QUANTIFYING THE BENEFITS OF GREEN INFASTRUCTURE IN MELBOURNE

LITERATURE REVIEW AND GAP ANALYSIS

CITY OF MELBOURNE

A CITY THAT CARES FOR THE ENVIRONMENT

Environmental sustainability is the basis of all Future Melbourne goals. It requires current generations to choose how they meet their needs without compromising the ability of future generations to be able to do the same.

Acknowledgement of Traditional Owners

The City of Melbourne respectfully acknowledges the Traditional Owners of the land, the Boon Wurrung and Woiwurrung (Wurundjeri) people of the Kulin Nation and pays respect to their Elders, past and present.

CONTENTS

July 2019

Cover Image: Aspire Melbourne, 299 King Street, Melbourne. Credit: Elenberg Fraser, ICD Property & Floodslicer.

To find out how you can participate in the decision-making process for City of Melbourne's current and future initiatives, visit melbourne.vic.gov.au/participate

INTRODUCTION

Objective

The objective of this literature review is to understand the potential benefits of green roofs, walls and façades within the public and private realm in Melbourne and the value associated with these.

It aims to:

- Synthesise the latest research about the benefits of green roofs, walls and façades in Melbourne or where local data is not available, in comparable climates and urban conditions.
- Quantify the benefits economically where data exists and identify information gaps and future research needs where local data is needed.
- Prioritise a list of indicators that reflect the benefits of green infrastructure which the City of Melbourne can use to rank projects.

Scope

This review is part of a larger project to quantify the value (economic, environmental, social) of the potential benefits of green roofs, walls and façades in the City of Melbourne.

The City of Melbourne has previously commissioned work that identified built form typologies suitable for retro-fitting green roofs, walls and façades and mapped specific buildings within the municipality (GHD 2015). Useable roof area across the City area, was classified according to their suitability for solar panels, cool roofs, and extensive and intensive green roofs. In all, 880 ha of roof space was identified. The area of roof space with no or low constraints for intensive green roofs was 27% and extensive green roofs 37%. Constrained, highly constrained and infeasible roof space for intensive green roofs was 59% and for extensive green roofs 45%. The overlap between intensive and extensive green roof suitability is over 90% (GHD 2015).

Total roof area covers about 23% of the total area of the City of Melbourne, similar to total tree canopy cover (22% in 2014). If all the suitable roof space was taken up by green roofs this would cover roughly half of the current tree canopy cover: 236 ha for intensive roofs or up to 328 ha for extensive roofs. About 30 new buildings are constructed in the City of Melbourne each year, so growth of new, suitable roof space will be fairly slow, except for the Fisherman's Bend urban renewal project. This creates a case for retrofitting existing roofs if faster roll-out is required.

In this review, benefits are grouped into four broad categories:

- Stormwater management
- Cooling Cities – the urban heat island effect
- Biodiversity
- Health and wellbeing

These categories comprise priority themes being considered by the City of Melbourne under strategies for enhancing green infrastructure to mitigate the negative effects of urbanisation. Empirical evidence is also required to support, quantify and measure these benefits – an important consideration when planning to implement an integrated system of green infrastructure initiatives. These will include regulatory controls at a municipal and/or city-wide scale that need to be evidence based.

These four categories have been widely investigated, with most emphasis focusing on stormwater management and Cool City – urban heat island effects. Other benefits of green infrastructure that have been reported on include air quality improvement (Currie and Bass 2008, Jayasooriya et al. 2017), property value increases (Clements and St Juliana 2013, Ichihara and Cohen 2011), building energy savings – particularly in summer (Wong et al. 2010), carbon fixation and O2 release (Agra et al. 2017), acoustic insulation (Azkorra et al. 2015) and emergence of new opportunities for technological, economic and employment development (Garrison and Hobbs 2011).

An overview of the four broad categories of benefits is provided, drawing on peer-reviewed journal articles from different climates. Each is followed by a summary of the most recent research (2011–2017) specific to Melbourne and comparable climates including Adelaide, Perth, the Mediterranean region, and semi-arid regions. Findings are also drawn from 'grey' literature (e.g. government reports) and unpublished research conducted by the Green Infrastructure Research Group at The University of Melbourne.

Where there is a paucity of data within the Melbourne climatic context, evidence from different climatic regions (e.g. UK, Sweden) and/or earlier studies have been presented. Literature searches were conducted via University of Melbourne library resources and associated databases including Web of Science, Scopus and Google Scholar in mid-2017 (May–July). Additional references were added in review to February 2018.

Definitions for green roofs, green walls and green façades are consistent with the Growing Green Guide (DEPI 2014):

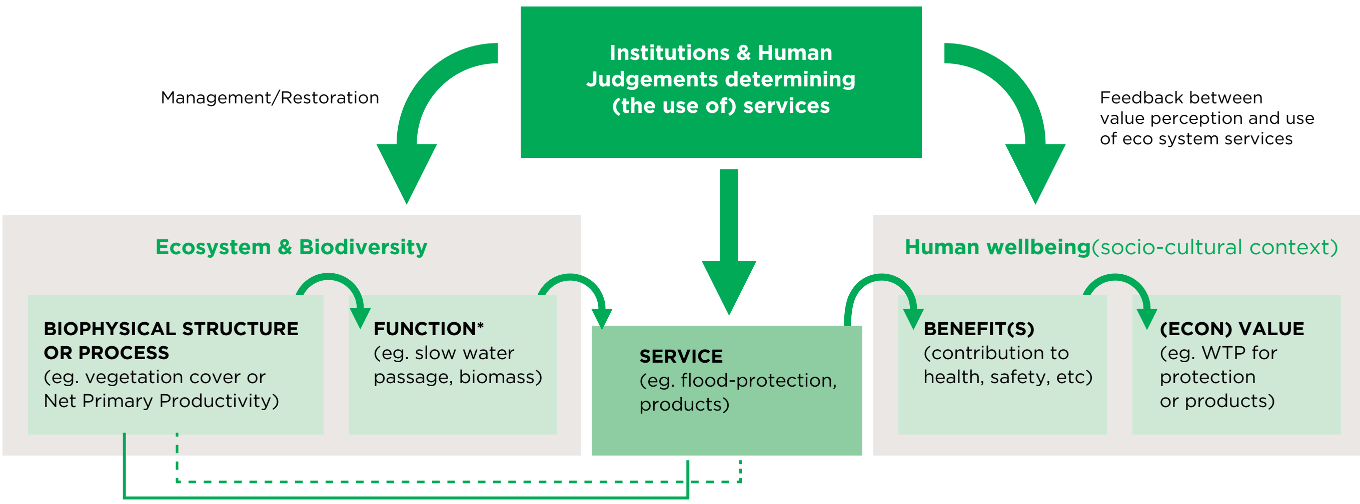
- **Green roofs:** Green roofs can be shallow extensive roofs, usually inaccessible and generally have substrate less than 200 mm deep. Green roofs with deeper substrates 200 mm and above (*intensive* green roofs) can generally support a greater range of plant types. They are engineered for higher weight loads and can be accessed by people and need more irrigation and maintenance than extensive roofs.
- **Green façades** involve growing climbing plants up building walls, either from plants grown in garden beds at its base or grown in containers installed at different levels on the building. Climbing plants can attach directly to the surface of a building, on a frame attached to the building, or grown on a free-standing frame.
- **Green walls** are comprised of plants grown in supported vertical systems that are generally attached directly to a structural wall, although in some cases can be freestanding. Green walls differ from green façades in that they incorporate multiple planted modules or a hydroponic fabric to sustain the vegetation cover rather than being reliant on fewer numbers of plants that climb and spread to provide cover. They are also known as 'living walls', 'bio-walls' or 'vertical gardens.'

This review relates to external systems only (i.e. no indoor green walls) as they have wider environmental and social benefits. Roof gardens comprising plants in pots are not considered here as they were beyond the scope of the project. Note also that the International Green Roof Association now have a semi-intensive category: 120–250 mm deep with grasses, herbs and shrubs, leaving extensive roofs up to 200 mm with groundcovers and grasses. We deal only with extensive and intensive categories here as they are what is represented in the literature.

Methodology

The methodology used is based on the pathway from ecosystem structure and function to the valuation of human wellbeing from de Groot et al. (2010), based on Haines-Young and Potschin (2010) and Maltby (2009). This is a common-sense framework linking biophysical structure and process that produce functions, which in turn, provide services. These services can be linked to benefits (or disbenefits) that can be valued. Not all services or benefits can be valued independently so are often assessed in combination; e.g. wellbeing and recreational benefits from park visits. Valuation also takes on differing degrees of complexity depending on what is being measured, requiring an iterative process to be undertaken between measures for function, service, benefit and economic value. Indicators can be taken from any two or more of these attributes as long as they are straightforward to measure, are accurate, relatively parsimonious and repeatable.

Part 1 of the review deals with the biophysical structure and processes of green roofs, walls and façades, in addition to how biodiversity can be addressed. Part 2 addresses how green roofs, walls and façades have been valued in the literature. It then describes how those benefits may be applied given our current state of knowledge. These address the four main categories of benefit, supplemented by a range of other benefits that can potentially contribute to whole of life cycle economic assessments of green infrastructure in the City of Melbourne.



* subset of biophysical structure or process providing the service

Adapted from Haines - Young & Potschin, 2010 and Malthy (ed.), 2009

Figure 1: The pathway from ecosystem structure and processes to human well-being (de Groot et al. 2010).

PART 1:

ECOSYSTEMS, BIODIVERSITY AND SERVICES

Figure 2: Council House 2, Melbourne.

STORMWATER

Key points:

- Stormwater runoff is a significant problem in urban areas because impermeable surfaces prevent natural infiltration and drainage. Stormwater degrades receiving environments, increases flood risk, and puts pressure on aging drainage infrastructure.
- Green roofs can capture stormwater, reduce runoff volume and delay the timing of peak flow.
- In Melbourne a 100 mm deep green roof can retain between 86–92% annual stormwater runoff because Melbourne has lots of small rainfall events.
- The performance (hydrological behaviour) of a green roof is site-specific and varies with local environmental conditions, vegetation type and physical properties of substrates and layers.
- Rainfall retention is enhanced by deeper substrates with greater water-holding capacity.
- Plant cover increases rainfall retention but there is considerable variation in water uptake among species.
- Substrate additives such as biochar can increase substrate water holding capacity and plant available water.
- Green roofs can negatively impact the quality of rainwater runoff. The quality of runoff – largely nitrogen, phosphorous and heavy metal concentrations – may vary with how the roof is constructed and maintained.
- Compost in substrates and added fertilisers can decrease runoff water quality through increased leaching of nitrogen and phosphorus.
    - Substrate additives such as biochar can increase nutrient retention.
- Well-designed green façade systems can help mitigate stormwater impacts; e.g. by planting climbing species in rain-gardens or by irrigating with captured stormwater.
- While green walls are unlikely to directly mitigate stormwater runoff, they could potentially utilise large volumes of captured stormwater for irrigation.
- Most green walls are engineered systems that require regular watering because of the limited volume of rooting substrate, which has a low water-holding capacity.
    - Green walls are water-intensive systems and can fail rapidly if irrigation fails.
- Most commercial green walls are hydroponic systems that generally require fertigation – the injection of fertilisers, soil amendments, and other water-soluble products into the irrigation system.

Urban areas are characterised by impervious surfaces and a significantly altered hydrology that impedes natural soil infiltration and groundwater recharge by rainfall. Because of the increased flood risk this causes, stormwater drainage infrastructure has traditionally been engineered to redirect and rapidly remove runoff from the urban landscape into waterways and ultimately out to sea. Large pulses of stormwater have significant environmental impacts and can severely degrade urban and local waterways (Walsh et al. 2012). In addition, climate change may increase the frequency and intensity of extreme rainfall events, further increasing stormwater runoff impacts (Arnell and Lloyd-Hughes 2014, Berndtsson 2010).

Stormwater mitigation infrastructure varies from city to city. For example, many cities in North America have combined sewer and stormwater systems, whereas many Australian cities including Melbourne have separate sewerage and stormwater systems. Each system produces different environmental and economic impacts during rain events.

Green roofs can provide greater stormwater benefits than green façades and green walls because they can cover large horizontal areas that directly intercept rainfall. As a result, most studies on the role of green infrastructure for urban stormwater management have focused on green roofs. In comparison, green walls are largely hydroponic systems, requiring regular, but controlled irrigation, so are the least likely to assist in stormwater mitigation. They also have additional energy requirements, generally requiring water (and nutrients) to be pumped to the top of the wall panel. Excess water draining from green walls is generally not reused because it can lead to excessive nutrient build up, so this water usually goes directly to stormwater or sewerage. It can be routed into raingardens and other green infrastructure designed for that purpose.

Green façades offer more opportunities for stormwater management. For example, suitable climbing plant species can be grown in raingardens alongside building walls. There may be considerable benefit in adopting integrated water management approaches for all these green infrastructure systems. Stormwater is increasingly being viewed as a resource to be captured, stored and re-used within cities (Berndtsson 2010, Walsh et al. 2012). For example, permeable pavements (permeable asphalt, pervious concrete or paver blocks) can be integrated alongside green infrastructure systems such as green façades to enhance their stormwater mitigation and improved runoff quality (Lee et al. 2015, Zhou et al. 2017).

Green roofs and stormwater mitigation

Green roofs are considered a valid tool to mitigate the effects of stormwater through rainfall retention in substrates and through evapotranspiration (ET) from plants and substrates. Rooftops account for approximately 40–50% of urban impervious surfaces (Stovin et al. 2012) and green roofs are a form of source control technology, providing stormwater runoff management in an otherwise unused space (Fletcher et al. 2015). Green roofs can mitigate the impact of stormwater by reducing and delaying stormwater runoff (Berndtsson 2010, Carter and Rasmussen 2006). Modelling suggests that retrofitting extensive (shallow) green roofs in Melbourne's CBD can reduce stormwater runoff peak flow, which may mitigate or reduce the frequency and severity of flash flooding (Meek et al. 2015). For a 100-year, 1-hour duration storm, water runoff peak flow was found to be reduced by 10.9–52.2% depending on the extent of green roof coverage. Greatest benefits were realised when 60–100% of potential roof area was covered by extensive green roofs. In Melbourne, due to a pattern of many small rainfall events a 100 mm deep green roof can retain between 86–92% of annual stormwater runoff (Zheng et al. in review).

Key hydrological mechanisms operating within a green roof are:

- rainfall inception by leaves;
- infiltration and retention in the substrate;
- storage in the drainage layer;
- runoff from the detention storage and;
- ET from plants and substrates (Stovin et al. 2015, Stovin et al. 2012).

As green roofs are comprised of several layers, water may be stored in substrates, the drainage layer and moisture retention fabrics. Deeper substrates with greater water holding capacity (WHC) generally have higher retention and more consistent performance than shallower substrates (Elliott et al. 2016).

Evapotranspiration dries out substrates and restores the green roof's water holding capacity between rainfall events. Evapotranspiration rates can vary with local environmental conditions (e.g. temperature, solar radiation, wind, humidity), substrate characteristics and plant species (Cipolla et al. 2016, Farrell et al. 2012, Farrell et al. 2013b, Rayner et al. 2016, Szota et al. 2017). Vegetated roofs are more effective at retaining and storing stormwater than substrate-only roofs from a long-term perspective because they can decrease stored water through transpiration between rain events (Poë et al. 2015). They effectively make space more rapidly so as to receive more during the next rainfall event.

Plant characteristics that can influence rainfall retention include the area of coverage (Berghage et al. 2009, Morgan et al. 2013, Szota et al. In prep) and the use of plants with high transpiration rates (Nardini et al. 2012). Plants with low-water use, such as succulents, are more likely to survive on green roofs, but are less effective for stormwater control. The optimum (or 'ideal situation') is to use plants that transpire rapidly after rain, yet can reduce their water use in response to low soil moisture content – for example, by opening and closing stomata (Farrell et al. 2013b).

The timing of rainfall events is important. Green roofs retain more rainfall when rainfall events are further apart (also known as antecedent dry weather period or ADWP) (Elliott et al. 2016). Sporadic rainfall that allows drying between events will lead to greater retention than closely-spaced events. For that reason, runoff reductions tend to be lowest in winter and highest in summer (Bengtsson et al. 2005, Mentens et al. 2006). For example, in 32 mm sedum roofs in New York, 28% of rainfall was retained in winter, and 70% in summer (Carson et al. 2013). Green roofs in temperate, Mediterranean and semi-arid environments retain a greater proportion of rainfall in summer when there is less rain and more days between rainfall events (antecedent days). Higher summer temperatures create higher evapotranspiration rates, which along with less frequent in rainfall events, enables substrates to dry out, maximising their ability to capture the next rainfall event.

Small rain events can be completely retained by green roofs (Volder and Dvorak 2014). Most rainfall events in Melbourne are small (averaging 3.7 mm) and would likely be completely retained in a substrate of 100 mm depth of scoria (Szota et al. 2017). Event size can also have a major influence on retention, independent of storage. As rainfall amount increases, the percentage of rain retained declines. Carter and Rasmussen (2006) found an inverse relationship between rainfall amount and percentage retention, with 88% retention of small storm events (<25.4 mm) and 48% retention for large storms (>76.2 mm). Similarly, for the UK, 80 mm green roofs planted with either sedums or seasonal meadow flowers where retention was 80% for rainfall events <10 mm, but lower in response to higher rainfall (Stovin et al. 2015).

Some native plants have been identified as suitable for stormwater control on Melbourne green roofs – plants that can both survive the harsh conditions and are effective at drawing water from substrates via transpiration. Farrell et al. (2012) undertook nursery experiments of 12 native species from Victorian granite outcrop habitats and one exotic succulent (sedum sp.) commonly grown on northern-hemisphere green roofs. Four granite outcrop species were particularly good at withstanding both high and low water conditions, while the exotic succulent was deemed to be a poor candidate for stormwater mitigation. This same sedum sp. and other exotic succulents have, however, been found to survive drought conditions longer than native succulent species (Farrell et al. 2012).

