a predicted reduction in summer cooling loads of 38% for the given test room, and 56% for a test room with a lower thermal mass. Winter heating loads were reduced by 13% and 11%, respectively.

Green roofs offer the highest energy savings for buildings with high roof-to-wall area ratios (Oberndorfer et al 2007; Saiz et al 2006), such as extensive low-rise warehouses, factories and shopping centres. A comparative life cycle assessment modelling the environmental impacts of a standard and a green roof on an eight storey residential building in Madrid indicated that the green roof reduced the energy used for summer cooling by 6% for the building as a whole, and by 25% for the top floors of the building (Saiz et al 2006). (It should be noted that these estimations assumed a base load provided by nuclear power, supplemented by coal and natural gas). Simulating the thermal performance of a green compared to a bare roof installed on a warehouse, Martens et al (2006) found that as the roof-to-building envelope ratio rose, the upper floor cooling load drew close to that for the entire building. For a one, two and three storey warehouse, energy savings were 73%, 29% and 18% respectively. Where green roofs are to be retrofitted to existing buildings, studies show that greater energy savings are achieved in non-insulated than in well-insulated buildings, in both cool temperate (Castleton *et al* 2010) and Mediterranean climates (Santamouris et al 2007; Sfakianaki et al 2009). For example, Niachou et al (2001) estimated that the cooling energy savings associated with the installation of a green roof ranged from 45% for roofs with no other form of insulation, to zero for well-insulated roofs.

3.4 Environmental life cycle analyses of green roofs at building scale

In general, studies indicate that over its lifetime (25-50 years), the net present value of an extensive green roof is considerably less than that of a conventional flat roof (Clark et al 2008; Niu et al 2010; Susca et al 2011) – the exception being a study by Carter & Keeler (2008). These studies focus on economic costs and benefits, including savings in energy required for air-conditioning, reduced costs associated with roof membrane replacement, reduced burden of human disease due to air pollution mitigation, and stormwater fee reductions (due to reduced run-off). Saiz et al (2006) and Kosareo and Ries (2007) conducted environmental LCAs assessing the broader environmental impacts of extensive green roofs on ecosystem quality, as well as the embodied energy required at all stages of the life cycle to manufacture, transport, install, maintain and decommission a green roof at the end of is usable life. Based on Spanish data and using LCA modelling software (SimaPro), it was estimated that replacing a conventional roof with a green one would reduce environmental impacts by 1-5.3%, with the greatest burden reduction occurring during the use phase of the green roof, particularly for abiotic depletion (associated with reduction in coal and lignite for electricity generation) and eutrophication. Because the model assumed that nuclear power provided the base load, global warming potential was reduced by only 1% (Saiz et al 2006). Even though the manufacturing process for polymers used in extensive green roof components (drainage, filter and water retention layers) are highly polluting (Bianchini & Hewage 2012), it was estimated that the green roof would extend the life of roofing materials under it from 10 to 40 years, offsetting the environmental burden associated with green roof components (Saiz et al 2006). Modelling by Kosareo and Ries (2007) based on U.S. environmental data predicted that an extensive green roof would have approximately half the environmental burden of a convention stone-ballasted flat roof, across four impact categories ('human health, ecosystem quality, climate change and resources' (p. 2611). Although the two studies are not readily comparable, the green roof in the latter appears to deliver greater environmental benefits, perhaps due to the greater reliance on fossil fuels for energy production in the U.S.

In both of these LCAs, information about the green roof components and systems tested is limited and the assumptions underpinning the models are not fully delineated. One cannot therefore assume that the results of these studies reflect all of the environmental impacts and benefits (tangible and intangible). Nor should the results be generalised to other green roof systems and sites.

3.5 Neighbourhood scale cooling and energy savings

Studies of the thermal benefits of green roofs at neighbourhood scale are virtually non-existent. Mitchell et al (2008) used water balance modelling (Aquacycle and SUES) to investigate the effects of several water sensitive urban design (WSUD) scenarios on evapotranspiration and stormwater flows in a suburban catchment in Canberra. One of the scenarios considered was replacement of all existing roofs with extensive green roofs having a water storage capacity ten times that of a conventional roof. Modelling indicated that the implementation of this scenario in the suburb of Mawson would result in a 49 mm per year increase in evapotranspiration (due to the interception of stormwater), which in turn would reduce peak afternoon temperatures by 0.4 °C. Modelling by Akbari et al (2001) using data from several cities in the United States predicted a rise in electricity demand for cooling of 2-4% for every 1°C increase in temperature. On this basis, Mitchell et al estimate that a temperature reduction of 0.4 °C would cut energy consumption for cooling by 2%.

While these findings provide an indication of the potential benefits of green roofs for human thermal comfort at the local scale, they need to be viewed with some caution. Firstly, the authors note that the effects of WSUD on air temperatures were likely to be under-estimated, because the models were designed to predict them for the lower part of the urban boundary layer, rather than for the space within the urban canopy layer. Secondly, the modelling by Akbari et al (2001) may not be applicable for Canberra. Thirdly, the model assumed that the green roofs would receive no supplementary irrigation during summer – which in the climate of south-eastern Australia, would be likely to lead to plant death. And finally, it would be hardly feasible to retrofit green roofs to 100% of buildings in a residential suburb.

Alexandri & Jones (2008) modelled the effects of covering the envelope of a hypothetical urban canyon with vegetation in nine different cities around the globe during the hottest month of the year for each city. Four scenarios were considered for each canyon: (i) no green; (ii) extensive green roofs planted with ground-covering grasses; (iii) green walls covered with 'ivies'; and (iv) 'green all', in which both roofs and walls were covered. Modelling demonstrated that the partitioning of radiative, evaporative, conductive and convective heat fluxes is very different on green compared to conventional roofs. Greatest day-time temperature reductions were achieved in arid climates with high levels of solar radiation – for example, the model predicted that a green roof would reduce maximum air temperatures one metre above the roof by 26.0 °C in arid Riyadh, and only 15.5 °C in the maritime temperate climate of London. The authors concluded: '[i]t can be said with certainty that, the hotter and drier a climate is, the more important the effect of green walls and green roofs on mitigating urban temperatures is' (p. 487).

While providing a valuable indication of the potential cooling and energy-saving benefits of green roofs at the neighbourhood scale, Alexandri and Jones assume that the hypothetical building envelope 'could be easily covered with vegetation' (2008, p. 481), regardless of the climate, ecoregion and availability of water of the city in which it is located. In fact, horticultural researchers to date have yet to develop comprehensive and place-specific selections of plant species for green roofs with performance characteristics that enable them to survive the extreme summer temperatures experienced in arid and Mediterranean cities, particularly if irrigation is unavailable. Scherba et al (2011) point to a number of other limitations of this study: canyon geometries were represented in only two dimensions thereby under-estimating total canyon surface area; because buildings were assumed to have no windows and no insulation, thermal storage is likely to have been over-estimated; and finally, the model was not validated against the thermal performance of an actual urban canyon.

3.5. City-wide scale cooling and energy savings

Only a few published studies to date have attempted to quantify the meso-scale urban climate benefits of green roof technology (Scherba et al 2011). These studies all point to the potential of widespread uptake of green roofs to reduce outdoor ambient temperature, improve the thermal climate inside buildings, and cut energy demands for heating, ventilation and air-conditioning.

Several studies conducted in New York City investigated the potential of green roofs as a climate change mitigation strategy (Rosenzweig et al 2006 a & b), using a model in which green roofs were assumed to have an albedo of 0.7 to 0.85 – not dissimilar to that of white paint. The results suggest that covering 50% of roofs across the urban landscape would result in a temperature reduction of up to 0.88 °C.