Szota et al. (2017) compared high and low water-use plants with either drought avoidance or drought tolerance strategies for a 30-year Melbourne climate scenario. Green roofs with low water-using, drought-avoiding species achieved high rainfall retention (66–81%) without experiencing significant drought stress. Roofs planted with species that utilise other strategies showed higher retention (72–90%), but they also experienced >50 days of drought stress per year, which may lead to plant death. However, not all species with the same strategy behaved similarly, therefore selecting plants based on water use and drought strategy alone does not guarantee survival in shallow substrates where drought stress can develop quickly. Despite this, green roofs are more likely to achieve high rainfall retention if planted with low water-use plants with drought avoidance strategies and minimal supplementary irrigation (Szota et al. 2017).

Studies from other cities with warm, dry summers have shown that green roofs can have significant stormwater benefits (Bengtsson et al. 2005). Sims et al. (2016) compared the retention performance of experimental green roofs (150 mm) in three different Canadian climate regions: Calgary (semi-arid, continental climate), London (humid continental) and Halifax (humid maritime). The drier climate was found to have greater percentage cumulative stormwater retention (67%) compared to wetter climates of London, Ontario (48%) and Halifax (34%). Drier climates have superior retention because substrates can dry out more between events. However, green roofs in moderate and wet climates still performed well, and over the study period retained the greatest depth of stormwater. Studies of moisture retention on similar green roofs in Auckland, New Zealand, have shown different retention rates of 56% (Fassman-Beck et al. 2013) and 66% (Voyde et al. 2010), but the studies differed in the time of year and duration of monitoring. This highlights the importance of including multiple seasons in green roof studies (Sims et al. 2016).

Brandão et al. (2017) studied native species on 150 mm experimental green roofs in Portugal (Mediterranean climate) during a 6-month autumn/winter period when short-lived but high intensity rainfall can cause flash flooding. Vegetated roofs retained 55–100% of rainfall, with 100% retention achieved in 69 of 184 rainfall events. Modelling for Lisbon showed that by installing green roofs on 75% of the available flat roof area 166,500 – 224,000 m^3 of water could be retained, relieving the drainage systems and reducing the likelihood flooding (Brandão et al. 2017).

The potential for extensive green roof development in Thessaloniki, Northern Greece showed that 17% of the built-up urban area could retain 45% of rainwater (Karteris et al. 2016). Beecham and Razzaghmanesh (2015) investigated the water quality and quantity of 16 experimental (unfertilised) extensive (100 mm) and intensive (300 mm) green roof beds in Adelaide, finding water retention rates of 51–96% with greatest retention in deeper, flatter, vegetated roofs. Vegetated roofs, particularly intensive roofs, performed better than bare substrates in terms of quality of runoff, and removed more nitrogen (N) and phosphate (P) due to the presence of plants. For non-vegetated experimental green roofs, extensive beds performed better than intensive beds presumably due to less substrate leaching fewer nutrients.

Most green roof water-retention studies have been undertaken in the northern hemisphere. Observation and multi-year modelling of full-scale, extensive sedum green roofs in New York demonstrated rainfall retention between 11%–76% with an average of 46.7% across all roofs (Carson et al. 2013). Most roofs were sedum -dominated, varying in depth (50 to 200 mm) and drainage area (12–7,000 m2). Earlier German studies showed extensive green roofs could retain 27–81% and intensive roofs 65–85% rainfall (Mentens et al. 2006), while Szota et al. (2017) cite a global range of ~5–85%. DeNardo et al. (2005) (Pennsylvania – humid continental climate zone) found that on average, 89 mm sedum roofs (+12 mm water-storing drainage layer) retained 45% of rainfall, delayed the start of runoff by 5.7 hours, and delayed peak runoff by 2 hours. Single-event rainfall attenuation for a 100 mm extensive green roof in Bologna, Italy, over a single year, averaged 51.9% (range 6–100%) (Cipolla et al. 2016). For extensive sedum green roofs in New York (31 mm and 100 mm), stormwater retention was highest in summer months due to increased evapotranspiration and green roofs retaining more rainfall due to longer periods between rainfall events (Elliott et al. 2016). Both roofs retained 100% of smaller storms (<10 mm).

Substrates with higher WHC can retain more rainfall, however not all of this water is available to plants due to varying substrate pore size and other physical properties that may bind soil moisture. Another related substrate characteristic – plant available water (PAW) – provides a better indication of water use by plants, with higher PAW linked to better green roof plant survival (Farrell et al. 2012, Fassman and Simcock 2012, Szota et al. In prep).

Farrell et al. (2012) looked at the effects of severe drought (113 days without water) in Melbourne on growth, water use and survival of three succulent sedum species and two native succulent species, exotic Sedum pachyphyllum, S. clavalatum, and native Carpobrotus modestus and Disphyma crassifolium, planted in three different green roof substrates (growing media) differing in water holding capacity. Plants survived 12 days longer in substrates with higher water holding capacity but native species (*D. crassifolium* and *C. modestus*), which had higher water use, died at least 15 days earlier than sedum species (low water users). Increased survival was not related to increased leaf succulence but was related to reduced biomass under drought. Working with the same vegetated and unvegetated surfaces Szota et al. (In prep) tested 3 different substrates (100 mm deep, 2o slope) planted with succulents. Evapotranspiration and therefore rainfall retention was higher for substrates with high WHC. The presence of vegetation also increased evapotranspiration by 13% compared to substrate-only roofs (Szota et al. In prep).

Results obtained from experimental green roofs tend to overestimate the amount of rainfall retention that substrates will have compared to full-scale, planted systems (Carson et al. 2013, She and Pang 2010, Szota et al. 2017), most likely due to the high porosity of the growing media.

Although deeper substrates with greater WHC are optimal for rainfall retention, weight restrictions on supporting buildings means that substrates are often shallow (Farrell et al. 2012, Oberndorfer et al. 2007). WHC and PAW can be increased without increasing substrate weight through the use of water-retentive additives such as silicates and biochar (Cao et al. 2014, Farrell et al. 2013a), although the weight of added water remains a factor in roof loading.

Farrell et al. (2016) examined the effect of adding silicates, biochar and hydrogel to substrates on WHC and PAW. Hydrogel and silicates increased WHC, but only hydrogel increased PAW – but did not delay permanent wilting. Biochar greatly increased WHC and PAW and reduced bulk density, with greater rates of addition resulting in lighter substrates. Researchers in Italy found that hydrogel significantly increased the amount of water available to plants on shallow green roofs in the establishment phase, but that the benefits were not evident after 5 months (Savi et al. 2014). The authors attributed this to breakdown due to high leaching rates, concluding that more research was needed to maintain high levels of PAW with hydrogels.

Rainfall retention can increase with roof age (Getter et al. 2007), roof geometry, slope and slope length, roof position (shadowed or not, orientation: i.e. north-south-east-west) (Berndtsson 2010). Generally, the lower the slope, the higher the retention; e.g. a 2-degree slope was found to retain 62% of rainfall while a 14-degree slope retained 39% for the same rainfall rate (Bengtsson et al. 2005, Berndtsson 2010, Villarreal and Bengtsson 2005). However, even experimental extensive green roofs with a 25% slope can retain an average of 76% (Getter et al. 2007). Roof orientation (e.g. north facing), shading from surrounding trees and buildings and number of direct sunlight hours can also influence green roof performance (Berndtsson 2010). In the northern hemisphere, south-facing roofs have the highest evapotranspiration rates among the four orientations, while north-facing roofs have the lowest rates (Mentens et al. 2003). This pattern would be reversed in the southern hemisphere, with northern roofs having the greatest ET.

Green façades, green walls and stormwater mitigation

There is limited published literature around the benefits of green walls and façades for stormwater mitigation, and what is available covers a multitude of different systems, climates and species. Comparing their performance is therefore difficult (Hunter et al. 2014). Terminology is also inconsistent, with vertical greening systems, green façades, living walls and green walls used interchangeably (Perini et al. 2011). Water storage and PAW varies considerably, depending on the green wall system (e.g. felt pockets vs. large, foam modules) with differing implications for plant survival. Green walls are much more expensive than green façades because of the materials involved, maintenance needed (nutrients and watering system including pumps) and the design complexity; however green walls usually have a wider variety of plants and offer more aesthetical potential (Perini and Rosasco 2013). Perini and Rosasco (2013) suggest that the high construction and maintenance costs of green walls may outweigh the benefits they provide.

Green walls can be relatively high water-users, with exterior walls in exposed locations using up to 20 L per m² per day (DEPI 2014). Unless irrigated with non-potable water, they may not be suitable for dry climates if restrictions are placed on potable water use (Prodanovic et al. 2017). However, Kew et al. (2014) looked at utilisation of captured stormwater for experimental green wall irrigation in Pennsylvania, USA, finding that green walls linked to rainwater tanks were able to retain stormwater, including half the volume of the first flush. Bigger tanks enabled more adaptable irrigation regimes. Riley (2017) suggest that for living walls to be sustainable, the industry must shift paradigms and evolve from designing stand-alone green walls, to developing entire systems including rainwater storage tanks.

The substrate volumes required to achieve long-term plant health and cover for green façades – both containerised and in-ground – is a significant knowledge gap that is considered a barrier to achieving wide-scale implementation in urban environments (Rayner pers. comm.). Limited understanding of appropriate substrate properties, lack of definitive values for substrate characteristics, and an absence of nationally-recognised standards for green façade, wall and roof substrates are also practical issues for industry. Limited root space is a primary cause of restricted growth of urban trees (Jim 2001, Lindsey and Bassuk 1992) and similarly, inadequate rooting volumes for green façade plants can lead to poor plant outcomes (Deeproot 2014, greenscreen 2015). Larger in-ground pits, use of Silva Cells and structural soils may offer opportunities to expand in-ground root volumes for green façade systems (Bassuk et al. 2005, Page et al. 2015), increasing their capacity to mitigate stormwater.

Green façades could potentially play a role in handling surface runoff and reducing off-site water discharge. Green façades have been successfully incorporated into vegetated swale and rain-garden projects in the USA – climbing species that thrive in seasonally inundated conditions should be considered for bioretention (greenscreen 2015). Green façade climbers could be planted into raingardens adjacent to building walls and irrigated by rooftop drainage systems using existing downpipes for water supply (Croeser 2016, Razzaghmanesh 2017).

The use of grey water as an alternative irrigation source has been investigated in Melbourne studies. Climbing façade species (Lonicera japonica, honeysuckle, and Vitis vinifera, ornamental grape) have been shown to remove pollutants in experimental greywater treatment studies (Fowdar et al. 2017). Barron et al. (2016) looked at the pollutant-removal capacity of climbing species and other ornamentals in biofilters for greywater including grape vines, Pandorea jasminoides, Parthenocissus tricuspidata (Boston ivy) and Billardiera scandens. Prodanovic et al. (2017) tested a range of green wall substrate media for pollutant removal of household grey water, identifying a coir-based and perlite-based substrate as effective in removing total suspended solids, total nitrogen, total phosphorus, chemical oxygen demand and Escherichia coli (E. coli) respectively. Trials were undertaken over a 10-week period, but did not involve planted modules, therefore no testing was done on plant performance for either media. The high salt content of grey water is likely to result in poor plant growth performance, especially lower down on green walls. As aesthetic values are an important consideration in green wall installations, as are the services provided by healthy plants, plant performance is vital.

COOLING BUILDINGS AND CITIES

Key points:

- Green roofs can regulate temperatures on underlying roof materials and rooms in the buildings below through shading, insulation, increased albedo and evapotranspiration. Improved thermal performance of buildings will reduce energy demand for cooling and heating.
- Cooling by green roofs can help mitigate the urban heat island effect, especially when green roofs cover a large area of urban impervious roof surface, and particularly when combined with other strategies such as increasing tree canopy cover, cool roofs and permeable pavements.
- Cooling effects of green roofs have limited effects at ground level, diminishing with increasing building height.
- Extreme summer temperatures can cause significant plant mortality on green roofs, particularly shallow (extensive) green roofs, unless the green roof has an irrigation system.
- Irrigation improves the cooling function of green roofs, and in Melbourne is essential in the establishment phase and to ensure plant survival over dry, hot summers.
- Plant characteristics including height, structural complexity, leaf area and leaf morphology can influence the thermal performance of green roofs.
- Green roof substrate characteristics can influence green roof thermal performance.
- Green façades can benefit urban cooling by shading buildings and through evapotranspiration.
- Green façades are a relatively cost-effective option for greening urban areas and can be used to cover large vertical surface areas.
- Green façades are ideal for greening urban canyons and a wide range of climbing plant species can grow in varying light climates.
- The area of green façade leaf cover is directly proportional to the rooting volume of the climbing plant. Planting pits need to be of sufficient size to maximise plant health, coverage and longevity.
- Green walls can lower microclimate temperature, but often cover limited areas of vertical wall surface.
- Green walls generally require energy to run irrigation pumps.

The urban heat island effect (UHI) of cities is a well-recognised phenomenon and is likely to become more pronounced by temperature increases associated with climate change (Norton et al. 2015). A continued increase in urban temperatures has significant ecosystem and human health implications (DHS 2009, Norton et al. 2015), which may partly be addressed by enhancing existing green infrastructure and installing new green roofs, façades and walls. These vegetated systems can help ameliorate the UHI effect through shading, increasing surface albedo, absorbing and reflecting solar radiation, and through evapotranspiration of plants and substrates (Coma et al. 2017, Georgescu et al. 2014). The health effects of cooling within buildings and more general amelioration of the UHI is summarised in the report chapter on Biodiversity and the economic effects are discussed in the Health and Wellbeing section of this report.

Norton et al. (2015) developed a planning prioritisation framework to assist in the integration of green infrastructure into urban public open space with the objective of improving the urban climate. They investigated how strategic implementation of green roofs, green walls, green façades (and other green infrastructure such as street trees and parks) in Melbourne and cities with comparable climates could reduce urban surface temperatures.

Green façades were particularly beneficial on walls with high solar exposure and where space at ground level is limited (Wong et al. 2010), on darker walls (which get hotter than light walls), and near pedestrians (Norton et al. 2015).

Green façades are able to help cool ground-level pedestrians, who would otherwise be exposed to greater urban heat, improving urban walkability and pedestrian comfort. Individual green roofs may lower surface temperatures and cooling requirements for buildings below, but will only positively impact humans at ground-level if green roofs are installed across a large-enough area (Gill et al. 2007). To maximise human health benefits, Norton et al. (2015) recommend green roofs be installed on large, low buildings, or in areas with little ground level open space. Modelling has shown that large-scale retrofitting of green roofs across Melbourne's CBD could potentially lower the UHI temperature by 0.7–1.5°C depending on the extent of retrofitting (Meek et al. 2015). This was based on a simple, linear relationship between green roof area and a potential reduction of 2.5°C based on differences between the least and most vegetated areas (Susca et al. 2011).

Green roofs and cooling

Roofs comprise a large area of the urban surface (23% in the city of Melbourne), and greening can modify these through shading, evapotranspiration, direct solar reflection and heat loss from leaves and substrates (Pianella et al. 2016a). These processes can lower underlying roof temperatures, decrease the heat released back into the atmosphere at night (UHI), reduce heat flux through roof matrix, and cool interior spaces directly below green roofs. Plant canopy characteristics (leaf area index (LAI) and stomatal resistance), height of plants, leaf reflectivity and leaf emissivity and the substrate features (thermal conductivity, heat capacity, density, and thickness) play a key role in the thermal and energy performance of green roof systems (Vera et al. 2017). Thermal performance is improved when green roofs are irrigated, maintain a high leaf area index, and when covered with taller vegetation (Lundholm et al. 2010). UHI mitigation potential of green roofs has been found to be highly dependent on the climate, roof U-value (rate of heat transfer), and latent heat loss (Santamouris 2014).

Deeper substrates, substrate properties (e.g. increased plant available water), appropriate plants selection based on a habitat template concept (habitat analogues) and irrigation enhance plant survival and green roof performance in Mediterranean climates and thus the benefits they can provide (Ondoño et al. 2016, Raimondo et al. 2015, Van Mechelen et al. 2014).

In an experimental analysis of an extensive green roof in Calabria, Italy, Bevilacqua et al. (2016) showed that the temperature of the underlying structural roof was on average 12°C cooler in summer compared to a black bituminous roof and 4°C higher in winter. Negative heat fluxes were found for the whole experimental period, indicating the green roof had good insulative properties. Passive cooling produced a 100% reduction in incoming heat during summer and a reduction of 30–37% of outgoing thermal energy in winter. In contrast, while Santamouris et al. (2007) found that green roofs are highly effective in reducing summer cooling demands in Athens, Greece, they had no thermal advantage during winter.

Modelling simulations based on Mediterranean cities (Greece) suggest that green roofs can increase albedo and when applied at a city scale, can reduce the ambient temperature by 0.3–3°C per 0.1 rise in albedo (Berardi 2016, Santamouris 2014). Karteris et al. (2016) modelled the likely outcome of large-scale retrofitting of extensive green roofs in Thessaloniki, Northern Greece representing 17% of the urban area. Depending on the vegetation type used, extensive green roofs at the city block scale were estimated to reduce heating (5%) and cooling (16%) energy requirements.

Small-scale green roof experiments and corresponding large-scale model simulations in Adelaide show that both extensive and intensive green roofs have the capacity to reduce the surrounding micro-climate temperature with significant cooling effects in summer time and potentially keeping buildings warmer in the winter (Razzaghmanesh et al. 2016). They found experimental green roofs were 2–5°C cooler during the day depending on media type and depth and were generally cooler than the ambient air temperature. At night, deeper roofs were 3–6°C warmer than ambient air temperatures because of their capacity to retain heat.