The City of Toronto recently put in place a by-law requiring the installation of green roofs on all new commercial, institutional and residential developments with a minimum gross floor area of 2,000m2. This regulation is supported by an incentive programme providing funds for the construction of green roofs covered by the by-law and for new institutional or commercial buildings with a floor area of less than 2000 m2. The City of Toronto also funded a report on the environmental benefits and costs of the implementation of green roof technology. Using experimental and modelling data from Toronto, Waterloo and Ottawa, Banting et al (2005) estimated that the installation of extensive green roofs on 75% of Toronto's buildings (equivalent to 5,000 hectares) would reduce ambient air temperatures by 0.5 to 2 °C (depending upon season), and result in savings in heating and cooling energy of $21 million per year.

Modelling by Smith & Roebber (2011) simulated the impacts of climate change & continued urban sprawl in late twenty-first century Chicago, Illinois, and then compared these results with a simulation of the impact of extensive adoption of green roof technology. The model predicted that increases in evapotranspiration and albedo (as established by Rosenzweig et al (2006b)) in the city-wide green roofs scenario would result in temperature reductions of up to 3 °C. However, the authors noted that increased humidity associated with this additional evapotranspiration would provide only 'marginal cooling' from a HTC perspective. The authors recommend a strategy involving the use of both green and 'cool' white roofs, to obtain optimal albedo values while avoiding excess humidity.

In a study investigating future climate change scenarios for Greater Manchester, Gill et al (2007) mapped urban morphology types (UMTs) and undertook aerial mapping of surface cover to enable assessment of the environmental performance of each UMT. They then ran a series of 'development scenarios' exploring the impact of altering of vegetation cover in each of the UMT categories, based on two models (surface energy exchange and surface runoff). Although this model is somewhat limited in that it does not distinguish between sub-surface, surface, canopy layer and boundary layer UHIs, findings suggest that green roofs may play a pivotal role in any climate change adaptation strategy: adding 10% green cover to high-density residential UMTs maintained 'maximum surface temperatures at or below 1961-1990 baseline temperatures up to, but not including the 2080s' (p. 122), while adding green roofs had an even more dramatic cooling impact, 'keeping temperatures below the 1961-1990 current form case for all time periods and emission scenarios' (p. 123).

These modelling studies suffer from the same limitations noted for the study by Alexandri and Jones (2008): the mathematical models and thermal simulation programmes used to predict the impact of the city-wide adoption of green roofs on UHI were not validated with experimental data. Further, the studies tend to assume that there are no horticultural obstacles to achieving uniform, vigorous and temporally stable green cover on all roofs across a given city, regardless of climate and ecoregion.

4. Vertical greening: vegetated facades and walls

4.1 The role of vertical greening systems in the urban environment

Although humans have been planting green facades for hundreds, if not thousands of years (Kohler 2008), it only since the 1980s that architects and landscape planners have begun to incorporate them deliberately into building design to provide shade and evapotranspirative cooling. This has occurred primarily in Europe where there is an established knowledge base. Between 1983 an 1997, urban redevelopment initiatives in Berlin led to the establishment of green facades covering 245,584 m2. Kohler (2008) identified 770 technical papers, popular journal articles and books devoted to green facades – all of these published in German. Although the field is rapidly changing, the number of publications remains scant outside Germany.

Vertical greening systems (VGS) have the potential to become an important component of the green infrastructure of cities. Compared to building roofs, walls tend to be poorly insulated (Heisler 1986). In Australia, residential buildings often have a thin layer of foil insulation only. VGS can be retrofitted to existing buildings or integrated into new building design to improve thermal insulation and reduce the internal temperatures of buildings. In the CBD and high-rise commercial/residential areas of cities, building facades comprise a large proportion of total surface area. Moreover, in dense urban areas, there is limited ground area that can be planted with shade trees (Cheng et al 2010; Jim & He 2011). Despite this, there are relatively few studies of the thermal and other benefits of VGS in urban settings, compared to the growing body of scientific literature on other forms of green infrastructure (Rayner et al 2010).

Based on their modelling of the impact of green roofs and VGS on urban canyon temperatures, Alexandri & Jones (2008) contend that green roofs have a larger impact on cooling the urban canyon than VGS. This is because the horizontal or near-horizontal surfaces of roofs are exposed to greater direct solar radiation compared to the vertical walls of buildings, which tend to be more shaded, particularly closer to street level. Their modelling indicated that for the nine cities at different latitudes, covering urban canyon walls with vegetation delivered smaller improvements in human thermal comfort compared to green roofs. For example, in the arid city of Riyadh, the model predicted that greening roofs would reduce maximum air temperatures 1 m above the roof by 26 °C, whereas vegetating walls delivered cooling of only 12.8 °C. Nevertheless, the latter represents a substantial cooling effect. The important difference is that green roofs are by nature roof-bound whereas VGS can be at street level and therefore can directly improve pedestrian thermal comfort by shading heat-absorbing concrete and asphalt, increasing the albedo of these surfaces, providing evapotranspirative cooling and reducing both direct and diffuse solar radiation.

4.2 Types of vertical greening systems

There are of two different types of VGS: *green facades* and *green (or 'living') walls*. Traditional direct green facades feature woody or herbaceous climbing plants usually planted at the base of a wall. Plants suitable for direct green facades include self-clinging climbers, which adhere to the building exterior by means of adventitious roots (eg. *Hedera helix*), suckers (eg. *Parthenocissus quinquifolia*) or thorns (eg. *Bouganvillea* spp.). Rambling and scrambling plants may also be positioned in such a way as to cascade down the side of a building, forming a 'green cloak' (Dunnett & Kingsbury 2004; Hopkins & Goodwin 2011; Schumann 2007).

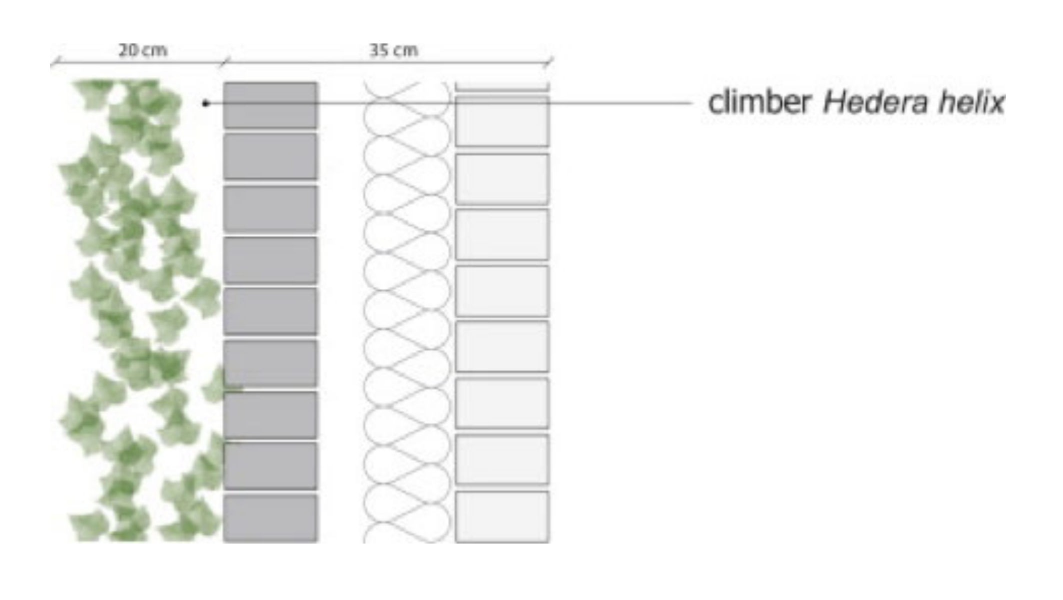


Figure 10: A typical direct green facade (source: Ottele et al 2011)