Simulations showed that an addition of 30% green roofs in a defined area of Adelaide's CBD could reduce summer cooling electricity consumption of 2.57 W per m2 per day (Razzaghmanesh et al. 2016). Similarly, modelling suggests that a 50% coverage of green roofs across Constantine, Algeria (arid climate), could decrease the ambient air temperature by an average of 1.3°C (Sahnoune and Benhassine 2017). While these models are useful tools for exploring future scenarios, there may be practical limitations, such as weight loading and plant survival concerns, to implementing green roofs as widely as modelled. The GHD (2015) study places upper bounds on what may be established for Melbourne in terms of roof suitability, but the types of green roof that may be most beneficial still need to be determined.

A range of non-climatic factors can influence green roof thermal performance including substrates, green roof components (e.g. drainage layers), plant morphology and physiology, and irrigation. In Greece, the composition and porosity of the substrate and its thickness influenced the heat flux penetrating the roof of a building (Kotsiris et al. 2012). For Melbourne, Pianella et al. (2016b) investigated the thermal conductivity values of three substrates comprised primarily of scoria, bottom ash and crushed roof tile under three moisture conditions. Thermal conductivity was greatest in crushed roof tile, which also had the highest density and lowest air-filled porosity. Substrate moisture increased thermal conductivity for all substrates but this was most pronounced for crushed roof tile. The authors concluded that of the three substrates tested, scoria-based substrate should be selected when the objective is to maximise insulation (Pianella et al. 2016b).

Increased substrate depth can improve thermal performance. Silva et al. (2016) investigated the thermal behaviour of intensive, semi-intensive and extensive green roofs in Lisbon, Portugal, in summer and winter experiments and subsequent models. Compared to traditional roof solutions, with no thermal insulation, extensive green roofs required 20% less energy annually than black roofs. Semi-intensive and intensive green roofs energy use was 60–70% and 45–60% lower than black and white roofs, respectively. Models of Toronto green roof performance showed that deeper substrates (30 cm) and higher leaf area index achieved greater reductions in above-roof air temperatures when compared to shallower 15 cm deep substrates with lower LAI (Berardi). Berardi (2016) found that increasing LAI would lead to an increased cooling effect of mean radiant temperature up to 0.2°C during the day at pedestrian level, and reductions up to 0.4°C with a LAI of 1 and 0.7°C with an LAI of 2 at the rooftop level.

Green roofs in climates with hot, dry summers such as Melbourne, require some supplementary irrigation to achieve the evapotranspiration benefits, as well as ensuring plant survival (Norton et al. 2015). Van Mechelen et al. (2015b) recommend that green roofs of all types and in all climates, should be irrigated during establishment and usually during the first growing season, with ongoing irrigation for roofs in semi-arid climates, and in small amounts in other climates. Integrated water management may need to be considered to sustain expanded urban greening, including utilising stormwater and other non-potable water sources (Norton et al. 2015, Van Mechelen et al. 2015b).

Investigating alternative water sources, Sisco et al. (2017) found edible plants grew well in experimental green roofs when irrigated with air-conditioning condensate in Beirut. However the condensate had higher EC than tap water, and the suitability of condensate for human health is largely untested. Coutts et al. (2013) compared an extensive sedum green roof with cool-roof treatment (rooftop coated with white elastomeric paint) over summer of 2011–2012 in Melbourne. The green roof performed less well than the cool roof combined with insulation, largely because low substrate moisture and low evaporation failed to provide the necessary insulation during the day. However, irrigation increased the roof's thermal mass, which counterbalanced this effect (Coutts et al. 2013). In contrast, Dvorak and Volder (2013) found that in south-central Texas unirrigated, succulent-based green roofs reduced soil surface temperature by 18°C and 27.5°C below the module in hot-dry summer conditions. This shows that while there may be a beneficial cooling effect, under unirrigated green roofs, it may not be as effective as other treatments.

In general, sedum species used extensively in green roofs in the northern hemisphere are low water-use plants offering low cooling benefits via transpiration. However, in Australia many exotic sedums and other succulents are very drought tolerant and can survive drought conditions and elevated temperatures longer than native succulent species (Farrell et al. 2012, Rayner et al. 2016).

Klein and Coffman (2015) investigated whether stress-tolerant sedums could complement native prairie species with rapid establishment (i.e. act as 'nursery' plants) in experimental green roof modules in extreme heat and dry conditions in Oklahoma, USA. Modules were watered 3 times weekly, however extreme drought conditions led to extensive plant dieback, particularly for sedums. Although vegetation cover declined, air temperatures were still generally lower over the green roof (>1°C) reflecting continued evapotranspiration benefits. The authors recommended planting extensive roofs with varying growth forms to help regulate water loss and optimise roof surface cooling, and caution against broad application of sedums in warm climates.

Bevilacqua et al. (2015) investigated the thermal performances of a 2000 m2 extensive green roof system in Lleida, Spain (dry Mediterranean climate) planted primarily with sedums. Plant cover and composition were investigated to determine the effect of initial (10%) and established (80%) plant cover in summer and winter. Sedum cover remained relatively stable over the study period while colonising species appeared in spring and early summer. While the green roof did lower roof surface temperatures, an increase in vegetation cover did not appear to affect the supporting roof environment because low moisture levels in the substrate layer limited evaporative cooling. While the vegetation layer blocked solar radiation during the day, it also limited night-time cooling. In contrast, dense 'low, perennial' vegetation (unspecified species) was found to enhance cooling for extensive green roofs over summer in Mediterranean regions of southern Spain (Olivieri et al. 2013). Dense vegetation lowered the thermal flux into the roof by about 60% compared with the roof with no vegetation – a benefit not seen for sparsely vegetated roofs.

The development of large retail spaces (shopping centres) has increased the area of large-flat roofs in urban settings that may offer opportunity for green roof retrofitting. Vera et al. (2017) investigated the influence of green roof design parameters and thermal insulation on the thermal performance of 'big-box' retail stores under three climate scenarios: Melbourne, semi-arid Albuquerque (USA) and semi-arid Santiago (Chile). Vegetation was found to be more effective than insulation on reducing cooling loads due to evapotranspiration and canopy shading, but insulation was better at reducing heating loads. Experiments in Santiago showed that uninsulated concrete slab without vegetation (but with substrate) had the largest heat gains during day time, peaking at 10 Wh per m2, while the same roof with vegetation had heat losses during typical working hours of retail stores (8am–10pm). The greater cooling than heating loads modelled for Melbourne means that over a whole year, a green roof would reduce energy use more than insulation. Combining both limited the thermal benefits of vegetated roofs (Vera et al. 2017).

Green roofs may not the best option for thermal performance if the building has existing high levels of thermal insulation, or if the roof to floor area ratio is small (Wilkinson et al. 2017). Niachou et al. (2001) showed through model simulations (Athens) that for well-insulated buildings energy saving through additional green roofs is less than 2%. Under simulated Mediterranean climatic conditions, Gagliano et al. (2015) found that green roofs provide higher energy savings and environmental benefits than highly insulated standard roofs and that minimally-insulated green roofs showed the best performance in relation to UHI mitigation.

Combining green roofs with green façades can increase their cooling benefits. Wilkinson et al. (2017) undertook small scale experiments in Sydney (and Rio de Janeiro) to test timber-framed vegetated and non-vegetated structures prototypes. They found that combining green roofs and green walls on experimental house modules yielded better thermal performance in the building envelope for human thermal comfort – measured as a heat index (temperature + relative humidity) than green roofs alone (Wilkinson and Castiglia Feitosa 2015). The maximum, minimum and average temperatures observed were 33°C, 15.5°C and 23.4°C in vegetated houses, and 42°C, 15.4°C and 26.1°C in non-vegetated houses.

The cooling benefits of green roofs may not be felt at ground level. As the vertical distance between the green roof and the ground increases, the impact on the microclimate at pedestrian level decreases (Savio et al. 2006). Jamei and Rajagopalan (2017) used modelling to investigate the effects of proposed structural plans (Department of the Environment, Land, Water and Planning (2017) including increasing increased building height, adding tree canopy coverage and adding green roofs on outdoor human thermal environment in Melbourne. They showed that while there would be an overall 5.1°C improvement in the Physiological Equivalent Temperature for extremely hot summer days, green roofs did not contribute to improvement in human thermal comfort at ground level (pedestrian thermal comfort). A greater effect was found from establishing small urban parks and increasing the tree canopy cover from 50–60%.

In contrast, modelling of extensive green roofs for a Toronto building (humid continental climate) showed an increased cooling effect of the air temperature up to 0.4°C during the day at pedestrian level (0.7°C at night) (Berardi 2016). The author suggested the maximum 2.6°C cooling of air temperatures at the rooftop level could also help boost the efficiency of the rooftop cooling system (HVAC – heating, ventilation and air-conditioning) as has been described elsewhere (National Parks Service 2017).

Modelling of the UHI with urban climate and urban rooftop models has been used to estimate the large-scale effect of rooftop greening on temperature. Most studies change surface albedo, or treat the roofs as shallow water bodies, but Sun et al. (2016) simulated the soil-plant-atmosphere interface to estimate the effects of 0–100% green roof coverage for the greater Beijing region during the 2010 heat wave. They found that the average temperature declined almost linearly with increasing coverage of green roofs, but also that the day-night timing of warming and cooling was affected. The 100% coverage scenario produced a reduction in surface air temperature of 2.5°C at midday, delaying peak temperature by about an hour, decreasing wind speed and increasing humidity. Based on previous estimates of heat-related mortality, they estimated that the cooling would reduce mortality by 25 deaths per 100,000 population (Sun et al. 2016).

Green façades and cooling

Green façades function by Hunter et al. (2014) (and references therein):

- Increasing albedo – (reflecting solar radiation);
- Shading – intercepting and absorbing solar radiation;
- Cooling through evapotranspiration;
- Creating a thermally-insulated air cavity; and
- Convective shielding – reducing wind speed.

Green façades use climbing plants (vines, scramblers and lianas such as grapes) to cover vertical building walls, which comprise a significant proportion of the total area of urban hard surfaces. Green façades may either have plants planted into the ground and grow directly on the wall surface (direct or traditional green façade) or may attach to a supporting structure fixed to the wall (double-skin green façade) (Hunter et al. 2014). Alternatively, green façades may be planted into containers at various heights on the wall and free-standing systems are also available (greenscreen 2015). Double-skin green façades also have an insulating layer of air between the foliage and the building wall (Köhler 2008), providing additional thermal benefits, and enabling a wider range of species to be utilised. Façades may also be built on double-layered wire panels, or 3D systems (greenscreen 2015) where the depth of foliage can be increased. Both double-skin and direct façades can be used as passive tools for energy savings in buildings and in climates with hot, dry summers can reduce external wall temperatures by 6°C (direct green façade) and 15.8°C (double-skin green façade) (Coma et al. 2017).

Green façades are relatively low-cost form of vertical greening when compared to green walls, particularly if they are self-adhesive climbers in soil at the base of a wall (DEPI 2014). Building walls comprise a significantly greater area than roofs in urban environments, therefore efforts to green walls may potentially have more effect on the building environment (Pérez et al. 2014), although physical limitations associated with building height and urban canyons place practical limits on where façades may be grown (Rayner 2010).

While there is documented evidence of the thermal benefits of green façades in Mediterranean, arid and semi-arid climates (Eumorfopoulou and Kontoleon 2009, Holm 1989, Pérez et al. 2017, Pérez et al. 2011, Tzachanis 2011), inconsistency in approaches and errors in research design can make it difficult to make comparisons between studies (Hunter et al. 2014). When comparing research findings of the cooling benefits and building energy savings of green façades for Melbourne and comparable climates, system designs (i.e. direct façade, double skin façade, containerised, planted in ground, substrates), plant types and data collection periods vary widely. Performance is also significantly mediated by local, site-specific conditions. For these reasons, it is difficult to make simple comparisons between studies, and the applicability of research from other areas to Melbourne requires further investigation.

In a review of green-façade thermal benefits, Hunter et al. (2014) highlight that the greatest cooling and energy benefits are most likely realised in climates with hot, dry summers (Alexandri and Jones 2008) and on walls with westerly aspects (Holm 1989). Similarly, buildings with substantial exposure to the sun will enjoy the greatest cooling benefits when shaded by foliage (Kontoleon and Eumorfopoulou 2010).

Green façades can cool building exterior wall surfaces by as much as 16°C in climates with hot dry summers (Kontoleon and Eumorfopoulou 2010) and can reduce indoor air temperatures by reducing the heat flux into the building's exterior walls and indoor space (Eumorfopoulou and Kontoleon 2009, Razzaghmanesh 2017). They can improve human thermal comfort within buildings (Holm 1989, Malys et al. 2016), are able to reduce energy demands for internal space cooling in summer (Pérez et al. 2014, Pérez et al. 2011) and can cool the external microclimate (Norton et al. 2015). Modelling results for thermal building performance in France suggest that green façades may improve indoor comfort throughout an entire building, whereas the effect of green roofs may be primarily confined to the upper floor (Malys et al. 2016). Because climate has such a significant influence, inferences about green-façade performance for local conditions should be drawn from comparable climates; however, such studies are limited (Pérez et al. 2014). In addition, few plant species have been trialled.

Climbing plants can be evergreen or deciduous and vary in leaf area and foliage density, so plant choice will determine the thermal performance of the façade (Wong et al. 2010). In turn, growth rate, foliage condition, density and coverage are influenced by physical and environmental variables of which low and/or variable light, wind speed, inadequate rooting volume and poor soils can be limiting factors. The capacity of a leaf to reflect, absorb and transmit solar energy varies between species but these differences may be less evident as foliage density increases (Hoyano 1988, Pérez et al. 2011). There is an absence of information on other aspects that may influence thermal efficiency of green façades; e.g. the configuration of supporting structures and optimal distance from walls (Hunter et al. 2014).

Establishing and maintaining persistent plant cover on façades can be challenging, particularly in arid and Mediterranean climates (greenscreen 2015). Scientific evidence to support their functions and benefits is often lacking, and practical and technical difficulties that impact on plant performance often prevent 'visions' for buildings enveloped in green façades from becoming a reality (Hunter et al. 2014). City buildings create challenging growing conditions and plants are (unrealistically) expected to thrive in sites with extreme gradients in light (e.g. deep shade at the bottom of buildings and intense solar radiation skywards) (Rayner 2010) and exposure (e.g. wind speed increases with increasing building height) (Croeser 2016). The challenges of urban environments for green façades was demonstrated on the City of Melbourne's CH2 building which, in 2006, was planted with 164 façade plants, from five species. Rayner (2010), two years later found that more than half of the plants had died or failed to cover even a small area of trellis. The high rate of failure was ascribed to multiple factors including low light, inadequate maintenance, wind burn, irrigation failure and overly mature plant stock (Rayner 2010).

Croeser (2016) used a combination of GIS and microclimatic modelling techniques to determine the biological potential for green façades in Melbourne's CBD, and identified 16 ha of potentially suitable wall space (up to 7 m high) of which 1.9 ha had optimal characteristics in terms of low wind stress and access to sunlight, 7 ha were considered good, and 7.5 ha were poor. The remaining 91.9 ha were found to be unsuitable. While Croeser (2016) considered factors like windows and access to fire exits in calculations, information on the load-bearing capacity of walls was not available. He acknowledged that information on how different species would perform on these walls was unknown and that this was an area for future research and testing – particularly for walls in less optimal environments.

Energy savings for cooling (usually air conditioning) have been calculated for many green façades, with reduced energy consumption potentially mitigating greenhouse gas emissions. Perini et al. (2017) investigated the summer thermal performance of a well-vegetated vertical greening system in Genoa, Italy, calculating energy savings of 26% as a result of reduced need for air conditioning. Coma et al. (2017) found that when compared to bare walls, the cooling-related energy saving was 33.8% for a double-skin green façade (deciduous climber) on experimental model houses in Lleida, Spain. Their system involved Boston Ivy (*Parthenocissus tricuspidata*) grown on metal trellis with a 25 cm air gap on south, east and west walls.

In a review of green walls and façades, Pérez et al. (2014) found façade orientation and foliage thickness are the most influential factors driving thermal differences in vertical greenery systems, reducing the exterior wall surface temperatures between 1.7°C to 13°C during summer. Maximum benefits were achieved on walls facing south with façades having west to east orientations limiting maximum solar exposure. In an earlier study (Pérez et al. 2011) showed that *Wisteria sinensis* grown on a double-skin façade (20 cm thick, 50–70 cm air layer) cooled the underlying wall by 5.5°C annually compared to bare walls, with a maximum 15.2°C reduction on a south-west façade in September. Haggag et al. (2014) found a direct green façade in the United Arab Emirates (desert hot arid) reduced the external wall temperature by 6°C.

Green façades may also be orientated horizontally, which is a traditional way of cooling in Mediterranean countries (e.g. grape vines grown over pergolas). Katsoulas et al. (2017) studied the effect of a hydroponic vertical (green wall) (20 m2 x 0.25 cm deep, south facing) and a hydroponic horizontal green structure (pergola) (56 m^2 x 2.6 m deep) on the microclimate conditions on university buildings in Arta, Greece. Covering 100% of the atrium area with a planted pergola (plants grown at roof level) reduced mean radiant temperature and Physiological Equivalent Temperature (a human thermal comfort index) values by 29.4°C and 17.9°C, respectively during the hottest part of the day. The green walls had no effect on microclimate but did reduce the building temperature behind the green wall by 8°C, which would result in reduced energy load for cooling.

A green façade (*Parthenocissus triscuspidata* – 25 cm thick) grown on an east-facing wall of a building in Thessaloniki, Northern Greece, reduced the range of annual minimum temperatures between the exterior (5.7°C) and interior surfaces (0.9°C) of the corresponding wall sections (Eumorfopoulou and Kontoleon 2009). Maximum summer temperatures on bare brick walls reached 45°C, while maximum wall temperatures under façades did not exceed 40°C. The authors suggested that human thermal comfort in indoor spaces over summer may be more favourable inside rooms with external green façades, although the mean daytime indoor temperature was only 0.9°C cooler. In a related study, Kontoleon and Eumorfopoulou (2010) used model simulations (based on data for a direct, *P. tricuspidata*, green façade) to determine exterior/interior wall temperature reductions on different wall orientations, finding the greatest benefit for west walls (16.9°C av. temp. with a 3.3°C reduction) and east walls (10.5°C av. temp. with a 2.0°C reduction), with lesser reductions for north and south-facing walls.

Studies in Greece indicate green façades can also help retain night time wall heat and do not cool as rapidly as bare walls (Eumorfopoulou and Kontoleon 2009). However, the overall cooling effect was greater than the heat retention effect, the net benefits depending on the structure and performance of the façade and the heat capacity and thermal resistance of the underlying walls (Eumorfopoulou and Kontoleon 2009). Schettinia et al. (2016) suggest that the night-time heat retention properties of walls under façades may result in energy savings for both summer cooling and winter heating, investigating the performance of green façades (*Pandorea jasminoides* and *Rhyncospermum jasminoides*) in Bari, Italy. Over summer, walls under façades were 3–4.5°C cooler than bare brick walls, but in cooler months at night remained 2–3°C higher than control walls. Retaining heat within a building may be more desirable in cold-temperate climates. For example, in Reading, UK, (Cameron et al. 2015) used small scale heated building models covered with ivy (Hedera helix) to demonstrate a potential reduced energy consumption in winter by 20–30%.

Larger leaves and increased foliar density with LAI of 3.5–4 (Boston Ivy) in double-skin façades in Spain (Pérez et al. 2017), was estimated to produce energy savings up of up to 34%. However, LAI does not always adequately represent the shading ability of plants, and can change with height (Pérez et al. 2017). Wolter et al. (2012) suggest that a Green Area Index be used instead, as this accounts for shading by all plant parts including stems, giving a higher, more realistic value.

As for urban trees, soil volume is critical for long-term success of climbing plants, both in the ground and in planters (Urban 2008). As density and area of leaf coverage is linked to rooting volume, success of green façades relies on adequately-sized containers and tree pits, particularly for woody climbers. Horticulturalists and green-façade installers in North America have recommended a minimum of 1 cubic foot (0.028 m3) soil for every 1 square foot of wall coverage (0.093 m2 = 930 cm2) (greenscreen 2015, Urban 2008). These values have also been extrapolated to match vine calliper measurements (greenscreen 2015), but optimum volumes for soil and other growth media need to be determined for a range for exotic and native climbing species likely to be used in Melbourne in both containers and in-ground plantings. Many façade greening projects have had unrealistic design outcomes in terms of container volume limiting vegetation growth and coverage, particularly over time. To avoid this situation and to obtain adequate coverage, a better understanding of the constraints imposed by limited soil volume in a variable climate such as Melbourne's is required.

Green walls and cooling

Green walls are generally one of two types: continuous geotextile felt (usually no substrate) or separate modules (plastic, metal, etc.) filled with a lightweight substrate. Thermal properties are influenced by depth and materials of the supporting structure, the vegetation layer and air cavity between the support and the underlying wall. Because of their low/no substrate volume, green walls need constant irrigation to retain moisture around plant roots and can rapidly dry when irrigation fails. Practitioners consider it difficult to maintain survival of plant material over large green wall surfaces for an extended period, they estimate that installation costs are about 3–5 times that of a green façade, and consider that green walls have significant ongoing maintenance and plant replacement costs (greenscreen 2015). While green walls can have cooling benefits there are few studies to support this claim, and fewer still for Mediterranean, semi-arid or arid climates.

For warm temperate climates, green walls have been found to reduce exterior wall daytime temperatures by 12–20.8°C in summer, and 5–16°C in autumn and night time temperatures by 2–6°C summer and 3°C autumn (Pérez et al. 2014). In urban canyons, green walls have a stronger effect on decreasing building energy cooling requirements than green roofs. Model simulations of the thermal effect of green walls (and green roofs) in urban canyons testing different geometries and orientations showed that urban temperatures can be lowered when the building envelope is covered with vegetation. This effect is greatest in hotter/drier climates, with energy savings ranging from 32–100% (Alexandri and Jones 2008).

The cooling-related energy saving benefits of green walls (planted with Rosmarinus officinalis and Helichrysum thianschanicum – evergreen species) on experimental model houses in Lleida, Spain were 58.9% when compared to bare walls (Coma et al. 2017). No major difference was found for heating-related savings. External wall surface temperature reductions of 12–31.9°C (daytime, summer) produced cooling benefits in all orientations (south, west and east) with the highest measured on south and west orientations. Also in Spain, Olivieri et al. (2013) measured external wall surface temperature reductions of 15.1–31.9°C for south-facing green walls.

The air gap tends to vary between 3–15 cm, and has a beneficial cooling effect on temperature (Pérez et al. 2014). Mazzali et al. (2013) examined felt green walls planted with shrubs, herbs and climbers on south-west orientation in Pisa (Mediterranean climate) with different air layer widths. Surface external wall temperature reductions for a wall with 5 cm air gap were 12–20°C (day) and 2–3°C (night), while a wall with 3 cm air gap had reductions of 16°C (day) and 6°C (night). Heat flux reductions were 90 W/m2 for the 5 cm air gap, and 1.5 W/m2 for the 3 cm air gap (Mazzali et al. 2013). Heat flux from the bare wall (90-100 W/m2) were 70–80% greater than the green wall (18–30 W/m2). Reduced heat flux reduces the cooling load supplied to the HVAC system, with a direct reduction in cooling energy consumption.

Perini et al. (2011) investigated the effect of air flow and temperature on the building envelope of a panel green wall in the Netherlands. They found no difference in wind speed at 1 and 10 cm in front of the wall, but wind speed was reduced in the air cavity, and the external building wall temperature was reduced by 5.5°C, which because monitoring was conducted in autumn, the authors suggest was at the lower end of the scale. Over a hot, dry summer in Hong Kong (subtropical) Cheng et al. (2010) found a strong association between moisture in the growing medium, vegetation coverage and cooling. During the afternoon, green wall panels reduced solar heat transfer to the walls with a heat flux for bare wall over 40 W per m^2 and 10 W per m^2 for the green wall. The lower heat inflow reduced the daily power consumption of a small room behind the green wall by 1.45–1.85 kWh.

The lack of research on the cooling effects of green walls in Australia is a significant knowledge gap. In an Adelaide-based study, the average wall temperature of a 7.2 m2 west-facing green wall planted with natives was 14.9°C lower than an adjacent bare brick wall, which in summer reached up to 59°C (Razzaghmanesh 2017). Less heat was also transferred into the adjacent building. Temperatures in front of both walls at distances of 0.50 m and 1.0 m were also measured but no appreciable difference was found. Only one small green wall and one control wall were studied so the results of this study are preliminary (Razzaghmanesh 2017).

BIODIVERSITY

Key points:

- The creation of green roofs can theoretically support urban biodiversity by providing new and unique habitats that can be naturally colonised by a range of animals and plants.
- Many of the purported biodiversity benefits of green roofs are largely untested and there is a paucity of data specific to Melbourne.
- Because green roof environments can be harsh, and are often disconnected, they tend to be dominated by invertebrates. More isolated roofs are dominated by highly mobile (e.g. flying) species.
- Biodiversity on roofs can be influenced by a range of factors, including surrounding land use type and distance to ground-level habitats, roof height, plant diversity and structural complexity of vegetation, proximity to other green roofs and roof age.
- Green roofs can act as ecological traps for some species. Green roofs' isolation and size can have negative consequences for reproduction and survival, unless they are carefully designed to provide minimum inputs for survival; e.g. food, water and shelter.
- Some species that add to the diversity of roofs may not be desirable.
- Plant diversity has been shown to improve green roof function.
- Of the few studies conducted, biodiversity on green façades tends to be lower than green walls, and significantly lower than green roofs, however green façades can provide 'habitat ladders' from ground level to roof areas and vice versa.

Green roofs and biodiversity

The City of Melbourne's biodiversity strategy, Nature in the City: thriving biodiversity and healthy ecosystems (CoM 2017) identifies goals and priorities to "...support diverse, resilient, and healthy ecosystems." Within this strategy, biodiversity is defined as: "the variety of nature, including all living organisms and the ecosystems they form", and encompasses both native and exotic species. Information on green roof biodiversity specific to Melbourne, or elsewhere in Australia is limited (See: Murphy et al. in review)). This is partly due to being a relatively new innovation in Australia. Williams et al. (2014) also highlight the lack of scientifically rigorous studies to assess biodiversity conservation or habitat restoration benefits of green roofs. However, the literature on biodiversity and engineered green infrastructure is gaining momentum, albeit from a low base.

Green roofs can support and increase biodiversity by providing habitat for animals – largely invertebrates (Gedge et al. 2014, Madre et al. 2013, Nagase and Nomura 2014), birds (Fernandez-Cañero and Gonzalez-Redondo) and lizards (Davies et al. 2010) and can be utilised for foraging by bats (Pearce and Walters 2012). As elevated habitats, they can be particularly useful for flying insects or those that are mobile during a particular life history stage – for example young spiders that disperse by 'ballooning' on silk (Brenneisen 2006, Latty 2016). Being removed from ground level threats such as predation and herbivory they can potentially act as sanctuaries for the conservation of vulnerable species such as birds (Baumann 2006, Gedge et al. 2014), rare invertebrates (Kadas 2006) and orchids (Brenneisen 2006).

While largely untested, they may also enhance biodiversity by acting as recruitment sources – dispersing seed or spores to colonise other roofs and ground level areas – and as habitat stepping stones – connecting habitat patches and associated biota in the mosaic of urban greenery (Braaker et al. 2014). The extent to which green roof populations are connected to each other (connectivity) and therefore their capacity to act as stepping stones depends on the dispersal ability of the animal or plant and proximity of roofs. Braaker et al. (2014) found that green roof communities of high-mobility invertebrates (bees and weevils) were connected, while low-mobility groups (carabid beetles and spiders) were more influenced by local environmental conditions and more connected to ground sites than other green roofs. The closer the roof, the more likely that less mobile species can connect. Green roofs within a city may form connected habitats (stepping stones) for only some species and more information is needed into the mechanisms involved (Braaker et al. 2014, Cook-Patton and Bauerle 2012).

Because green roofs are generally small in area and can be isolated and harsh environments, the types of animals and plants they can support are limited, particularly for extensive green roofs. Beyond a certain height and/or distance from natural habitats, green roofs may not be connected to external populations (Williams et al. 2014). Roof height, roof size, proximity and type of nearest roof, and surrounding land-use type will influence the resident biota (Braaker et al. 2014). Increasing roof height has been found to reduce numbers of nesting solitary bees and wasps (MacIvor 2016) and negatively affect the abundance of spiders and the taxonomic composition of bug and beetle communities (Williams et al. 2014). Green roof substrates are often too thin, too hot and too dry to support soil-dwelling animals.

Like other urban habitats, green roofs tend to be dominated by native and exotic generalist invertebrates (animals that can inhabit a wide range of habitat types) rather than specialists (animals with requirement for a specific habitat or plant type) (Williams et al. 2014). Invertebrates inhabiting green roofs may in turn provide food for other species however the resource requirements for large vertebrate fauna like birds and bats include food, roosts and nesting habitat and water – are unlikely to be contained in one roof (Latty 2016). Pearce and Walters (2012) found that the feeding behaviour of 3 species of bat in the UK was significantly greater over biodiverse roofs than conventional roofs or roofs planted with sedums. Similarly, 5 of 9 potential bat species were recorded over green roofs in New York City, with overall levels of bat activity higher over green roofs than over conventional roofs (Parkins and Clark 2015). In this study, the type of surrounding vegetation also had a strong effect on bat activity – the roofs with highest activity levels within each roof type were those with more surrounding green space in the form of trees, shrubs and grass.

On green roofs, metrics of animal (usually invertebrate) species diversity have been found to increase with increasing plant diversity (Cook-Patton and Bauerle 2012, Madre et al. 2013), substrate depth (Brenneisen 2006), structural diversity of the habitat (Lundholm et al. 2010, Madre et al. 2013), roof area (Madre et al. 2013), and substrate heterogeneity (Jones 2002). Conversely, negative relationships have been associated with building height and isolation from surrounding habitat (Braaker et al. 2014, MacIvor 2016, Murphy et al. in review).

For Australia, invertebrate communities have been surveyed on extensive green roofs across Melbourne (Murphy 2013, Murphy et al. in review). All roofs had less than 300 mm scoria-based unirrigated substrates and were planted with either succulents or a range of native forb and grass species. Murphy et al. (in review) found 2,194 invertebrates on 6 green roofs across Melbourne comprised of 13 orders including amphipods (e.g. slaters), flies, beetles, bugs, moths and butterflies. No difference was found in diversity between grassland roofs and succulent roofs. The study found no difference in community composition (orders) of green roof invertebrates on roofs compared to adjacent ground level sites or at ground-level sites with similar habitats, but abundance was significantly lower on green roofs. The diversity and abundance of invertebrates on roofs was strongly influenced by the percent cover of green space surrounding the site and suggests that the effectiveness of green roofs to provide invertebrate habitat is highly dependent on location and their horizontal and vertical connection to other habitats. Roof height was also found to influence invertebrate communities on Melbourne's green roofs (Murphy et al. in review) with lower numbers of invertebrates from functional groups like detritivores and herbivores with increasing roof height. Age of the roof (ranging from 7 years to less than a year) had an effect, with older roofs having greater biodiversity, but no strong difference was found between roofs planted with native species and those planted with succulents.

A study of 13 intensive green roofs in Sydney found roofs with at least 30% green cover had twice the abundance and twice the number of invertebrate species compared to conventional roofs (Berthon 2015), which is not surprising. Winged invertebrates were the most common, highlighting the fact that more mobile species are likely to inhabit roof tops, and six groups including gastropods, annelids (worms) and amphipods found on green roofs were absent from bare roofs. Results indicated that biodiversity conservation was more effective on green roofs that were closer to ground-level habitat patches, and that building height was the most significant connectivity measure that influenced invertebrate composition.

Davies et al. (2010) surveyed a New Zealand green roof (100–300 mm deep, 500 m2) planted with native species four years after establishment. Most animals were exotic species typical of degraded urban habitats along with a number of ubiquitous native species (Davies et al. 2010). The authors suggest that biodiversity on green roofs can be enhanced by irrigation (at least initially), microclimates (different substrate depths and mounds across the roof), addition of refugia (wood and specific plant species) and rapid plant coverage. Native bees on Chicago green roofs occurred at lower abundance and diversity than in reference habitats although populations increased with greater plant diversity (Tonietto et al. 2011). Overall, bee abundance and species richness increased with a greater proportion of green space in the surrounding landscape, but not where surrounding green space was dominated by turf grass. Similarly, Brenneisen (2005) found sedum roofs attracted only half the number of bee species compared with green roofs planted with multiple forms of vegetation, largely because sedums have a shorter flowering period and thus provide less food.

Research aimed at selecting suitable green roof plant species has investigated habitat analogues that have similar environmental conditions to green roofs (Lundholm 2006, Lundholm et al. 2010). Farrell et al. (2013b) tested the suitability of 12 species from granite outcrops in regional Victoria. Although some variation in performance was observed, monocots, herbs and shrubs all showed a capacity to utilise water when it was available and reduce transpiration and water use under dry conditions. Their relatively high water-use and drought tolerance, particularly when compared to succulents (Wolf and Lundholm 2008), also make them effective at controlling stormwater runoff. Australian native dry grasslands have been identified as potential green roof analogues, and species are currently being tested on the biodiversity green roof at Burnley, Melbourne. Monitoring of native plant species (from Victorian dry grassland and granite habitats) on 300 mm deep green roof modules on the Pixel Building, Melbourne, showed 75% survived after three years (Williams unpublished). While green roofs can be modelled on natural ecosystems, they should not be considered as surrogates for ground-level habitats.

While a number of design guides have been produced (e.g. Brenneisen 2006, Torrance et al. 2013), further research is required to determine how green roofs can be designed to maximize biodiversity conservation benefits. This will need to be species-specific and potentially city-specific involving comparisons of 'biodiverse' green roofs with other green roof types and ground-level habitats. Incorporating specific habitat elements into the design of green roofs such as by planting preferred plant species – for example Asteraceae (daisies) for specialist bees (Cook-Patton and Bauerle 2012), or providing refuges such as hollow logs for carabid beetles (Meierhofer 2013, Venn et al. 2013) may increase the likelihood of the specialist species colonising the green roof, provided the species is physically able to access the roof. Having diverse plants that flower at different times may ensure food availability throughout the year for pollen and nectar feeders.

Planting roofs with diverse species that have different phenological responses (e.g. have different growing or flowering periods, establish from seed or re-sprout from bulbs, vary in water utilisation) may enable green roofs to function better in the face of environmental fluctuation (Cook-Patton and Bauerle 2012) and ensure year-round plant coverage and aesthetics. To optimise the multiple benefits that green roofs can provide, a mixture of species with different traits (e.g. water capture, evapotranspiration) may be desirable, as no single plant can perform all functions with equal effectiveness (Lundholm et al. 2010). Cooling effects below diverse green roofs can be greater (Kolb and Schwarz 1986), structural complexity may assist with minimising water runoff (Brandão et al. 2017) and increased plant species richness can enhance nitrogen retention in green roof plots (Johnson, 2016). Increasing biodiversity alone may not improve function – green roofs with mid-level diversity have been found to perform better than highly diverse roofs. Understanding and selecting for species traits is important in order to maximise green roof benefits (Lundholm et al. 2010).