More recently, the development of engineered support structures (modular trellises, stainless steel cables, or stainless steel/HDPE mesh) have facilitated the development of 'double-skin' green facades or 'green curtains', in which an insulating layer of air is created between the foliage and building wall (Kohler 2008; Ottelle et al 2011; Perez et al 2011a&b). The support structures used for double skin green facades do not provide a surface to which self-clinging climbers can readily adhere; consequently, twining climbers (eg. *Trachelospermum jasminoides*) and climbers with specialised leaves for attachment, such as tendrils (eg. *Vitus* spp.) are most often used for this form of façade greening (Dunnett & Kingsbury 2004; Melzer et al 2012). They are also more commonly used where there is a concern that self-clinging climbers may damage building wall surfaces (such as render, weatherboards etc) or where wall surfaces are composed of polished stone, metal or plastic cladding (Dunnett & Kingsbury 2004). It should be noted that there is some debate as to the actual damage self-clinging climbers do to historic masonry: evidence suggests that the cover they provide can play a 'bioprotective' role, reducing wall temperature extremes and fluctuations (Sternberg et al 2011).

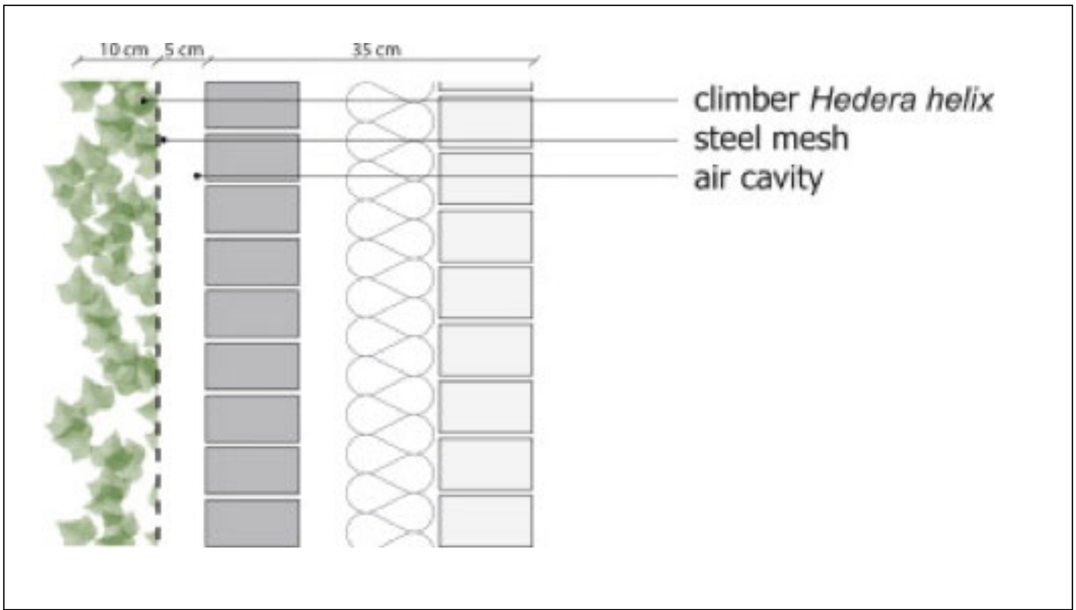


Figure 11: A typical double skin green facade. Note that the air cavity between the support structure and masonry is often much larger than 5cm. (source: Ottele et al 2011)

Green or 'living' walls have received attention largely due to their aesthetic rather than thermal qualities – the 'mur vegatal' designed by Patrick Blanc being the most emblematic. Green walls may either be constructed from prefabricated, modular panels or planters containing a lightweight growing medium or from geotextile felts. No rooting space is required at ground level; ferns, epiphytes, small herbaceous perennials and/or grasses are planted directly into the growing medium or felt (Kohler 2008; Kontoleon & Eumorfopoulou 2010; Perez et al 2011a). Water and nutrients are often provided to the plants via a hydroponic system (Ottele et al 2011). While there is a growing range of these proprietary systems on the market, the design of green walls is still in its infancy. Green walls are generally expensive to build and maintain – a problem that has led to some caution in their adoption. In 2009, an irrigation fault led to the spectacular death of a 30 m green wall at the Paradise Park Children's Centre, Islington, UK. The conspicuous demise of this showpiece drew the ire of many locals, who accused the Islington Council of wasting £100,000 of taxpayers' money on a 'green extravagance' (London Evening Standard, 21 Aug 2009). There have also been high profile failures of green walls in Australia that have led to court battles.

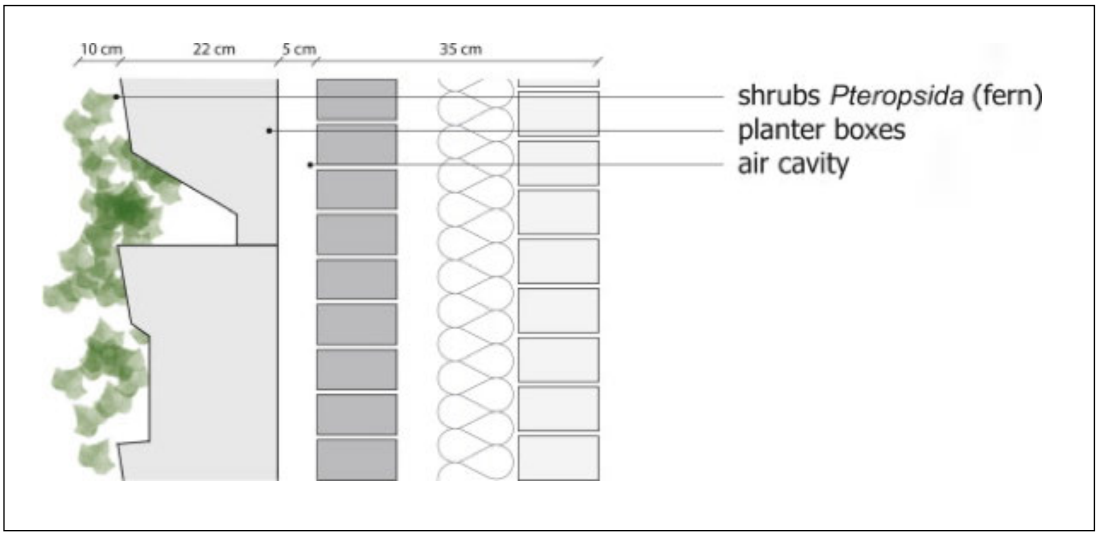


Figure 12: A typical green wall composed of planter boxes (source: Ottele et al 2011)