Some green roofs could be ecological traps (Hale and Swearer 2016) if animals select suboptimal habitats with negative consequences for survival and the production of viable offspring. Baumann (2006) found that Northern Lapwings were nesting on green roofs, and while eggs hatched, no chick survived to adulthood because of lack of resources (e.g. food and water) even after efforts to improve vegetation had been undertaken. There is local evidence of this with Masked Lapwings nesting on the Monash Civic Centre roof when it was covered in river pebbles, over several years dying soon after hatching (Williams pers. comm.)

Biodiversity on green roofs is not always welcome, as substrates and plants combine to provide more habitat for both 'good' and pest species. For example, Berthon (2015) found mites on green roofs and none on bare roofs. Woody and herbaceous weeds are often found to have spontaneously colonised Melbourne green roofs. Pest and weeds can be accidently transported to roofs via substrates and plants, highlighting the need for good horticultural hygiene. Pest, pathogens and weeds still need to be controlled like ground level gardens. Human translocations of 'good' invertebrates (e.g. ladybugs that eat aphids) can be undertaken, but may result in ecological traps if these green roof populations are not self-sustaining, or are not connected to the wider metapopulation. Visiting possums can cause significant damage through foraging on green roof plants such as observed on the Burnley demonstration green roof (Farrell, pers. comm.) and in Westbury, St Kilda (Sonia Bednar, pers. comm.). For other 'pests' green roofs are inhospitable habitats. For example, in Hong Kong green roofs had significantly smaller mosquito populations than similar ground-level sites because elevated temperatures and wind speeds made them unsuitable (Wong and Jim 2016).

Green roofs can be planted or seeded with select species, as well as provide opportunity for colonisation of new plants transported via wind-born seeds or animals. Colonisers can survive and thrive as a result of a deliberate design and maintenance regime, or via benign neglect. Surveys of 115 green roofs in northern France found that of 176 colonising plants, 86% were native species (Madre et al. 2014) and greater substrate depth supported higher wild plant diversity. Of these native species, 67% were reproduced by seed, 26% reproduced by seed and vegetatively, and 4% were strictly vegetative and showed a range of dispersal mechanisms: 63% dispersed by wind or gravity, 32% by animals, and 3% with no external vector (Madre et al. 2014).

As plants grow and increase biomass, animal abundance may increase with a corresponding increase in habitat, and this is particularly true for intensive roofs. Plant species diversity and/or structural diversity is thought to be an important factor for arthropod diversity on green roofs (Gedge et al. 2014, Tonietto et al. 2011). Madre et al. (2013) found arthropod species richness and abundance was significantly higher on French green roofs with more complex vegetation. The surrounding environment, green roof area and height above ground level (0–25 m) had only a minor influence.

Biodiversity of green façades and green walls

Green façades and walls have been identified as providing habitat and food for birds, invertebrates and small mammals (Bendict and McMahon 2006, Köhler 2008, Loh 2008). However, few studies have assessed the biodiversity values of green façades or green walls, and the limited studies there are appear to focus on simple façades with only one species – predominantly Boston Ivy (*Parthenocissus tricuspidata*).

Madre et al. (2015) looked at beetles and spiders on three types of vegetated- façades – green façades (climbing plant façades), felt green walls (felt layer façades) and modular green walls – with bare control walls as a control. They examined 33 different systems located in and around Paris (France), comparing the effects of façade type with the area and properties of the surrounding landscape on spider and beetle assemblages. Green façades were described as hot and dry habitats like cliffs, whereas felt green walls and modular green walls were damp and cool habitats, similar to vegetated waterfalls (Madre et al. 2015). They counted 356 spiders (31 species) and 254 beetles (31 species). Beetle abundance was highest in modular green walls and significantly lower in felt walls while spider abundance was lowest in green façades, followed by felt walls then modular walls. Despite the presence of few rare species of Northern France, the assemblages were dominated by generalist species.

Figure 3. Boston Ivy (*Parthenocissus triscuspidata*), amongst a variety of creepers in Coromandel Place, Melbourne.

HEALTH AND WELLBEING

Key points:

- Roof tops provide opportunities for city residents and workers to access communal or private open spaces and enjoy the health and well-being benefits that accompany these. These accessible spaces may be configured to be wholly, or partially, covered with plants.
- Extensive green roofs, where access is limited by weight restrictions, can still have visual benefits for neighbours.
- Extensive green roofs can have a restorative effect on workers overlooking roofs and help improve task accuracy.
- Melbourne research suggests that people prefer certain vegetation forms and colours on extensive green roofs.
- Urban agriculture can be practiced on green roofs and communal, productive gardens have the potential to enable social interactions and enhance social cohesion, however the evidence for such benefits is largely derived from ground-level studies.
- Data quantifying the health and well-being benefits of green roofs is limited, with few quantitative studies for green façades or green walls.
- Green walls are primarily established for aesthetic reasons and can have high visual impact.

Health and wellbeing can be influenced by green roofs, walls and façades through cooling and general insulation effects within, cooling around buildings, attenuation of noise, removal of pollutants and through sensory exposure to nature and the natural environment.

For the greater Melbourne region, Loughnan et al. (2012) mapped dwelling type, UHI and urban and population density as part of the urban form contributing to mortality and morbidity. Urban density was the only one of five indices to make a significant difference to the spatial distribution of vulnerability and aged-care homes was the largest single contributor. However, UHI was highly correlated with (in decreasing order), ethnicity, population density, dwelling type, disease burden, aged-care facilities and high social vulnerability scores (Loughnan et al. 2012). For the City of Melbourne, high density and the UHI will be the largest contributing factors to heat risk on vulnerable populations.

For greater Melbourne between 1988–2009, Gasparrini et al. (2015) estimated that excess deaths due to cold was 5.99% of all non-accidental deaths and excess deaths due to warm temperatures was 0.49%. The minimum mortality temperature, selected as having the least deaths with respect to temperature, is 22.4°C (Gasparrini et al. 2015). This temperature is situated at the 90th percentile of the temperature range (temperature was averaged from seven stations within 50 km of Melbourne's centre). Curves showing heat and cold excess relative risk (as a proportion of 1) are shown in Figure 4. The relative risk for extreme heat is shown as increasing more than it does for cold, demonstrating that heat risk increases nonlinearly with warmer temperatures. Green infrastructure at the building and city-wide scale have the potential to partially manage this risk by cooling buildings, providing cool spaces and reducing the UHI effect.

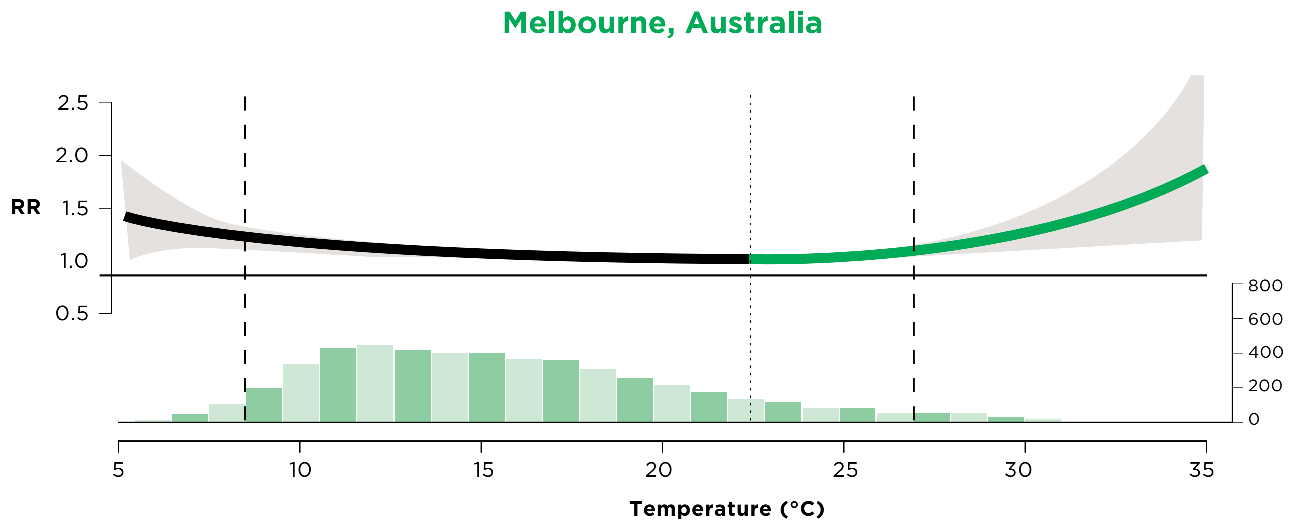


Figure 4: Cumulative exposure-response relationship for Melbourne 1998–2009 showing cold and warm relative risk (RR) and average annual number of deaths for each degree °C over the temperature range (Gasparrini et al. 2015).

Nature provides multiple health and wellbeing benefits to urban inhabitants through air quality, physical activity, stress reduction and social cohesion with positive effects on human cognitive function and mental health (Bratman et al. 2012). Research on the beneficial effect of nature on human health was pioneered by Roger Ulrich (Ulrich 1993, Ulrich 2002), and the subsequent move to place biophilia into architectural design is driving much of the innovation in the integration of green, roofs and walls into landmark architectural projects, where human health and wellbeing is a principal aim.

Despite this, there is limited direct scientific evidence underpinning the stated health and well-being benefits of green roofs for Australia. Bowen and Parry (2015) reviewed the evidence-base for linkages between green infrastructure, public health and economic benefit for Victoria. While they aimed to include green roofs and walls in their study, this was not possible due to a scarcity of peer-reviewed research. Most quantitative information relates to the reduction of heat transfer through building roofs and walls, improving indoor comfort and lowering heat stress associated with heat waves (cooling effects are discussed in this report's section on Cooling Buildings and Cities).

Views of nature can promote relaxation (Korpela and Kinnunen 2011) and nature in cities can be restorative (Hartig et al. 2014). More than 90% of Australians live in cities (Shanahan et al. 2016) and ensuring adequate green space in urban areas can help mitigate the negative impacts of urbanisation (Fernandez-Cañero et al. 2013). In large cities with high building density, green roofs may be the only opportunity for many people to personalise and enjoy outdoor space in their homes (Dunnett and Kingsbury 2004). Cityscapes need to be modified to maintain the health and wellbeing of city residents (Shanahan et al. 2016) and this may include the implementation of green roofs, walls and façades. The integration of nature into urban areas can improve perceptions of that area and greenery may be particularly desired in urban environments since it has restorative properties that appear to combat stressors such as noise and crowding (van den Berg et al. 2007, White and Gatersleben 2011).

Investigating the health benefits of nature in Brisbane, Shanahan et al. (2016) found that people who managed to get a 30 minute or more ‘dose of nature’ each week are less likely to have high blood pressure or depression. Depression is estimated to cost Australia $12.6 billion annually and around 1/3 of Australian adults have high blood pressure. Analysis showed that prevalence of depression could be reduced by up to 7% and blood pressure reduced by 9% if everyone met this 30-minute minimum guideline. Their work also suggests the benefits of exercising in natural surrounds are greater than the same amount of exercise indoors, conferring a synergistic effect on health benefits.

Green infrastructure can improve air quality by intercepting pollutants that include visible dust, microparticles (e.g. PM10 and PM2.5) that can include black carbon and airborne chemicals that include SO_2, NO_x, CO and O_3. Pollution has both direct and indirect effects. Direct effects are linked to health and include allergenic reactions, exacerbating heart and respiratory conditions that can lead to hospitalisation and death. Melbourne’s air is comparatively clean, to the point where the EPA have removed their Carlton monitoring station. This is unfortunate, as ongoing data collection from this location would help set local benchmarks for the City of Melbourne.

The main way that air pollution is removed by green roofs/walls/façades is through dry deposition. Most estimates worldwide are made through models rather than direct measurement. Most of the relevant measurements of modelled deposition rates come from the UFORE model applied in North and South America (Escobedo and Nowak 2009, Nowak et al. 2006, Nowak et al. 2013). Vegetation types have widely varying rates of deposition. There is also little agreement between rates on trees and shrubs found on intensive green roofs and grasses, herbs and low shrubs found on extensive green roofs. Abhijith et al. (2017) conducted an extensive review of urban green infrastructure on air pollution, which includes a summary of the research on green roofs and green walls. These have been less well studied than other urban vegetation, especially trees.

Hop and Hiemstra (2013) reviewed the large-scale ecosystem services of green roofs and green walls in cities. While ground-level urban vegetation like parks can provide a higher level of ecosystem services than green roofs and walls, the latter are a valuable addition where ground-level room is scarce. Of roof and wall types, intensive green roofs were identified as providing the highest level of ecosystem services and they concluded that roofs could mainly satisfy physical needs, and green walls more likely to satisfy social and psychological needs (Hop and Hiemstra 2013).

Green roofs and health and wellbeing

Green roofs have been widely promoted as a way of improving community liveability in built up urban areas, improving local aesthetics and increasing recreational opportunities by providing outdoor areas for people to use and enjoy. Shared, accessible green roofs can foster improved community interactions that help build social capital. Some green roofs incorporate urban agriculture and include herbs and vegetables that can be harvested for use by the building's occupants or the community. An accessible green roof increases urban green space and can provide an aesthetically pleasing view or environment. Less accessible extensive roofs can still have high visual amenity and can assist in health and wellbeing of people in multi-story buildings. Green roofs also have the potential to increase community interest in green infrastructure through their aesthetic appeal and provide opportunity for public education – developing community awareness and understanding around the urban heat island effect, stormwater and sustainable water resource management.

Viewing a green roof has been found to have a restorative effect on university students' sustained attention and cognitive function. In a Melbourne study of 150 individuals, Lee (2015) found that 40 second micro-breaks spent viewing a virtual city scene with a flowering meadow green roof led to a significant improvement compared to those that viewed a virtual city scene with a bare concrete roof. The green roof scene was perceived by participants as more restorative, as well as boosting their concentration levels by 6% while the concentration levels of participants viewing the concrete scene falling by 8% (Lee 2015). In a subsequent study using real city views, Lee et al. (2017) found that flowering meadow green roof views were easier to comprehend, which meant that subsequent work tasks felt less effortful. This was associated, in turn, with better performance and lower tension. There are few comparable studies except for Loder (2014) who found that views of living roofs influenced North American employees' perceived ability to concentrate. In cities, restorative vegetation in the form of street trees and parks is largely at ground level and may offer little benefit to people living or working in elevated buildings where rooftops and walls of other buildings may dominate their view (Lee 2015).

In a green roof choice experiment, Melbourne office workers were shown images of green roofs with different plant types and flowers, tall, green, grassy vegetation was found to be highly preferred and was associated with psychological restoration (Lee et al. 2014). Lower-growing, red succulent vegetation (characteristic of some succulent species common in overseas green roofs) was the least preferred. All living roofs were preferred over bare concrete roofs. These results are consistent with a UK study (White and Gatersleben 2011) where there was a low preference for flowering red succulents, with most people preferring meadow roofs over green turf roofs and ecological brown roofs.

Lee et al. (2014) also assessed preference for green roof plant diversity using vegetation characteristics as proxy. They found that moderate diversity was preferred over no and low diversity. Highly diverse living roofs were significantly more preferred than moderately diverse roofs. All flowering images were significantly more preferred than non-flowering roofs. The authors recommend species richness be incorporated into green roof designs by using different plant species similar in life-form, height and foliage colour.

In one of the few comparable studies, Fernandez-Cañero et al. (2013) undertook a visual preference study of 450 people in southern Spain to investigate people's preference for 8 different roof types from extensive sedum roofs to intensive green roofs with shrubs and trees. A gravel roof was used for comparison. Green roofs with more considered design (i.e. intensive green roofs), greater variety of vegetation structure, and more variety of colours were preferred over alternatives. Respondents' socio-demographic characteristics and childhood environmental background influenced their preferences. People were also asked what they thought might be the advantages and disadvantages of installing green roofs. The highest-ranking perceived advantages were reduction in air pollution, increase in biodiversity in urban areas and improvement in the thermal insulation of buildings. The three biggest potential disadvantages were perceived as causing problems for people with allergies, having a high installation cost, and promoting insects and rodents (Fernandez-Cañero et al. 2013).

The ability of green roofs to remove air pollution has not been widely assessed, although they have been nominated as having an effect at the large scale (Abhijith et al. 2017, Currie and Bass 2008, Speak et al. 2012). Speak et al. (2012) tested four extensive green roof species in Manchester, UK measuring deposition of PM10. They found interspecies differences that depended on plant characteristics including leaf area and that deposition varied with distance from the source. In a scenario involving 325 ha of sedum green roof in the city centre, they calculated a 2.8% removal rate. This shows that although vegetation has a beneficial effect, it is marginal as a mitigation strategy for air pollution, the best strategy being to manage it at source.

In a modelling study, Yang et al. (2008) estimated the removal of pollution by green roofs in Chicago. They simulated deposition rates of 85 kg per ha per yr, consisting of 52% of O3, 27% of NO2, 14% of PM10 and 7% SO2. In addition to being pollutants, O3 and NO2 are both greenhouse gases whereas SO2 is a greenhouse suppressant, so the net effect is a dual benefit of reduced air pollution on health and reduced net greenhouse effect. Baik et al. (2012) assess the effect of cool air flowing into street canyons and dispersing pollutants, suggesting that more efficient air flow and lowered temperatures can reduce pollutants considerably.

Research into the human health and wellbeing benefits of using green façades, walls and roofs for food production is limited. In a desktop review, (Russo et al. 2017) investigated the importance of 'urban provisioning' and whether implementation of edible green infrastructure can offer improved resilience and quality of life in cities but this study was largely focused on large-scale intensive farming. Plans for a 2,000 m2 rooftop garden, farm and greenhouse on top of a shopping centre have just been announced for the Brickworks development site in Burwood, Melbourne (Editorial Desk AAU 2018). The aim is to use closed-loop management of water and waste.