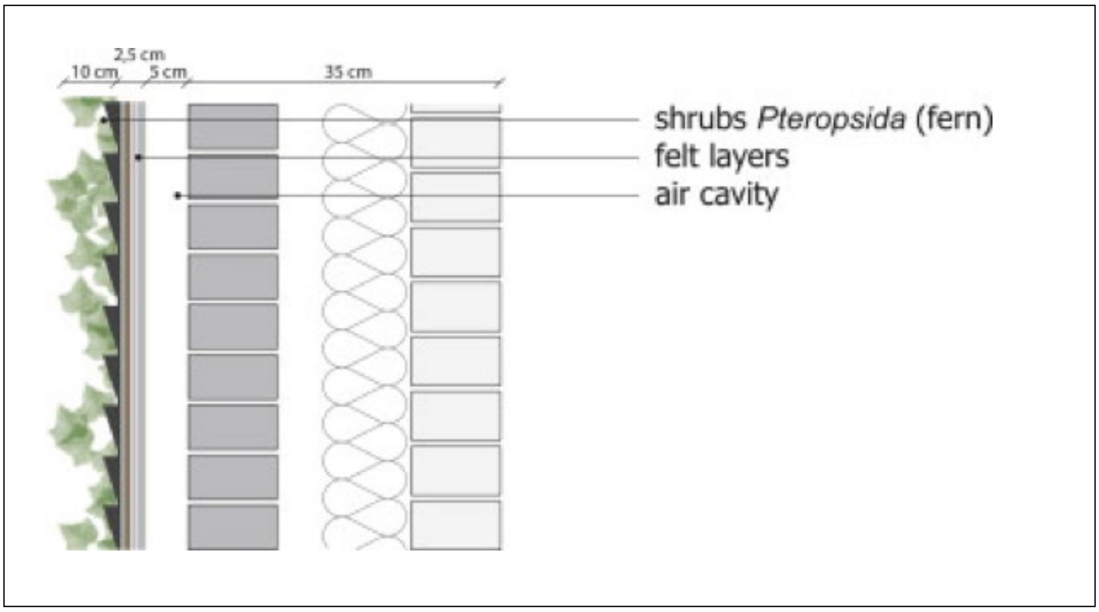


Figure 11: A typical green wall with a geotextile felt substrate (source: Ottele et al 2011)

The research literature on VGS is currently dominated by the disciplines of architecture and engineering. Much of this literature falls foul of two dubious assumptions. One is that all forms of vertical greening are inherently environmentally sustainable, despite the marked lack of research quantifying their thermal performance – or their life cycle environmental costs more generally (Ottele et al 2011). The other – as discussed in sections 3.4 and 3.5 in relation to green roofs – is that the facades of high-rise buildings, no matter how tall, can be entirely covered with a permanent swathe of vegetation. Establishing and maintaining persistent plant coverage on green roofs has been challenging in arid and Mediterranean climates. Arguably it is even more the case for direct green facades and double skin green facades, as many climbing plants originally derive from forest ecosystems, where they are not subject to the wind velocities common at height on tower blocks. Covering an entire ten storey apartment block in turf using a green wall system may be readily achieved in a simulation model (Wong et al 2009), but is likely to be fraught with technical difficulties in practice.

4.3 VGS under extreme environmental conditions

In the deep street canyons of dense, inner-city areas, conditions are frequently harsh, exposing vegetated facades to strong solar radiation and/or very deep shade, high wind loadings and temperature extremes (Cheng et al 2010, Rayner et al 2010; Stec et al 2005). In urban areas characterised by low rise, single and double storey buildings, conditions are generally more benign, permitting the use of less heavily engineered systems and a wider selection of plants.

On high building towers, plants and support structures for VGS must be able to withstand high wind loadings. An understanding of wind behaviour around aerodynamically 'rough' multi-storey buildings is essential to the design of effective VGS. On the windward side of tall buildings, strong localised wind currents form, creating downdrafts toward street level and updrafts toward the upper floors (Hopkins & Goodwin 2011). As height above ground increases, so does wind speed: research in Melbourne found that at 'sixty-five metres above the ground… the winds often gust at velocities well over 100 kilometres per hour' (O'Loan 2009 in Hopkins & Goodwin 2011, p. 53).

High winds can strip plants of their leaves, rip them away from support structures and pull support structure fixings out of the building wall. Strong winds also accelerate evapotranspiration (Hopkins & Goodwin 2011) particularly if air temperature is high and vapour pressure low (arid and Mediterranean climates), potentially outstripping the capacity of the plant to take up water from the soil or substrate, regardless of substrate composition or irrigation rates. A search of the literature failed to find any peer-reviewed studies of the effects of wind velocity on VGS. There is a great need for experimental work to address this issue – particularly observations and experiments to identify plant traits and subsequently species that are capable of maintaining growth and physiological function at height.

On high-rise buildings, plant survival is affected by the location of VGS on the building's façade. In the lower levels of an inner city street canyon, plants may be in deep shade for most of the day, while in the higher levels, they may be exposed to excessive levels of solar radiation and wind. Rayner et al (2010) found high plant failure rates in the double skin green facade installed at the CH2 building in Melbourne's central business district. Plant death and poor cover values were traced to a number of factors. However, for all species, the highest rate of failure was found at the lower levels and eastern aspect of the building. It appears that plant species selected for their shade tolerance were nevertheless unable to thrive in the deep shadow cast by the building (Rayner et al 2011). On low sections of an east-facing façade during the height of summer, plants may be exposed to intense solar radiation for a short period in the morning during which their role in cooling surface and air temperatures may be important. Consequently, they must be able to survive extremes of both high and low light intensities – a situation that is rarely found in natural ecosystems.

Aspect also affects light and wind exposure, and thus the thermal performance of VGS. Sternberg et al (2011) found that an east-facing wall with a plant cover thickness of 45 cm exhibited a greater moderating effect on seasonal extremes of temperature and relative humidity than a south-facing wall with a cover thickness of 95 cm. These findings are broadly consistent with modelling of the thermal behaviour of a single-storey masonry building in the humid Mediterranean climate of Thessaliniki, Greece (Kontoleon & Eumorfopoulou 2010): in summer, the daily maximum temperatures of the east-, south- and west-facing surfaces of a direct green facade (250 mm thick cover of *P. tricuspidata*) were 10.53 °C, 6.46 °C and 16.85 °C lower respectively, than equivalent exposed walls. It should be noted however, that one of the assumptions of this model was that the morphology of the surrounding area was open, with no other buildings influencing thermal performance. The importance of aspect may be moderated or affected by other parameters in built-up areas, particularly where buildings are tall and streets narrow. Modelling by Alexandri and Jones (2008) suggests that in urban street canyons, aspect (or canyon orientation) is less significant in determining air and surface temperatures than the extent of vegetation cover and canyon geometry (height and width).

4.4 VGS and building thermal performance

As with other forms of green infrastructure, VGS cool buildings by intercepting solar radiation (Holm 1989; Hoyano 1988); providing thermal insulation (via dense foliage, and in the case of a double skin green facade, an additional layer of air between foliage and building wall); evapotranspirative cooling; and altering air movement (Perez et al 2011a&b). VGS reduce heat gain by absorbing and reflecting solar radiation: for example, Di and Wang (1999, p. 245) found that of the solar radiation absorbed by 'ivy' on a direct green facade, '40% was lost via convection, 42% by transpiration, and the rest by long-wave radiation to the environment'.

Shading (by leaves, branches and support structure) shields the building wall from direct sunlight, reducing exterior surface temperatures and thus heat transfer into the interior of the building. In winter, the reverse occurs: the heat held by the thermal mass of the building wall is isolated by the insulative effect of the vegetation and air cavity, reducing heat loss.

During the 1990s, engineers and architects began to develop double skin façade systems using glass, timber, metal or masonry shading devices to improve the thermal performance of buildings with high glazing fractions. These systems generally comprise external and internal glazed façades, separated by an intermediate space. Adjustable shading devices are installed in this space (Wenting et al 2005; Shameri et al 2011), which may vary in width from 200 mm to 2 m (Chan et al 2009). The thermal performance of these architectural systems can be tested via established methodologies and measurement techniques. As yet, no such standardised methodologies and techniques have been developed for VGS. Unlike constructed shading devices, VGS are 'dynamic, self-regulating thermal control system[s]', especially when planted with deciduous species, which are capable of responding to an early spring by sprouting earlier or to a late autumn by retaining its leaves for longer than usual (Holm 1989, p. 21). The sensitivity of deciduous climbers to seasonal change offers considerable advantages over constructed shading structures, such as awnings and screens. However, the plasticity, diversity and dynamism of plants means that quantifying thermal performance is inherently more complex.

4.4.1 Plant shading properties

Although LAI alone does not entirely capture the cooling potential of plants (see section 2.2.4 of this report), several studies of climbing plants in urban environments have shown that their thermal performance is primarily a function of leaf area and foliage density (Kohler 2008; Wong et al 2009 & 2010). Although the capacity of a leaf to reflect, absorb and transmit solar energy varies considerably from one plant species to another, these differences tend to decrease as foliage density increases. In a relatively early study of the thermal effects of leaf cover on external walls in a hot, arid environment (Pretoria, South Africa), Holm (1989) found that for a direct green facade at a cover depth of 200 mm or more, *H. helix*, *P. tricuspidata*, *P. quinquefolia* and *Vitus vinifera* displayed virtually equivalent optical and thermal properties. The outer layers 'act[ed] like optical filters while the deeper layers act[ed] like insulation material' (Holm 1989, p. 21). Similarly, Ip et al (2010) found that leaf transmissivity values declined from 0.45 for a single leaf layer, to 0.12 for five leaf layers. Beyond five layers, leaf transmissivity values tended towards zero, meaning that very little solar radiation was filtering through to the building wall. Perez et al (2011a&b) reported light transmission reductions of the same order of magnitude for a double skin green facade (*Wisteria sinensis*) in full leaf at mid-summer, while Hoyano (1988) observed even lower average leaf transmissivity values for *P. tricuspidata* (0.02-0.07) at multiple sites in Tokyo, Japan.

Percentage foliage cover is also a significant parameter: modelling of a single-storey building with a direct green facade of *P. tricuspidata* in a Mediterranean climate indicated that as the proportion of foliage covering a wall increased, indoor minimum air temperatures decreased in a linear fashion. With 100% vegetation coverage, the mean daytime indoor and outdoor ambient air temperatures were almost the same (Kontoleon & Eumorfopoulou 2010).

There appears to be little empirical data available regarding growth rates and quality of total foliage cover for VGS in urban environments across different climatic zones. Wong et al (2010) found that a double skin green facade performed poorly in comparison to the eight green wall systems tested at HortPark, Singapore, as it only achieved a 4.36 °C reduction in wall surface temperature. Inadequate foliage coverage may be the reason for this, as the lower areas of the wall were virtually bare. Some climbing plant species provide only sparse cover close to ground level, with denser foliage massing at the top of the support structure (for example, *Hardenbergia violacea; Cissus antarctica*). Experience at the CH2 building in Melbourne suggests that better cover values for double skin green facades may be attained with nursery stock that have been formatively pruned to encourage extensive lateral branching and the growth of basal shoots (Rayner et al 2010).

One of the most conspicuous limitations of the available research on direct green facades is the reliance on a handful of plant species – principally, *H. helix, P. tricuspidata* and *P. quinquefolia*. These species are very commonly used for façade greening in Europe and North America, as they exhibit the capacity to cover large areas very rapidly (climbing to a maximum height of 20-25 m), persist for decades or even hundreds of years (Sternberg et al 2011), tolerate heavy pruning and cope with limited space in the root zone (Dunnett & Kingsbury 2004; Kohler 2008; Ottele et al 2011). With the exception of plants selected for the green facades at the CH2 building, Melbourne (Rayner et al 2010), studies of double skin green facades were also based on a restricted selection of plants: *Luffa cylindrica*, *Vitus* spp., *Wisteria sinensis, Lonicera japonica* and *Thunbergia grandiflora*. It should be noted that almost all of the species mentioned above have proven to be invasive in Australia. Experimental work is needed to identify alternative plant species for specific eco-regions and climates, and to determine which of these will deliver the best thermal performance, without introducing or contributing to the spread of weeds. Studies of climbing plants in forest ecosystems may identify a wider range of plant species with potential for use in direct green facades and double skin green facades (Kohler 2008) – for example, Carter & Teramura (1988) on the climbing mechanics of indigenous and exotic woody vines in the south-eastern United States; and Gallagher et al (2011) on the differing functional traits and ecological strategies of Australian climbing plants from tropical and temperate regions).

4.4.2 Evapotranspiration

As with other forms of green infrastructure, water availability plays a crucial role in maintaining plant biological processes and facilitating evapotranspirative cooling in VGS. Water availability to plants is largely determined by substrate design, rooting volume and irrigation regime.

Substrate design

In general, the method descriptions in published VGS manuscripts rarely provide information about substrate composition – for example, one study simply referred to a 'universal substrate … for topsoil' (Perez 2011b). Only one of the studies reviewed specifically considered the relationship between the magnitude of evapotranspirative cooling and substrate design: Cheng et al (2010) examined the influence of plant and substrate moisture levels on the cooling capacity of a modular green wall system planted with *Zoysia japonica*, a warm season grass. Unfortunately, it appears that due to the use of a proprietary system ('slabs of Grodan® hydroponic medium' (p. 1780)), no details were provided regarding substrate composition and properties such as air-filled porosity, water holding capacity and hydraulic conductivity. (These properties indicate the capacity of a given substrate maximize both water and air availability to roots, allow infiltration of water through the substrate profile and permit effective capillary movement of water to the root zone (Craul 1999; Handreck & Black 2004; Rayner et al 2010). Consequently, little could be concluded, other than that evapotranspiration made a significant contribution to cooling, and that cooling did not rely on the thermal mass of the substrate alone. Similarly, although Wong et al (2010) rated the relative thermal efficiency of nine VGS (eight of them green walls) they assessed, details on substrate design and irrigation regime were sparse, making it difficult to discern the basis by which one system out-performed another.

There is an enormous need for empirical research in which specific substrate properties are manipulated to investigate impacts on evapotranspirative cooling. Such research needs to be informed by horticultural knowledge, and must not rely solely on proprietary systems protected by commercial 'in confidence' clauses. There is also a need for research to determine whether the felt substrates pioneered by Patrick Blanc in Europe have sufficient water-holding capacity to tolerate summer conditions in arid and Mediterranean climates.

Rooting volume

The simplest forms of direct and double skin green facades involve planting directly into the soil at street level. Urban soils are often compacted, contaminated, low in oxygen, hydrophobic and offer limited rooting volume. There is a large urban horticultural literature dealing with these issues (Craul 1999). However, green walls and double skin green facades at height on high-rise buildings rely upon containerised systems. Planter boxes, modular panels and felts need to provide adequate space for healthy root development. Their design is important so as to optimise the availability of both water and oxygen in the root zone. None of the studies reviewed specifically examined the effect of different planter-box and module designs on root development, root-to-shoot ratios, root temperature or soil water availability – all of which have a critical impact on evapotranspiration rates (Handreck & Black 2005). More research is needed to develop container and module designs for specific climatic regions and plant selections.

Irrigation systems and regime

The high-profile demise of the Patrick Blanc-designed green wall on the Trio residential tower, Camperdown, New South Wales (the only multi-storey green wall in Australia to date) is likely to have been primarily caused by an irrigation fault. Similarly, the failure of the large green wall at the Paradise Park Children's Centre in Islington, UK, was ascribed to irrigation failure (Fulcher 2009). Moreover, the poor plant performance of the CH2 Building in Melbourne has been attributed to a malfunction in the sub-irrigation system (Rayner et al 2010). Despite these failures, and the centrality of irrigation systems in ensuring the survival of plants, empirical data on the performance of these systems is scarce. None of the studies reviewed specifically examined the effects of irrigation frequency and application rates on the evapotranspirative cooling in plants commonly used for VGS. In many cases, it was simply assumed or stated that an adequate supply of moisture was provided.