Beyond the benefits associated with food production and the natural environment, community gardening is claimed to improve human well-being (Okvat and Zautra 2011). Orsini et al. (2014) looked at food production and consumption in urban areas and developed a case study to quantify the potential of community vegetable production in the city of Bologna (Italy) including yards, balconies and rooftops of buildings. Orsini et al. (2014) cite studies that have demonstrated the mental health and therapeutic benefits of community gardening and more passive forms of contact with nature (e.g. taking a walk in a garden) including reducing psychological disorders (e.g. against dementia) enabling stress recovery and fostering cardiac rehabilitation.

Wilkinson and Dixon (2016) describe rooftop gardens in Sydney and how they are combining food production with health (medical and general) and social wellbeing outcomes. Horticultural therapy was trialled for mental health patients within one garden, with patients reporting very positive outcomes from the activity (Wilkinson and Orr 2017). The Fiona Stanley Hospital in Perth WA was a $2 billion development on a 32 ha green field site structured around evidence-based design integrated into the natural environment with extensive green infrastructure development incorporated into the architectural design including green roofs (Keniger and Bennetts 2014). Green roofs, gardens and court yards are used to linked the built environment to conservation areas, using local species wherever possible. A green roof has also been incorporated into the new Peter MacCallum Institute building in Parkville, green roofs are incorporated into the new Bendigo Hospital and biophilic design in the form of moveable 'leaves' as exterior blinds in the Royal Children's Hospital Parkville. Overseas, food production projects are being incorporated into Changi General and Khoo Teck Puat Hospitals, Singapore and the Boston Medical Centre, and Vanguard Weiss and Stony Brook University Hospitals, USA.

Green walls and façades and health and wellbeing

Green walls and façades may enhance the aesthetic value of a building, and for green walls this is still the main motivation for their installation (Köhler 2008, Madre et al. 2015). In the UK, houses with vegetation covering external walls were found to be more preferred than those without (White and Gatersleben 2011). Houses with some type of building-integrated vegetation were significantly more preferred, were considered more beautiful, restorative, and had a more positive effect on perceived quality than those without. Green façades have potential for urban agriculture, and overseas have been planted with productive and ornamental species such as bitter melon, sword bean, *Apios* (an edible legume), Kudzu (Japanese arrowroot), *Luffa* sp. (dishcloth gourd) and green beans (*Phaseolus vulgaris*) (Koyama et al. 2013, Pérez et al. 2014). Green walls can be used to grow herbs and vegetables (Downtown 2013) and a large number of commercial green wall providers promote this function.

The potential of green walls to moderate air pollution is thought to be even better than that of green roofs, because of their ability to have a large leaf area index over a small horizontal area, and their potential to be constructed close to the street where people are present. Simulations carried with i-Tree for trees, walls and roofs at the Brooklyn Industrial Precinct in Melbourne showed the best reductions were gained from trees with lesser reductions from green roofs and walls (Jayasooriya et al. 2017). As the most polluted area in Melbourne, the simulated pollutant removal would be higher than which could be achieved in the City of Melbourne. Joshi and Ghosh (2014) assessed the efficacy of a façade covered in tropical vines in Hong Kong, finding that it effectively removed background SO_2 pollution a finding they extended to other species. Pugh et al. (2012) found that vegetation in street canyons could remove NO_2 by up to 40% and particulate matter up to 60%.

Using Southampton, UK, as a case study Collins et al. (2017) estimated the public's perceived value of green walls to urban biodiversity, in the form of their willingness to pay (WTP). Three green infrastructure policies were tested; a green (living) wall, a green façade and an 'alternative green policy'; and compared against 'no green policy'. Results indicated a WTP associated with green infrastructure that increases biodiversity. Attitudinal characteristics such as knowledge of biodiversity and aesthetic opinion were significant, providing an indication of identifiable preferences between green policies and green wall designs. A higher level of utility was associated with the living wall, followed by the green façade. In both cases, the value of the green wall policies exceeded the estimated investment cost.

PART 2: ECONOMIC BENEFITS

Figure 5. Rankins Lane, Melbourne.

ECONOMIC METHODS

Green roofs and other green infrastructure have in the past been considered an additional cost to the cost of built infrastructure. Conventional economic analysis has valued green roofs, walls and façades as a net cost because they provide no direct, or market-based income, although as property values start to show a premium for green buildings this is changing.

Studies applying environmental economics are revealing the economic benefits from green infrastructure through the provision of ecosystem services to society. Conventional economic analysis has a limited role in valuing such diverse benefits; instead, a range of valuation methods is required. This is often referred to as a heterodox economic approach, as contrasted with an orthodox approach.

Although the focus of this review is aimed at assessing priority public benefits, a variety of different types of benefits can be identified by:

- Who benefits?
  - Two separate groupings are public and private; and individuals, communities and institutions.
- Where are the benefits felt?
- Scales here are divided into host building location and within the immediate microclimate, city-wide or global.
- Nature of the benefit
  - Does the benefit reduce future costs that would otherwise be experienced through risk reduction, offer net benefits that otherwise would not have been experienced, or both?

These attributes help define the kind of economic approach may be most suitable for valuing each type of benefit across a diverse range. For example, a private benefit to individuals will generally be dealt with using conventional market-based approaches. A public benefit to the community will contribute to social and environmental health and welfare, and qualities such as community welfare and resilience, but may also contribute to labour productivity. Benefits to the whole of society, from political through to cultural are generally assessed as institutional benefits. These become successively more difficult to attach a dollar value to.
The main approaches in use, along with topics relevant to valuing green roofs, walls and façades, as shown in Figure 1 are outlined in the following sections.

The so-called 'gold standard' for economic analysis is to undertake a cost and benefit analysis using the whole-of-life cycle for green infrastructure. The total economic value of the ecosystem services provided and any co-benefits such as extended roof life will provide the benefits, and total life cycle investment including maintenance provides the costs. To our knowledge, there is nothing in the literature that comes anywhere near reaching this standard. A notable example of where a comprehensive city-wide approach has been taken is described by Acks (2006) for metropolitan New York who referred to it as an initial cost-benefit analysis.

The practical path is to undertake a comprehensive evaluation of existing data supporting both costs and benefits, preferably to a given standard of service delivery, to ensure that the project provides positive returns (taking in monetary, social and environmental values) and can be compared with other projects, both green and conventional. A selection of partial cost benefit analyses is summarised in this report's section on Green roofs and walls: selected cost benefit analyses.

The two main hurdles that need to be overcome are technical and economic. The technical challenges are outlined in Part 1 and the economic challenges are outlined below.

	LOCAL	CITY-WIDE	GLOBAL
PUBLIC	• Public space amenity • Local cooling (shade) • Energy savings (public buildings) • Urban food (community gardens) • Neighbourhood identity • Reduced noise pollution	• Pollution reduction (air & water) • Flood peak flod and volume reduction • Improved views (amenity & health) • Cooler city • Biodiversity conservation • City identity • Resilient city	• Co_2 sequestration (reduced climate impacts) • Very small cumulative effect on planetray social-ecological boundaries • 'Me too' effects
PRIVATE	• Building/rental value • Worker/resident amenity • Corporate image • Energy savings • Longer roof life • Urban food	• Preferred destination (tourism, work & economy) • Improved physical encironment and views (productivity)	• Preferred destination (tourism, work & economy)

Figure 6: Multiple benefits of green roofs, walls and façades arranged according to who benefits and the scale at which the benefits occur.

Market and non-market benefits of green roofs

Some benefits of green roofs can be measured relatively easily and have verifiable market values (for example, the energy savings due the insulation provided by the green roof as opposed to a plain roof (Tselekis 2012). However, the technical challenges in assessing those energy savings may be complicated, where the calculation of energy and water savings, for instance, depends heavily on the physical context of the buildings, their environment and climate.

The 'purest' market test in the classical economic sense is where a building owner installs a green roof, wall or façade, which provides a whole-of-life cycle return where avoided costs and increased property value exceed the net present value of the investment. The private benefits of investing in green infrastructure to the building owner may not be assessed as cost effective if only a limited number of benefits are considered. However, total benefits can become cost effective when the full range of public and private benefits are considered (Blackhurst et al. 2010, Rosenzweig et al. 2006, Tomalty et al. 2010). Often not considered, is that many buildings because of their location, form or design, have a deleterious local effect through their contribution to the urban heat island effect, potential wind tunnelling and so on. These all add social costs, while providing private benefits; traditionally, these social costs have not been taken into account (Kats 2013, Peng and Jim 2015).

Non-market benefits cannot be valued directly, because they are not bought and sold in markets; e.g. the health and wellbeing benefits of a rooftop garden. Consequently, quantifying these relies on indirect valuation methods. The number of studies that specifically focus on the economic valuation of non-market benefits of green roofs, walls and façades are limited. Most of those do not apply data specific to green roofs, walls and façades but instead, draw upon studies that assess other forms of green infrastructure.

Valuation methodologies for non-market goods and services

To manage the many and diverse benefits provided by ecosystems and biodiversity, the concept of Total Economic Value (Fromm 2000, ten Brink 2011) has been developed. Methods for valuation have also been developed as part of the The Economics of Ecosystems and Biodiversity (TEEB) program (TEEB 2012). The two main categories of benefit are use and non-use values. Use values are further divided into direct use and indirect use. Direct-use benefits refer to the benefit from using the service or good (e.g. recreation); while indirect use refers to the benefit people derive from a green roof without consciously using it (e.g. climate regulation, water purification). Non-use value is the value that people place on environmental amenity without any plans to use it. Non-use value is divided into existence value and bequest value. Existence value is the value people ascribe to things such as rain forests simply for their existence. Whereas bequest value refers to the value in knowing an environmental amenity is to be passed on to future generations.

Another category of environmental option value is also part of total economic value. Option value refers to the value in preserving a public asset even if there is little probability of it ever being used, but the option exists that it might be used in the future (ten Brink 2011).

Three broad categories of non-market valuation methodologies exist for valuation of direct use benefits of green roofs. These methods include revealed preference methods, stated preference methods and avoided cost analysis.

Revealed preference methods

Revealed preference methods include approaches such as hedonic pricing and shadow pricing. These methods analyse existing behaviour and data gained from markets to provide an estimate of non-market values. Various studies have used these approaches have been used to determine the value of green roofs.

Hedonic pricing

Hedonic pricing is a well-established methodology that is often used to determine the economic value of a diverse range of non-market environmental goods and services including air and water quality, appealing views and distance to green spaces or recreational areas. The most common application of hedonic pricing is to assess the proportion of value of an environmental amenity (Malpezzi 2003).

Hedonic pricing regards the value of an overall good (e.g. a house) to be the sum of its individual attributes including any environmental attribute. The method includes decomposing the total value into its component parts and using regression analysis to determine the proportion each part adds to the whole (Hidano 2002). Hedonic pricing techniques have been used to estimate variation in house prices based on attributes such as: the area of a property, the age of the property, number of bedrooms, number of bathrooms, number of units, number of storeys, distance from the central business district (CBD), transportation access and the socio-economic aspects of the neighbourhood (Sirmans et al. 2005). The drawback with hedonic pricing is the data required to establish a relationship with the service or benefit being investigated. For example, Mahmoudi et al. (2013) investigated open space in Adelaide using house prices, applying dozens of variables including those expected to have a negative effect, in order to separate out the influence of open space on house prices.

For green roofs, most hedonic pricing analyses have used open-space data as a proxy. An example of hedonic pricing from the US General Services Administration (GSA 2011) showed that real estate market valuation figures based on the expectation that the market would value green roofs as it does green buildings estimated a real estate effect of US$130 per m^2 across the USA and US$108 per m^2 in Washington DC.

Shadow pricing

The shadow pricing method analyses similar goods or services to the one being studied and infers values from this comparable market as a proxy price for that good.

This approach uses real data based on actual cost provision and consumer preferences to infer these values. When there is no comparable private market, then fees charged by local or state governments are used as proxies (e.g. park entrance fee prices as a measure of the value gained from visiting a public park). However, such fees often fall below market rates so are considered to be a minimum for any good or service (Yakkundimath 2013). An example of market-based shadow pricing would value business meetings in a rooftop garden according to commercial meeting room fees, or the cost of floor space for extra office rental.

Stated preference methods

Stated preference methods assign monetary value to non-market goods and services based on preferences obtained from survey as opposed to valuing observed behaviours and preferences (revealed preferences). The most common used technique is contingent valuation, where surveys are used to ask people how much they are willing to pay for a given good or service. Alternatively, respondents may be asked how much they would be willing to accept in compensation for the loss of an environmental amenity. This per capita figure is then used to estimate a value for the population as a whole (Lo and Jim 2015).

This method has been the subject of some criticism in the literature (Lin et al. 2013) as various studies have suggested that people do not accurately express their willingness to pay or accept often over estimating the amount they are willing to pay and underestimating willingness to accept. The other drawback is loss and gain are psychologically incommensurate, and care has to be taken on how questions are framed. Despite this, stated preference techniques do provide a method of estimating prices and values for non-market goods and services (Champ et al. 2003).

Avoided cost methods

A further valuation method for non-market goods is avoided cost, where costs estimated for a conventional approach to risk mitigation are used to value equivalent mitigation efforts using green infrastructure (Sproul et al. 2014). A common example of this is where wetlands can remove pollutants and improve water quality compared with the cost of providing conventional water treatment processes. This valuation methodology is particularly applicable to green roofs (De Groot 1992). For example, the current Melbourne Water offset for nitrogen removal is $6,645 per kg, based on the cost of physically removing nitrogen from stormwater and runoff (Melbourne Water 2018).

Economic life cycle analysis – methods

Many studies extend the unit-based cost savings or benefits to incorporate the life cycle of an investment using cost benefit analysis. Cost benefit analysis (CBA) takes all flows of costs and benefits in both the present and future that can be monetized. Methods for the economic life cycle analysis of engineering projects include Net Present Value (NPV), Internal Rate of Return (IRR) or Payback Period (PBP), which is sometimes discounted (DPBP), and Benefit Cost Ratio (BCR) (Bierman 2007, Blanchard and Fabrycky 2011). Often future costs and benefits are discounted to account for the incompatibility between future and current time preferences. Discount rates range from commercial rates that may exceed 10%, to social discount rates, which can grade down to zero. The varying discount rates, time periods, benefits and costs used by different studies makes direct comparison difficult.

Net Present Value (NPV)

NPV is a measurement of the profitability of an undertaking that is calculated by subtracting the present values of cash outflows (including initial cost) from the present values of cash inflows over a specified period of time. Incoming and outgoing cash flows are also known as benefit and cost cash flows, respectively (Bierman 2007). Ideally, the whole of life cycle for the green roof, wall or façade until replacement or major refurbishment should be included.

Internal Rate of Return (IRR)

The internal rate of return on a project is rate of return that makes the NPV of all cash flows (both inflows and outflows) equal to zero (Bierman 2007) and is generally accrued annually.

Payback Period (PBP)

The payback period is the amount of time needed to recover the cost of an investment, usually expressed in years. Longer payback periods are usually considered less desirable for investment. The payback period often ignores the time value of money; i.e. discounting (Bierman 2007), but can also include discounting.

Benefit-cost ratio (BCR)

The simple ratio between benefit and cost calculated using simple or discounted costs and benefits, as per above.

Time period

The time-period chosen for analysis has a large impact on the NPV. A long-lasting green roof will derive more benefits over its lifetime that can be incorporated into the analysis than a short-lived one, particularly if conventional roofs have a shorter duration. Numerous studies suggest green roofs can last 40 years (e.g. Clark et al. 2008), some suggest 60 years (e.g. Acks 2006), whereas the lifespan for a conventional roof is usually found to be 20 years. The most common time period used is 40 years.

Discount rate

Discount rates measure the future value of money as a proportion of its value at the time of investment. The size of the discount rate depends on the rate of return required to justify the investment, the level of risk over time related to the risk tolerance of the investor and the opportunity cost of making the investment (compared to what else funds might be invested in). Commercial, short-lived investments tend to have high discount rates and generally require competitive financial returns, whereas social, long-run investments have lower discount rates and a higher proportion of non-monetary returns (e.g. social and environmental returns).

The discount rate is just as important as the time-period, as a high discount rate will favour projects that have a higher return in a short period of time. Under high discount rates, benefits accruing further into the future quickly trend towards zero. For example, with a discount rate of 10% the present value of $1.00 40 years into the future is $0.02, whereas with a discount rate of 2%, the same $1.00 has a present value of $0.45.

Private or commercial discount rates can reach 10% or more. Public or social discount rates are often applied to environmental projects with irreversible outcomes (e.g. where an ecosystem may be permanently lost or a species becomes extinct) and to intergenerational equity (Cline 1992, Pearce and Ulph 1998, Bateman et al. 2004 and Stern 2007). Both Cline and Stern used rates in the range of 0–2% in assessing the benefits of climate change policy over century-long timescales. Social returns that contribute to human health and wellbeing are also often considered over intergenerational timescales, so green infrastructure projects that contribute to happier, healthier lives would also attract low social discount rates. The UK Treasury Green Book suggests a rate of 3.5% for the first 30 years and declining rates after (HM Treasury 2011), but those rates were still higher than those recommended by Stern (2007).

Social discount rates recommended and applied in Australia are some of the highest in the world (Jones et al. 2015). Australians do not necessarily place less value the future of their environment and society less than others, but when such rates are used it has that effect. The most up-to-date review of the use of CBA in social projects for Australia and New Zealand is Dobes et al. (2016). Social CBA assesses all benefits covering economic, social and environmental areas. This takes CBA beyond the utilitarian concept inherent in much economics, where all benefits across society are boiled down in a single measured of utility, or where direct financial return is measured, as in private industry. They also emphasise that CBA is preferably used to inform, rather than justify, decisions (Dobes et al. 2016). This is consistent with usage elsewhere such as the World Bank (Hallegatte 2011, Hallegatte et al. 2012).