4.4.3 Plant support systems and climbing mechanics (double skin green facades)

Each climbing plant species exhibits distinctive climbing mechanisms and growth habits and the support systems selected must be matched to these characteristics. The literature on green facades is not yet grounded in a strong theoretical grasp of climbing plant ecology, physiology and climbing mechanics. Knowledge of plant traits (vigour, climbing mechanics, mature size, plant biomass (before and after rain)) is essential so as to ensure that systems are strong enough to support the mature plant even when wind loadings are extreme (Dunnett & Kingsbury 2008; Wassman 2002)).

4.5 Cooling and energy savings of VGS at the building scale

4.5.1 Direct Green Facades

Studies of direct green facades have measured a range of variables including: temperature (outside ambient (wet and dry bulb), leaf surface, within canopy, exterior building wall surface, interior building wall surface, interior ambient); relative humidity (outside, within canopy); thermal conductance (W/m2); and cooling load reduction (often in percentage values). Wind velocities were not always provided, or were assumed to be zero. Few studies measured all of these variables and units of measurement frequently varied from one study to another. Comparisons between studies are therefore somewhat difficult to make. The metric most commonly measured was exterior building wall surface temperature.

All studies reviewed found that direct green facades improved the thermal performance of building. Most focused on the summer cooling benefits of reduced 'near wall' air and wall surface temperatures, and increased relative humidity. As with trees, the placement of a direct green facade relative to the building significantly influences the magnitude of summer cooling and energy savings.

In the arid, inland climate of Pretoria, South Africa, modelling by Holm (1989) indicated that for a typical South African home of lightweight construction (insulated fibro-cement sheeting) optimal thermal performance on a an annual time-scale could be achieved with deciduous leaf cover on the equator-facing (north) wall, and evergreen cover on all east- and west-facing aspects. This reduced summer daytime indoor air temperatures by 5 °C, obviating the need for air-conditioning. The most pronounced improvements in thermal performance were observed when a direct green facade was retro-fitted to a poorly-oriented, west-facing, low-mass dwelling.

Interestingly, the application of Holm's (1989) model to high-mass buildings in a Mediterranean climate suggested that direct green facades would offer negligible benefits, reducing the maximum indoor air temperature experienced on summer days for a west-facing building by only 1 °C. However, a simulation model validated using field measurements taken in Greece rather than South Africa, pointed to dramatic improvements in the thermal performance. The model predicted that a direct green façade (*P. tricuspidata*) retrofitted to a hypothetical single-storey masonry building in a Mediterranean climate would reduce external wall surface temperatures (averaged across all walls) by 10.79 °C. Reductions in cooling energy demands were greatest for west- and east-facing walls (18.17% and 20.08% respectively), while a vegetation layer on the equator-facing (south) wall resulted in a smaller reduction of 7.6% (Kontoleon & Eumorfopoulou 2010).

Even in more temperate climates, the summer cooling and energy-saving benefits of direct green facades have been observed. In the humid inland climate of Beijing in China, 'ivy' cover on the south- and west-facing masonry wall of a double storey building reduced summer cooling loads by 28% (Di & Wang 1999). Average conductive heat flux through the bare wall was 2.045W/m2, while for the vegetated wall it approached zero. In a similar study of a double storey house in Tokyo, the daily maximum heat flux through the west-facing concrete wall was approximately four times greater (223.6 W/m2) compared to a vegetated section of the same wall (Hoyano 1988). These studies focused only on summer data and did not attempt to determine whether the benefits of summer cooling outweighed the costs of winter warming in these climates. However, in Germany summer air and surface temperatures at the building wall surface behind a direct green facade (*H. helix*) were found to be 2 to 6 °C cooler compared to a bare wall (Bartfelder & Kohler 1987 in Perini et al 2011), while in winter, the vegetation layer prevented up to 3 °C heat loss (Kohler et al 1993). Work by Sternberg et al (2011) investigating the impact of *H. helix* on the stone surfaces of several British historic buildings has highlighted the moderating effect of direct green facade vegetation on daily and seasonal extremes of temperature and relative humidity. Statistically significant differences were detected between the mean temperature ranges for vegetated (2.27 °C) and exposed walls (8.21 °C), while mean relative humidity fluctuations were 2.7 times greater on exposed walls compared to vegetated ones.

There is a paucity of studies comparing the thermal benefits of direct green facades and structural forms of insulation, such as rockwool and polyester batts. Nevertheless, Kohler et al (1993 in 2008, p. 427) has claimed that direct green facades have 'greater relative insulation benefits than a well-insulated new building', and Eumorfopoulou and Kontoleon (2009) found that the thermal conductance of *P. tricuspidata* with a depth of 250 mm approached 2 W/m2, which is roughly equivalent to the effect of double glazing or a static air space of 75 mm in width.

4.5.2 Double skin green facades

In addition to foliage, double skin green facades incorporate an intermediate space between the vegetation layer and the building wall. The relatively still air held in this cavity provides an extra layer of insulation, enhancing the thermal performance of the system. In the dry, continental Mediterranean climate of Lleida, Spain, Perez et al (2011a&b) investigated the thermal performance of a free-standing steel double skin green facade (62% covered by *Wisteria sinensis*), which stood 800-1500 mm from the building itself. In spring and summer, building wall surface temperatures in the mid-afternoon were on average 5.5 °C cooler in shaded compared to sunny areas, reaching a maximum difference of 15.18 °C on the south-west side in spring. At the height of summer, the relative humidity in the intermediate space was up to 7% higher than that measured outside, demonstrating the effects of evapotranspirative cooling. The study demonstrated that a microclimate developed in the air cavity: in winter, air temperatures were up to 3.8 °C higher, with lower relative humidity, while in summer, air temperatures were 1.36 °C lower, with higher relative humidity than the outside air.

The air exchange rate in the intermediate space is important to cooling function (Ottele et al 2011), as wind velocity has a strong influence on the thermal transmittance of a building wall. Perini et al (2011) compared wind velocity decreases inside or behind the foliage for the three types of VGS. Within the foliage of the direct green facade, wind velocity decreased by 0.43 m/s to 0.08 m/s. While wind velocity decreased inside the foliage of the double skin green facade by 0.55 m/s, it *increased* in the air cavity by 0.29 m/s, to 0.39 m/s. The authors suggest that the 200 mm air cavity was too wide to provide an insulating layer, and that the optimal air cavity thickness may be smaller (40-60 mm). There appears to be scant research and little consensus yet as to the optimal width of this cavity for different plant species, building aspects, heights above ground level and climatic zones. As noted above, the double skin green façade studied by Perez et al (20011a&b) was much larger (800-1500 mm).

It is also unclear as to whether the foliage covering a double skin green facade inhibits or facilitates natural ventilation both behind the foliage and within the building. Hoyano (1988) found that the ambient daytime air temperature of a south-west facing, second storey verandah fitted with a double skin green facade (consisting of vertical and 35 degree-angled elements and planted with *Luffa cylindrica syn*. L. *aegyptica*) was 2-4 °C lower than an unscreened verandah with the same aspect and dimensions. However, the double skin green facade diminished the cross ventilation ratio (17% as opposed to 46% for the unscreened verandah), suggesting that green facades of this type should incorporate openings to enable air circulation.

Another study in a tropical climate yielded contrary results: higher ventilation rates were achieved in a test-room fitted with a double skin green facade (planted with *Thunbergia grandiflora*) compared to an identical room without one. In each room, both the window and a door opposite the façade were left open. The authors surmised that lower air temperatures amidst the foliage resulted in an air pressure gradient between the double skin green facade and the open door, facilitating the movement of air. Daytime interior ambient temperatures were reduced by an average of 3.63 °C (and up to a maximum of 9.93 °C) (Sunakorn & Yimprayoon 2011).

These studies all point to the cooling potential of double skin green facades, but are not sufficient to indicate whether this form of façade greening is more effective than direct green facades. Only one of the papers reviewed sought to quantify the peak energy savings that might be delivered by double skin green facades. Stec et al (2005) compared the thermal performance of a double skin green facade against blinds adjusted to equivalent transmissivity values (the composition of these blinds was not specified). Using a scale model of glazed wall and UV lamps to simulate solar radiation, the study found that behind the double skin green facade, the temperature of the building wall surface and intermediate air space were 20% and 20-35% lower, respectively, as compared to that behind blinds, thus demonstrating the role of evapotranspiration in cooling both surface and air temperatures. Simulations at the whole building scale, validated by this laboratory scale model, indicated that a double skin green facade would reduce annual energy consumption for heating, ventilation and air-conditioning by approximately 19%, as compared to the use of external blinds.

4.5.3 Green walls

There are few studies in English assessing the thermal performance of green walls, but those that do exist indicate their dramatic cooling potential. Studies of their effects on peak cooling load reductions are even more scarce.

An experimental study in Singapore (Wong et al 2010) found that, compared to a bare concrete 'control' wall, the temperatures at the wall surface behind eight different green wall systems were substantially lower during the day (by 4–12 °C, with a mode of 10 °C), and somewhat cooler at night (by 3–6 °C). During the day, the substrate surface temperatures rose rapidly compared to wall temperatures. At night, the reverse occurred: substrates tended to lose heat faster than the concrete walls (which had a higher heat capacity). Three of the VGS compared for their effects on ambient air temperatures: while the double skin green facade produced no effect on ambient air temperature at 0.30 m from the foliage, a noticeable difference in air temperature could still be observed for the two green wall systems at 0.60 m from the wall. These results suggest that green walls not only moderate building wall temperatures, but can also be used to reduce air intake temperatures for heating, ventilation and air-conditioning systems, resulting in savings in energy cooling loads (Wong et al 2010).

Cheng et al (2010) found that a green wall (modular panels pre-planted with *Zoysia japonica*) reduced maximum wall temperature by 16 °C, with a four-hour time lag in heating of walls. Temperature fluctuations were much reduced behind the green wall: temperatures at the wall surface covered by the green wall were fairly constant with a range of 27.9 to 29.5 °C, compared the temperature of the exposed wall, which climbed to more than 44 °C on hot afternoons.

Wong et al (2009) used modelling to compare the thermal performance of hypothetical identical multi-storey buildings with and without green walls on all facades, and for a range of window configurations. The application of green walls to all facades of a windowless building reduced the mean radiant temperature (MRT) from 34.39 to 24.01 °C. Due to heat transfer through glazing, the MRT reduction was far more modest for a building with windows (2 x 2 m): from 36.57 to 35.30 °C.

There is insufficient evidence to determine whether the combination of plants and substrate in green wall systems gives rise to a greater cooling effect than that produced by green façades. However, Perini et al (2011) observed differences between surface temperatures of leaf layer and building wall of 5 °C for a green wall (planter box), compared to only 1.2° C for direct green facade and 2.7 °C for double skin green facade.

4.6 Environmental life cycle analysis of VGS at the building scale

A search of the literature yielded only one environmental life cycle analysis of VGS. Ottele et al (2011) assessed the life cycle environmental impacts of four VGS compared to a bare facade: a direct green facade (*H. helix*); a double skin green facade with *H. helix* cover over a steel mesh support; a green wall (planter boxes) with 'ferns'; and a green wall (felt) also upholstered with ferns. Drawing on the Dutch National Environmental database, the LCA considered the environmental impacts of 'raw material depletion, fabrication, transportation, installation, operation, maintenance and waste' (p. 3420) for the bare façade and each VGS. An inventory analysis provided a breakdown of all system components for each type of VGS (mortar, bolts, spacer brackets etc), the weight of these components, distance transported and service life.

The LCA assumed a service life of 50 years for the bare wall, the direct green facade and double skin green facade. Replacement frequencies were assumed to be 10 years for the green wall (planter boxes) and 3.5 years for the green wall (felt). The automatic irrigation system for both green wall systems would be replaced every 7.5 years, while irrigation systems for direct green facade and double skin green facade were not costed as it was assumed that rainfall would provide sufficient water. Finally, it was assumed that for all systems, components would be recycled where possible at the waste stage of the life cycle. It should be noted that the environmental life cycle impacts of the nutrients and water used for the hydroponic green wall (felt) system were not included in the analysis, nor were the impacts of the plant layer in any of the systems.

The analysis determined that environmental impacts were only significant for the categories of global warming, human toxicity and freshwater ecotoxicity. It showed that the material components comprising the support systems contributed most significantly to the overall environmental burden. The global warming impact of the green wall (felt) system was 'more than double' compared to the other VGS (p. 3424), due to the need for frequent replacement, and fact that few of its components could be readily recycled. The human toxicity and freshwater aquatic ecotoxicity impacts were high for all VGS except the direct green facade. The direct green facade was found to be sustainable in all cases; the double skin green facade was potentially sustainable if recycled stainless steel used for the support; the green wall (planter boxes) may be sustainable if integrated into building structure (replacing masonry); while the green wall (felt) had a high environmental burden. The environmental costs of these systems were offset against their potential cooling and energy-saving benefits at micro-scale, based on modelling by Alexandri & Jones (2008). The authors acknowledge that they did not take into account less tangible benefits of VGS at larger scales, such as increased biodiversity, reduced burden of human disease, the air quality improvement and mitigation of UHI effects.

This study challenges the commonly-held assumption that VGS are inherently 'environmentally friendly'. It raises real concerns regarding the sustainability of green wall technologies, and indicates that research should seek more sustainable alternatives to stainless steel components in double skin green facades. It suggests that the uptake of low-impact direct green facades should be encouraged, wherever feasible.

Ottele et al (2011) also applied their LCA calculations to the Mediterranean climate of Genoa, Italy, and found that the thermal benefits of the VGS would be twice as high as that calculated for the Netherlands. The validity of this finding is somewhat questionable, as it relies on Dutch environmental data and a model (Alexandri & Jones 2008) that was not validated by actual field data. Nevertheless, it does suggest that in climates with warm to hot, dry summers, the thermal and other benefits of VGS are more likely to outweigh their environmental impacts over the life cycle. This may well be the case in parts of Australia with Mediterranean and arid climates. However, the global warming impacts of system components is likely to be greater in Victoria, due to our heavier dependence on brown coal. Moreover, any LCA using Australian data would need to factor in the cost of irrigation systems for direct green facades and double skin green facades.

4.7 Cooling and energy savings of VGS at local- and meso-scales

While there is a limited but growing body of evidence for the cooling and energy-saving benefits of VGS at the building scale, virtually no published studies could be identified that investigated the potential benefits of this form of green infrastructure at local- and/or meso-scales.

Prognostic modelling by Alexandri and Jones (2008) suggests that unlike green roofs, which have the potential to contribute to wider UHI mitigation, VGS provide highly localised cooling, primarily within the urban canopy layer While the term 'urban canyon' implicitly refers to the local- rather than building-scale, as previously noted their findings are based on a two-dimensional, microscale model that was not validated via experimental or observational studies.

In Singapore, Wong et al (2009) used a simulation model to predict whether the installation of VGS on building facades throughout an industrial estate would mitigate localised UHI effects. The hypothetical VGS was planted with *Nephrolepsis exaltata* (Boston fern) – a plant with a very high LAI of 6.76. Ambient estate air temperature was calculated for different vegetation cover of building facades: 0%, 25%, 50%, 75% and 100%. As vegetation cover increased, the minimum air temperature in the industrial estate decreased. At 100% cover, the minimum air temperature was 1 °C lower than at 0% VGS cover. However, even with 100% vegetation cover, decreases in average and maximum estate air temperature were not significant (0.32 and 0.30 °C, respectively). Consistent with the findings of Alexandri and Jones (2008), this study suggests that VGS have a very modest effect on localised ambient air temperatures and therefore the UHI at this scale. Consequently, they may have greater value in reducing internal air temperatures, and thus reducing summer peak cooling loads.