Social cost benefit analysis (SCBA) is more complex to undertake than conventional CBA because of difficulties in assessing benefits, uncertainties about what discount rates to use, a lack of understanding of how to apply CBA in different areas of government and public organisations and different application within those areas if it is used (e.g. transport and health) (Dobes et al. 2016).

The discount rates in studies examining green roofs vary considerably. Acks (2006) used a private real discount rate of 8% for buildings in New York City, and the Treasury Board of Canada (1998) suggested a similar general rate of 10%. These rates are both high compared to what might be expected for social returns.

Estimated net present value and payback periods when comparing green roofs and conventional roofs vary widely. This lack of consistency makes comparison difficult. Differences include factors such as different climates, electricity and gas costs, type and age of buildings, thermal insulating values, time of year of analysis, extensive versus intensive green roofs, annual or life cycle analysis, city or district or individual building. In addition, some studies examined private costs and benefits, others public costs and benefits, and some examined both private and public. As a consequence, for the most part each study must be examined separately.

There is a need to develop standard valuation assessments for all types of green infrastructure, capable of combining commercial and social returns. Ross Garnaut and John Quiggin (pers. comms.) have suggested separately that for public infrastructure, it should be the government bond rate or inflation rate with a 0–1% premium. Privately-financed infrastructure would have higher discount rates but may also want to discount a public component at lower social discount rates, particularly if there is a regulatory requirement mandating green roofs, walls and façades as part of private developments for public benefit.

BENEFITS OF GREEN ROOFS WALLS AND FAÇADES

Ecosystem services have both private and public benefits that can be difficult to separate. For example, a green roof or wall may have private amenity benefits for the occupants of a building and public amenity benefits for those in other buildings or on the street.

Many of the studies identified used a benefits-transfer approach, where values from studies conducted elsewhere (e.g. air pollution removal by vegetation) are transferred to the target location. This is usually done because the collection of local data is resource intensive, takes time and requires established roofs, walls and façades. Models are often used for the same reason. Most studies assessing costs and benefits analyse two or more benefits of green roofs, subtract installation and running costs over a specific time frame to generate a Net Present Value (NPV), Internal Rate of Return (IRR) or Payback Period (PBP).

Studies that address the specific benefits of interest, stormwater, urban heat island, air quality, energy savings, amenity, biodiversity are discussed below to illustrate indicative values for each type of benefit. Combined cost-benefit and life-cycle-analysis studies are explored in this report's section on Green roofs and walls: selected cost benefit analyses.

Stormwater

Most stormwater studies estimating benefits either use an avoided cost approach or are valued according to a fee-based approach offsetting the cost of added flood damage. These fees may themselves be underpinned by avoided cost estimates. Avoided costs can be calculated through damage costs per unit of stormwater or substitution costs for alternative forms of protection. This includes conventional infrastructure, such as higher capacity drainage systems or including other green infrastructure also valued according to cost per unit of stormwater removed.

Carter and Keeler (2008) examined the monetary benefits of stormwater reduction due to green roofs. Modelling an extensive green roof (growing medium 75 mm deep with a water retention capacity of 42.7 L per m2) over a 40-year period. They used cost data from the US EPA in $1999 and found a combination of bio-retention areas, porous pavement, and sand filters would cost US$212.15 per kL of runoff treated. The estimated avoided cost was US$9.06 per m2 of green roof.

Clark et al. (2008) examined the stormwater benefits of green roofs through the reduction in stormwater fees for property owners using data from a number of cities. The average annual fee of US$0.17 per m² for non-permeable surfaces, was halved to US$0.08 per m² per yr assuming a 50% interception rate. They also presented an example of city-wide stormwater benefits by reducing the need for capital expenditure on new infrastructure.

A report for the City of Waterloo (2005) in Canada estimated that the stormwater retention benefit provided by green roofs is worth C$1.56 per m2. They assessed the quality of stormwater by assuming a reduction in the pollutant load of 90%, which would result in a one-off water quality benefit of C$0.49 per m2 (C$4,914 per ha). This report assumed the stormwater retention and pollution benefits to be co-dependent and consequently not additive – we would disagree.

Contrary to this, Banting et al. (2005) considered the water quality benefit to be independent of the stormwater volume benefits and therefore additive. The total value of the benefit, which is a sum of the retention, pollution mitigation and erosion control benefits, lies between C$1.73 to C$27.20 per m2. If all 4,984 ha of flat rooftops in Toronto were covered with extensive green roofs, an estimated one-time benefit worth C$41.8 million and C$118 million in avoided infrastructure costs would be generated (Banting et al. 2005).

For green roofs in Washington DC, Niu et al. (2010) calculated the benefits of stormwater volume reductions between 35–50% through savings from stormwater infrastructure investment and stormwater fees. They concluded the stormwater infrastructure benefits totalled $1.04 million per yr, while fee-based stormwater benefits were $0.22–0.32 million per yr.

We recommend treating the volumetric and water quality aspects of stormwater mitigation as separate and additive benefits, allowing both to be valued independently.

Urban heat island

The most detailed assessments of urban heat islands (UHI) use city-wide climate models to measure the transpirative cooling effect of increased leaf area from green infrastructure. More local studies often use a rule-of-thumb reduction estimated from change in energy balance due to increased transpiration.

Public benefits from a reduction in the urban heat island effect were estimated by Acks (2006), assuming air temperature is lowered by between 0.1°C to 1.5°C with the addition of 50% more green roofs in New York. By incrementally testing sensitivity across a plausible range of change, he found lowering temperatures by 0.1°C, 0.8°C or 1.5°C would reduce summer energy demand by 0.7%, 5%, and 10%, respectively. The benefits were included in a more comprehensive cost benefit analysis described in this report's section on Green roofs and walls: selected cost benefit analyses, but the benefits of cooling with the high-performance scenario were 16 times greater than the low-performance scenario for avoided CO_2 and 29 times greater for reduced cooling demands.

Blackhurst et al. (2010) converted UHI impact of green roofs in a generic US example into reduced energy demand, comparing public neighbourhood benefits to be an order of magnitude higher than private benefits accruing to building owners. Although their assumptions are unclear, the results suggest the indirect benefits through UHI were more than ten times the direct benefits due to energy savings. In studies that assessed the direct energy savings of green infrastructure, Perini and Rosasco (2013) recognized that green walls and façades ameliorated the UHI effect but were not able to quantify it due to insufficient data, as also was the case for Sproul et al. (2014).

Peng and Jim (2015) used microclimate modelling which suggested widespread installation of EGRs and IGRs could reduce neighbourhood air temperatures by 0.65°C and 1.45°C in a population-dense district of Hong Kong. From this, they estimated economic benefits from reduced air conditioner use between US$3.99–8.92 million per yr (Peng and Jim 2015). Razzaghmanesh et al. (2016) used a similar modelling approach for Adelaide but did not calculate the economic benefits of reduced temperatures.

Energy cost savings

Energy cost savings from green roofs is the most frequently examined benefit in the research literature. Depending upon the climate of the area studied, energy cost savings came from either reduced heating or cooling or both. Many of these studies compare air temperature and energy used for cooling and utilised either experimental set ups; e.g. Anwar et al. (2013), Carter and Keeler (2008) and Chan and Chow (2013) or modelling; e.g. Banting et al. (2005), Berardi (2016), Celik et al. (2010), Mahmoud et al. (2017), Peng and Jim (2015) and Sailor et al. (2012). Detailed modelling studies require a great deal of information, so many studies have used simpler rule of thumb models to conduct what is essentially an informed sensitivity analysis.

Acks (2006) estimated that a 5% reduction in energy demand for cooling, would result in total cost savings of $213 million for New York. Berardi (2016) found a green roof retrofit of university buildings in Toronto resulted in a total energy demand reduction of 3%, but also significantly improved indoor comfort levels. Carter and Keeler (2008) had a similar result with a 3.3% energy saving based on university buildings in Georgia, which translated into savings $0.37 per m2. In hot, humid environments Mahmoud et al. (2017) found energy costs savings to be between 24% and 35%. Anwar et al. (2013) found green roofs could lead to a 11.7% energy saving in sub-tropical Queensland. In the Mediterranean climate of Turkey, Celik et al. (2010) estimated that on a resort scale of 10 ha, green roofs could generate savings of over US$2,000 per day.

Castleton et al. (2010) assessed building stock in the UK, finding that older buildings with little insulation benefited most from retro-fitted green roofs in terms of energy savings. New buildings with much tighter insulation building regulations hardly benefit at all. Chan and Chow (2013) set up an experimental green roof to determine which factors contributed most to energy savings. They found thicker soil, shorter plant height and a greater leaf area index were the key factors in cost savings.

Blackhurst et al. (2010) show that different building types, in addition to building condition, have a significant influence on energy cost savings. Ulubeyli and Arslan (2017) reviewed seven studies assessing the energy performance of extensive green roofs, concluding that six provided positive private benefits, and the one that reported negative private benefits (Blackhurst et al. 2010), was positive for both public and private benefits. They also modelled a Turkish extensive green roof using a range of scenarios covering input costs, performance and benefits, applying four valuation methods. The best case outweighed most other studies and the worst case was only slightly negative (Ulubeyli and Arslan 2017). Jayasooriya et al. (2017) found that simulated green roofs and walls in an industrial setting in Melbourne's west saved substantial amounts of energy assuming heating and cooling in the site buildings of 3,324 MWh equivalent to an economic benefit of $1.16 million. This figure is hypothetical, given that many of those buildings host heavy industry and are not heated or cooled. However, it indicates the potential for industrial areas that are being upgraded.

All of these studies found green roofs reduced energy costs; however, they varied in whether the costs outweighed the benefits in isolation from other benefits that were also considered. Some studies concluded that irrespective of other benefits, energy cost savings outweighed the installation and maintenance costs (e.g. Anwar et al. 2013), while others found additional benefits needed to be included if the benefits were to outweigh the costs e.g. (Blackhurst et al. 2010).

The broad findings are that savings are greater in warmer climates and with older buildings with poorer insulation. In the section on economic application, studies that contrast different roof types are summarised, concluding that although white roofs offer greater benefits for energy savings in many cases, they do not offer the other benefits provided by green infrastructure.

Greenhouse gas mitigation and sequestration

The benefits of reducing CO_2 were given low priority in the project brief, but its treatment in the literature suggests that all aspects of CO_2 reduction in the green roof life cycle are worth considering, especially CO_2 offset by energy savings. Energy savings from both direct insulation and indirect air temperature reductions will result in reduced energy use, saving varying amounts of CO_2 depending on the greenhouse gas intensity of the energy supply mix. Energy use in pumping of irrigation systems, and of stormwater disposal if not gravity-fed, needs to be accounted for as a cost in terms of emissions. Direct sequestration of CO_2 will occur through plant growth, only really having an impact in intensive rooftop installations. Alternatively, embedded CO_2 in the manufacture and installation of green roof, wall and façade systems would need to be accounted for and offset before economic benefits can accrue.

Blackhurst et al. (2010) conducted a US-wide assessment that included energy saved via insulation and reduction in urban heat, directly sequestered and reduced sewer outflow pumping for domestic single and multi-family dwellings and commercial buildings. According to their assumptions, the additional floor space under multi-family dwellings and commercial buildings leads to higher efficiency than in single-family dwellings. In all cases they examined, reductions in the UHI reduce CO_2 emissions by more than ten times direct energy mitigation, which was more than ten times greater than direct sequestration through plant growth. In their model, the unit reductions in single-family homes were least due to benefits produced for a single floor, whereas multi-family homes were over four times as cost effective and commercial buildings, twice as cost effective. Embedded CO_2 in green roof materials were 20–30% of the GHG reductions, while embedded energy was negligible.

Hong et al. (2012) analysed sequestration and energy offset CO_2 for schools in Korea, finding that the payback period for a 40-year life cycle analysis came in the 27th year, assuming low market exchange rates for CO_2 permits of US$4.49 t CO_2-e. Deeper pay-offs were possible if double glazing and LED light replacements were included. Payback periods differed according to local climates, being faster in hotter climates. For direct energy savings reducing CO_2 emissions, Nurmi et al. (2016) assumed that because a CO_2 tax had been paid on fossil-fuel-generated power, this expense was already covered. It does not, however, account for any difference between the taxation rate and social cost of carbon, based on anticipated future damages caused by CO_2 emissions.

The impacts of green walls and façades is assessed by Wong and Baldwin (2016) who examine the feasibility of applying a double-skin green façade to high-rise residential buildings in Hong Kong in order to reduce energy consumption for cooling in hot and humid summers. They suggest substantial energy saving is possible, however, these results were not costed. Their analysis suggests that vertical green wall systems can reduce 2,651 x 106 kWh of electric power and 2,200 x 106 kg of CO_2 emissions in a year in Hong Kong.

Biodiversity

As for amenity, few studies attempt to monetise the biodiversity benefit of green roofs, walls and façades. Collins et al. (2017) used a willingness to pay (WTP) approach to determine a value of biodiversity. Aggregating various scenarios, the WTP estimates across the entire region of Southampton covering over 90,000 households, produced total annual WTP of £5.2 million for a living wall policy that increased biodiversity, and £4.8 million for a green façade policy. In some jurisdictions where the construction of green roofs is mandatory, performance measures have been developed that require permit applicants to demonstrate compliance with green roof designs that provide habitat for endangered species, e.g. Black Redstart, a small UK bird listed as endangered in the Red List of Birds of Conservation Concern. The intrinsic value of biodiversity is reflected in these planning controls. These qualify as institutional values and can be considered in any assessment.

Health and wellbeing

Heat stress

Heat stress is associated with poor building insulation and demographic vulnerabilities such as age, poor socio-economic circumstances, pre-existing medical conditions such as heart, respiratory and kidney disease and poverty, especially homelessness and energy poverty, and occupational exposure. When combined with high summertime temperatures as in Melbourne, and the UHI effect, vulnerable populations face higher levels of risk than the general population (Bambrick et al. 2008, Loughnan et al. 2012, Loughnan et al. 2013). As a rule, the health implications of heat stress have not been factored into economic assessments of green roofs, walls and façades, although they have for retrofitting building insulation (Alam et al. 2016, Barnett et al. 2013, Ren et al. 2014).

Economic assessments are based on avoided lives lost, often with a dollar value for Value of Statistical Life estimates or Quality of Life Years, two health and mortality measures (Abelson 2008). van Raalte et al. (2012) estimated emergency presentations and mortality for single and three consecutive day events over 30°C for the City of Melbourne. They estimated a total cost in 2012 of $7.2 million and an incremental cost of UHI of $2.2 million for heatwaves and $19.7 million and $2.6 million UHI cost for single days above 30°C. UHI estimates were roughly 0.5°C at 40°C and 0.8°C at 30°C. This suggests that with more reliable and up-to-date data, an estimate of UHI benefits from green infrastructure could be calculated.

Air quality

The Urban Forests Effects (UFORE) model was developed in the 1990s to evaluate health benefits of pollution removal from urban forests associated with nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), particulate matter of 10 micrometres or less (PM10), and ozone (O_3) (Kowal 2008). The UFORE model estimates pollution removal capacity of plants and associated economic benefits (Nowak and Crane 1998). Currie and Bass (2008) used this model to estimate the potential for pollution reduction in Toronto, finding that while trees have the highest capacity to mitigate pollution, shrubs and grasses (more prevalent on green roofs and walls) also have a significant effect. However, the analysis was carried out on LAI index and not leaf absorption properties. Covering all flat roofs (approximately 20% of the study area) by extensive green roofs would result in US$17,481 in avoided health care costs. Converted to an annual city-wide figure for Toronto would result in US$0.04 in avoided health care costs per additional m² of green roof (Banting et al. 2005).

Clark et al. (2008) examined the economic impacts of nitrogen oxides (NOx) uptake by a green roof scenario for the University of Michigan. Uptake rates were based on Morikawa et al. (1998) then translated into health benefits using methods developed by the US EPA. Avoided deaths and cases of premature bronchitis translated into benefits of between $1,680 and $6,380 per t. For 35 ha of modelled roof cover at the University of Michigan, 94.31 t NOx per yr could be removed from the air providing an estimated public health return between $158,720 and $601,930 per yr.

Niu et al. (2010) examined air pollution from an avoided costs and pollution interception perspective. Avoided CO_2, NOx and SO_2 emissions were based on reductions in electricity and natural gas consumption to quantify the NOx uptake by green roofs. The scale was informed by the 20-20-20 vision of 20 million ft² for green roofs in Washington DC by 2020. Using US EPA health models, benefits in the order of US$0.09–0.41 million per yr were identified.

For the avoided pollution benefits of SO_2, NO_2 and PM10 from the Peng and Jim (2015) study of Hong Kong mentioned in the previous section, the overall monetary benefits were US$0.75 million and US$1.15 million for extensive and intensive green roofs per yr, respectively.

Welfare benefits from avoided pollution can be measured as general welfare that comes through wellbeing and liveability benefits. For air quality, two key US studies have assessed willingness to pay to have clean air and self-reported happiness correlated with air quality. Bayer et al. (2009) estimate marginal willingness to pay given a wide range of variables on household income and air quality measured as PM10 levels. Lower income is associated with higher pollution areas after a range of confounding factors have been allowed for. They factor in the price of moving from one location to another as not being a 'free' service of exercising the choice of moving to a clean air location. The result is expressed as a cost of household income for a 1 µg per m³ reduction in PM10 (US$149 to US$185 in 1982–1984 prices).

Levinson (2012) used self-reported happiness and income data as a function of air pollution to derive a hedonic (shadow) price for pollution. This was converted into a factor of median household income per 1 µg per m³ reduction in PM10. By explicitly linking happiness to income and unhappiness to short-term pollution events, this study derives a hedonic value for wellbeing based on pollution levels. These studies did not look at green roofs but were utilised to estimate benefit transfer to value air quality interventions by Jones and Ooi (2014), discussed in this report's section on Health and Wellbeing.