Further research is needed to determine the local- and meso-scale thermal effects of VGS across climatic gradients. Modelling work must be validated using region-specific empirical data.

5. Conclusion

5.1 An issue of scale

Urban sprawl and densification are leading to the loss of vegetation in Australia's cities. As warming associated with urban development and climate change intensifies, vulnerable social groups will be at greater risk of heat-related ill-health. There is an urgent need to address this problem without increasing emissions of greenhouse gases via the strategic development of urban green infrastructure.

The international research reviewed in this report has shown that trees, green roofs and VGS can reduce surface and ambient temperatures at the micro-scale. However, there is a need for further research to determine the potential magnitude of cooling and energy-saving benefits that may be achieved at local- to city-wide scales, particularly for green roofs and VGS (Bowler et al 2010; Oke 1989), as it cannot be assumed that cooling at larger scales arises in a linear fashion from the cumulative effects of micro- to local-scale cooling within the urban canopy layer (Oke 1988 & 2009). In addition, research is needed to quantify the type(s), extent and distribution of green infrastructure required to best mitigate the adverse impacts of urban warming at local- to city-wide scales (Bowler et al 2010).

At smaller scales, there is a lack of site-specific and species-specific quantification of the cooling and energy-saving benefits of green infrastructure (Pataki et al 2011a, p. 34). Without this research, there may be a perception that green infrastructure can be implemented in a generic manner, without consideration of important variables such as regional climate, soil type, natural vegetation communities, specific urban form, density and extent, and cultural or community values (Pataki et al 2011a; Bowler 2010). In fact, the heterogeneity of urban landscapes means that no single type or configuration of green infrastructure can be regarded as being "the best" or "optimal" for ameliorating the UHI under climate change conditions everywhere (Gober et al 2011).

5.2 Green urban infrastructure for Australian climates

In comparison to Europe and North America, green infrastructure research is not well established in Australia. We know little about the thermal performance of different forms of green infrastructure in Australia's diverse range of climates and eco-regions. Nor do we fully understand how variables such as native plant traits, vegetation health, the availability of irrigation or the composition of soils/substrates influence the performance of different green infrastructure systems.

5.2.1 Urban trees

In arid and Mediterranean climates, the international literature has shown that the benefits of urban trees in creating cool microclimates and reducing energy demands associated with air-conditioning far exceed the increased heating costs due to winter shading of buildings. However, in these climates there is inevitably a trade-off where water is limiting, between optimising shade and evapotranspiration (through selection of trees with high LAI and providing irrigation), and maintaining an urban tree population that can tolerate drought conditions, high temperatures and low vapour pressure deficits. There is a critical need for further research into the water status of different urban tree species under a range of water availability scenarios, with a particular focus on street trees, which are generally more vulnerable to the impact of urban warming than trees in large parks and residential gardens.

While there is a substantial and growing North American and European literature pointing to the thermal benefits of urban trees (at least at the micro- to local-scales), the Australian research in this field is virtually non-existent. There is an urgent need for empirical data on the water use, ecophysiology, thermoregulation and microclimate cooling benefits of trees commonly planted in Australian cities. At present, the existing research cannot provide answers to questions such as:

- What cooling benefits do fine-leaved, sclerophyllous trees, such as Eucalypts and Allocasuarinas offer compared to broad-leaved exotic species, such as *Planatus orientalis* and *Ulmus nobilus*?
- Given predicted increases in urban temperatures over the coming decades, which plant traits will increase tree survival rates, particularly in our southern cities?
- What irrigation rates and frequencies are required to optimise the thermal performance of specific native Australian and exotic tree species?
- What vegetation cover rates are required for each genus or species to optimise net cooling benefits at local- and meso-scales?

5.2.2 Green roofs

Most published research on the thermal performance of green roofs has been conducted in the temperate climates of northern Europe and North America. Although there is a growing body of research from Singapore, Hong Kong, Greece and Italy, there are generally fewer published studies from arid, Mediterranean, sub-tropical and tropical climates. Paradoxically, it is in these latter climates that green roofs are likely to deliver the greatest benefits by cooling microclimates in and around buildings in summer.

While observational studies pointing to the cooling and energy saving benefits of green roofs are common (see for example, Fioretti et al 2010; Liu & Baskaran 2003; Niachou et al 2001; Onmura et al 2001; Spala et al 2008; Wong et al 2003), only a small number of researchers have used controlled experimental methods to identify the most suitable plants and substrates, irrigation regimes and systems for specific climates and eco-regions (Bowler et al 2010; Dvorak & Volder 2010). To date no published studies have considered regionally appropriate plant species and substrates to optimise thermal performance of green roofs, although there is a comparative study in three Canadian cities with different climates underway (Lundholm pers. comm..)

The roofs of Australia's cities represent an unexploited opportunity for urban greening. Estimates of the horizontal surface area of typical urban environments covered by roofs varies from 20% (Akbari et al 2009) to 32% (Oberndorfer et al 2007). While the precise proportion of surface area occupied by roofs will vary from one city to another depending on urban form, density and functional land use, roofs nevertheless represent a large component of urban impervious surfaces. The scientific literature suggests that green roofs can cool urban climates at multiple scales and create substantial reductions in carbon emissions by cutting summer cooling loads. However, there is a paucity of experimental research quantifying the effects of system design (plant selection, substrate depth and composition, and irrigation regimes) on the magnitude of potential cooling and energy-saving benefits that might be achieved Australian climates. Because of the strong season rainfall differences it is unlikely that green roofs that substantially cool the surrounding area will be viable in most Australian climates without supplementary irrigation. Consequently, the development of integrated green roof systems that harvest and utilise non-potable water sources is a priority.

5.2.3 Vertical greening systems

Compared to other forms of green infrastructure, the international literature on the cooling and energy-saving benefits of VGS is slight. Despite this lack of comprehensive empirical research, the indications are that, as for other forms of green infrastructure, VGS promise to deliver the greatest cooling and energy-saving benefits in Mediterranean and arid climates, if water is not limiting.

There is vast scope for expanding the use of direct green facades across Australian cities, as a cost-effective and sustainable means of cooling buildings. However, research is required to increase the diversity of non-invasive plants suitable for use in this context. Australia has seen few working examples of double skin green facades or green walls. As with green roofs, research efforts must focus on plant selection, substrate and container design, and irrigation regimes that will maintain plant health and survival rates in the extreme summer conditions experienced in Australia's southern cities. Given that green walls are expensive, resource intensive and prone to poor performance without uninterrupted irrigation, it is arguable that research efforts should prioritise the development of direct and double skin green facades.

5.2.4 Cost-benefit analyses

Further research is required for all types of green infrastructure at micro-, local- and meso-scales to provide proof of concept and enable the preparation of credible cost-benefit analyses. The assumptions upon which LCAs of green infrastructure are based will vary from one country to another, due to different market characteristics (such as local construction practices and costs; industry experience with green infrastructure technologies; energy sources), regional ecosystems and climatic factors (such as the added cost of irrigation systems in arid and Mediterranean climates). In addition, analyses may differ in the assumptions made regarding projected utility and regulatory costs over the lifespan, and the valuation of less tangible benefits, such as creation of habitat or aesthetic value. Clearly, there is a need for detailed LCAs of the different types of green infrastructure specific to Australian climates, ecosystems and economic markets, using regionally-specific environmental impact datasets.

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