Amenity

Visual amenity

Few studies have directly quantified the visual amenity benefit of green roofs, most relying on benefit transfer. A research report for the City of Waterloo (2005) derived an amenity value by considering it to be the same as a park or passive recreation area, combining both viewing and visiting amenity, allocating a value of $0.14 per square foot (approximately $4.40 m²). For example, the green roof on a library in Vancouver was designed to provide a visual amenity for occupants of surrounding office buildings (Peck et al. 1999). MacMullan et al. (2008) record that rooms at a local hotel beside a 200 m² green roof were $80 more per night than comparable rooms without the view. This equates to an annual figure of $29,000 per room, assuming 100% occupancy rates.

For city-wide assessments, Acks (2006) produced preliminary data based on assumed low, median and high values of willingness to pay by adjacent residents of $10, $20 or $50 for instalment. The probabilistic cost benefit analysis undertaken by Bianchini and Hewage (2012) used ranges of 2%–5% for extensive and 5%–8% for intensive roofs. Both sets were based on assumptions based on ranges taken from literature survey.

Nurmi et al. (2016) provide the most detailed treatment of visual amenity located. They use apartment prices in Helsinki to estimate the value of property in proximity to open space. They use evidence of preference for green space from the literature and for welfare benefits to construct a relationship between proximity, value and park size. Subtracting small parks from that relationship gave them a value of 0–1.25% m². Average viewing radius was calculated from GIS as 30 m. They concluded that the value of a small park was €130 per m² for a radius of 30 m. The value attached to a small park 30–50 m was €20, which was interpreted as the value for visiting. Given that rooftops can be seen but not visited they assumed that the residual (€130–€20 or €110) within 30 m was the viewing radius. In percentage terms, this ranged up to 2.3% of property price, but allowing for the limitations of rooftops on lines of sight, this was reduced to 1.2%.

Sound attenuation

Although sound attenuation was not on the priority list, it is becoming an important part of the general amenity of green walls, façades and roofs, particularly in regions such as the EU where sound regulations are in place. Sound attenuation by green roofs, walls and façades occurs through absorption and diffusion in terms of reflected sound and absorption through transmitted sound, where the installation acts as a barrier.

Costing for sound has been on the basis of annoyance, where a value is allocated per dB. Amenity benefits can provide the upside of that, where noise is below nuisance level but provides amenity contributing to mental health and general welfare, where a courtyard or roof provides an oasis from the broader noisy city environment (Veisten et al. 2012). Having a noise oasis or refuge on one side of a dwelling is seen as three to five times as beneficial as reducing noise on the noisy side as measured in dB. Applying a model to simulate green façades in a European example, Veisten et al. (2012) estimated that a welfare benefit of €2.47 per m^2 provided mostly positive returns using a Monte Carlo cost benefit analysis allowing for input uncertainties, whereas a low-end value of €1 per m^2 was marginal.

Property value including public benefit

While many studies show green infrastructure has a positive effect on value and marketability of buildings, this benefit would be expected to accrue to both the owner(s) of a building with a green roof, wall or façade and to the owners of surrounding properties. Direct benefits are usually carried out by direct survey of buildings with and without green infrastructure, but proximate effects are usually assessed using hedonic valuation techniques.

These are used to measure the relationship between the selling price of a residence and its distance from an urban greenspace, park, community garden or wetland. The positive relationship between the value of a dwelling and its distance from green infrastructure is called the proximity principle (Edwards 2007). This phenomenon is well studied, dating back to Olmsted in the 19th century who examined Central Park in Manhattan (Olmsted 1865). The proximity principal suggests that the value of green infrastructure is captured in the price of surrounding real estate as well as property taxes.

Mahmoudi et al. (2013) calculated values per metre distance from a variety of different types of open space in Adelaide using house price data collected during the 2000 Millennium Drought, showing that benefits to house prices were strongly nonlinear. They accounted for a wide variety of confounding factors in the analysis pertaining to property features affecting house price and other proximity effects both positive and negative. The size of benefits depended on the type of open space. Sports areas, linear parks and manicured areas were positive and natural areas such as national parks were negative, speculatively due to fire risk, aesthetics and snakes. A square metre of private open space added $17 to the value of a median-sized house whereas a square metre of building added $810, so building capital is much more highly valued than private open space. For public open space, for a simulated example of expanding a pocket park of 0.4 ha to 1, 2 and 3 ha, the benefit to capitalised value was estimated at about $160 per m^2 (Mahmoudi et al. 2013).

Most studies valuing the benefits of green roofs on property prices use a benefits-transfer approach using results from the hedonic valuation of other green infrastructure. For example, Tomalty et al. (2010) suggest the value of buildings with green roofs can be compared to that of buildings with conventional roofs while controlling for other variables known to affect property prices. They considered a specific type of green roof; e.g. recreational or food garden, could be matched with similar green infrastructure where a recreational space would be considered equivalent to a park and a food garden equivalent to a community garden. Due to access, these benefits would not advantage the public at large but rather the occupants of the building only.

Tomalty et al. (2010) draw on several studies to estimate green roof property benefits. Taking the suggestion from Crompton (2005) that homes adjacent to public parks have about a 20% higher property values than similar homes distant from parks, and removing a view benefit of 9%, the focus on the residual 11%. For productive rooftop gardens, this was based on Voicu and Been (2008) who found that, on average, properties abutting typical community gardens increased in value by 7.4% by five years after the construction of the garden. To measure the proximate benefits, Tomalty et al. (2010) used values based on Wachter (2004), where street tree planting increased the value of a property by 9% but restrict the estimate to green roofs with trees. They suggested this could also be used to capture value for multi storey-dwellings where only the apartments facing the green roof have an increased value.

Table 1: Property value estimates, green roof/wall converted to unit value per m in $A 2015 (adapted from Veisten et al. (2012).

STUDY	YEAR DATA	COUNTRY DATA	PROPERTY PRICE	GREENERY % VALUE	GREENERY SIZE (m^2)	UNIT VALUE (per m^2)
Peck et al. (1999)	1999	Canada, Toronto	C$230,000	10.50%[1]	50	$537
Hunt (2008)	1999	Canada, Toronto	C$230,000	9%[2]	50	$460
Gao and Asami (2007)	1999	Japan, Tokyo	¥602,400	1.40%[3]	25	$5
	2003	Japan, Kitakyushu	¥73,200	2.70%[3]	25	$1
Ichihara and Cohen (2011)	2000	US, New York	US$73,024	16.20%[4]	50	$429
Des Rosiers et al. (2002)	1999	Canada, Québec	C$112,000	3.90%[5]	50	$97
Tomalty et al. (2010)	2010	Canada, Toronto	C$395,460	20%[6]	50	$1776
	2010	Canada, Toronto	C$395,460	7%[7]	50	$658

[1] Estimated as equivalent to 'good tree cover' 6–15%, midpoint 10.5%

[2] Estimated premium 3–15%, midpoint 9%

[3] Green walls and façades scenarios tested with estate agent valuers

[4] Rental survey converted into property price.

[5] Houses with hedges (green walls)

[6] Recreation roof garden (intensive), based on Crompton (2005)

[7] Productive roof garden (intensive), based on Voicu and Been (2008)

Table 1 lists the results from a number of studies from Veisten et al. (2012), converted into value estimates per m^2 in A$2015. In a survey of rental prices in New York, Ichihara and Cohen (2011) found that rental prices in green roofed apartments in the Battery Park Area were about 16% higher than without. This was converted into a property price by using expected price/equity return on rental income (Veisten et al. 2012). Note that the lowest three estimates are for green walls or façades, whereas the others are for green roofs or their proxies. The median estimate, taking out the lowest three and the highest value is A$498 m^{-2} in 2015 currency.

Green roofs and walls: selected cost benefit analyses

Below are summarised a range of cost benefit analyses on green roofs, walls and façades with an emphasis on research undertaken in the last 10 years.

Clark et al. (2008) analysed stormwater benefits, energy savings and air pollution reduction (nitrogen oxide) on a per unit basis for a case study based on buildings in the University of Michigan and then undertook a probabilistic cost benefit analysis. Their approach was to determine the length of time required for a return on investment in a 2,000 m^2 green roof (40-year lifespan) using a NPV analysis using a discount rate of 5%. They compared this with a conventional roof (20-year lifespan) and found over a 40-year time frame the green roof had a better NPV of between 25% and 40%. This benefit was calculated as a private benefit to the owner of the building.

Niu et al. (2010) extended this study using the same methods for calculating costs and benefits but extended the analysis to the city-wide scale for Washington, DC, which was used as a test bed because of the proposed targets in the 20-20-20 vision (20 million ft^2 by 2020). Both recurring (Stern et al. 1999) and one-time (capital outlay) benefits were incorporated in their 40-year NPV analysis, and they also assumed a 20-year replacement for conventional roofs. Their analysis incorporated stormwater operational savings, avoided pollution emission benefits, and stormwater and energy infrastructure investment reductions. The latter would result in a further improvement of the NPV of the green roof by approximately 5–15%, the uncertainties being due to experimental or modelled NO_2 uptake. Health benefits from air improvements influenced the breakeven period prior to roof replacement, the most optimistic estimate having green roofs break even 7 years before conventional roofs. They suggest energy-related savings and stormwater reduction benefits have the greatest impact on NPV.

Zhou et al. (2017) used the City of Portland EcoRoof Evaluation unit values for energy savings, air quality, habitat provision, recreation space, food production, reduced flood risk over a 10-year analysis, benefits using 3% annual interest. They found green roofs reduced annual water yield by 22% for residential buildings and 49% for non-residential buildings and massively increased nitrogen and phosphorus retention leading to annual benefits of between US$390–$402 million. However, as most of these benefits accrued from non-residential buildings, they suggest commercial and public buildings should be the focus of green roofing projects.

Banting et al. (2005) estimated the initial and annual benefits of city wide scale of extensive green roof installation for Toronto. The total available green roof area city-wide was 5,000 ha. Initial savings, those savings generated by the installation of green infrastructure, either reducing damages or forgoing other infrastructure costs, were US$313 million. Annually recurring cost savings due to air quality improvements, energy savings and reduced CO_2 emissions were US$37 million per yr. This study can definitely be seen as a forerunner of the current study being undertaken here.

Sproul et al. (2014) analysed the relative benefits of white, green and black flat roofs in the US. Their analysis incorporated life cycle costs over 50 years with green roofs replaced after 40 years and white and black roofs replaced after 20. They included roof installation, replacement and maintenance, energy-related benefits (cooling/heating costs, A/C downsizing, peak saving), avoided power plant emissions (CO_2, NOx and SO_2), equivalent CO_2 offset by albedo changes and stormwater-related benefits (reduced fees and installation costs). They did not examine urban heat island mitigation, biodiversity, air quality, CO_2 sequestration, or increased property value as they considered these effects to be small or too difficult to measure.

Sproul et al. (2014) found that relative to black roofs, white roofs provide a 50-year net savings of $25 per m^2, while green roofs have a cost of $71 per m^2. They suggest that despite the longer lifespan of green roofs, their benefits do not overcome the additional installation costs. Directly comparing white roofs to green roofs, the 50-year net saving of white roofs is $96 per m^2. The annual difference is $3.20 per m^2 per yr. They conclude white roofs are three times more effective than green roofs at mitigating global warming, however, if local environmental benefits are considered then green roofs are preferable due to their stormwater management and aesthetic qualities. These conclusions are inconsistent with Niu et al. (2010), Clark et al. (2008) and many other studies, but do accord with other studies weighted towards energy savings, where white roofs are most cost effective.

For example, Sailor et al. (2012) used the EnergyPlus building energy simulation program to analyse the effects of green roofs on energy consumption, comparing 9 variations of green roofs to black and white membrane control roofs. Their investigations included 8 buildings – new office and new multi-family lodging buildings in 4 cities representing diverse climatic conditions: Houston, New York, Phoenix, and Portland. Building energy performance of green roofs improved with increasing soil depth and leaf area index. They found heating energy savings were greatest for lodging buildings in colder climates while cooling energy savings varied for the different building types and cities. However, in all cases a baseline green roof resulted in a heating energy cost savings compared to the conventional black membrane roof. Despite this, in 6 of 8 buildings the white roof resulted in lower annual energy cost than the baseline green roof. In terms of total energy use, green roofs performed best in colder climates in buildings that require night-time heating.

Acks (2006) conducted an exploratory cost benefit analysis for green roof development in New York applying two scenarios: (1) a 75% coverage of an average flat roof and (2) a 50% take-up of available flat roof space (public) in New York City. The benefits public and private were split across two tiers, Tier I effects were examined in the New York study of Rosenzweig et al. (2006) and Tier II included preliminary estimates of a broader range of benefits. The scenario lifetime was 55 years. Scenario 1 was private with an 8% discount rate and Scenario two was private and public with a 5% social discount rate. Both assumed an inflation rate of 3% (resulting in total rates of 11% and 8%). Performance was rated as low, median and high benefits, and high, median and low costs. The benefit cost ratio was only positive for the private scenario under high performance and for the public scenario at medium performance when both Tier I and II public and private benefits were added. The BCR for the public scenario was 1.02 for both Tier I and II for moderate performance but was 3.87 for high performance (Acks 2006).

Mahdiyar et al. (2016) examined the cost benefit analysis of green roofs from a strictly private perspective. This included the installation, operation and maintenance costs and energy saving, sound attenuation and property value benefits. They used Monte Carlo simulation to generate both an NPV and PBP utilising a benefits-transfer approach using prior studies to obtain unit values. They applied high discount rates of between 8–15%, thus treating green roofs as a purely commercial concern. Using this approach, extensive roofs had a higher NPV than intensive roofs, and the probability of loss when selling the property is higher than a gain for both intensive and extensive green roofs, depending on input assumptions and performance.

Mahmoud et al. (2017) examined the private costs and benefits of installing different types of green roofs on a 4-bedroom house in the Middle Eastern climate. They analysed energy savings, installation and maintenance costs and compared these with a conventional roof. As with many studies, the lifespan for the green roof was 40 years and 20 years for the conventional roof. They found energy savings for green roofs to be in the range of 24% to 35% that translated into a positive NPV but only at the end of the 40-year timeline. In a similar climate, Celik et al. (2010) found that a pilot region with 99,440 m2 roof areas in the Aegean region of Turkey would generate daily energy savings of $2,188 by whole-site roof greening within the pilot region.

Carter and Keeler (2008) used experimental extensive green roofs at the University of Georgia and found them to have an NPV 10–14% less than conventional roofs. They used the 40:20-year green–conventional lifespan. They examined energy savings, stormwater benefits, air quality improvements (NOx) and omitted UHI effects or property value increases. Using a 4% discount rate, their analysis showed that varying market conditions have a significant influence on whether green roofs have a positive NPV. They point to the experience in Germany where costs are much lower than the US due to the maturity of the industry.

Kim et al. (2012) developed a model for optimal selection of green roofs for elementary schools in Korea considering both economic and environmental factors. They analysed three soil types and five plant types and their respective life cycle CO_2 absorption characteristics. These characteristics were converted to monetary values using emission reduction carbon credits. They found that when only considering local private costs, conventional roofs performed better economically. However, when the life cycle cost analysis that included the environmental value of emissions credits were included then six of the fifteen scenarios were superior economically ranging from 6.4% to 11% higher returns.

Peng and Jim (2015) focused on the climate-related benefits of intensive and extensive green roofs in Hong Kong. They studied six benefits including thermal insulation, urban heat island mitigation, avoided CO_2 emissions, air pollution and greenhouse gas sequestration. They compared extensive and intensive in terms of annualised costs and benefits as well as life cycle cost effectiveness on a district scale. Their results suggest that green roofs can significantly reduce energy consumption and avoided CO_2 emissions if installed in a widespread fashion. For the study area of Yau Tim Mong (150 ha) in Hong Kong, extensive green roofs had a potential value of US$10.77 per m^2, and a benefit cost ratio of 3.84 with a PBP of 6.8 years. Intensive green roofs. Intensive green roofs had a BCR of 1.63 and a PBP of 19.5 years. The economic evaluation is based on the unit figures in Carter and Keeler (2008), Celik et al. (2010), Tomalty et al. (2010), Bianchini and Hewage (2012), and Chan and Chow (2013).

Chan and Chow (2013) modelled future climate scenarios in their analysis to determine the best performing characteristics of green roofs. They found a combination of thicker soil layer, lower plant height and higher leaf area index (LAI) give better thermal insulation of green roofs. Their results show a LAI of 5 can maintain the year-round energy consumption from air conditioning similar to or less than current levels, ranging from -2.4% to -10% under future climatic conditions (2011–2030 and 2046–2065, for two emission scenarios). This generated a PBP of approximately 10 years.

Anwar et al. (2013) focused on measuring/determining temperature profile and air conditioning energy savings by implementing rooftop greenery systems in subtropical Central Queensland. An experimental set-up was installed at Rockhampton campus of Central Queensland University, where two standard shipping containers were converted into small offices, one with a green roof. Temperature differences of up to 4°C and energy savings of up to 11.7% can be achieved in March in the subtropical Central Queensland climate.

One of the few studies to undertake an economic analysis of green walls was performed by Perini et al. (2017), although with data only for a single year. They undertook field monitoring in Mediterranean climate with a green wall to mitigate outdoor and surface temperatures, improve comfort conditions and reduce building surfaces warming (contributing to urban heat island mitigation). They found a theoretical energy saving potential for air conditioning of 26% for the summer season. Manso and Castro-Gomes (2015) point to the great differences in costs with green walls and façades, outlining the need to align costs with purpose and benefits. The significant savings in energy consumption and greenhouse gas emissions by Wong and Baldwin (2016) above suggest that significant savings can be made by systems with appropriate design.

ECONOMIC APPLICATION

The following headings cover a range of potential economic applications for key areas identified in the brief. Also included are other benefits identified within the literature survey that may have sufficient technical and economic information to provide a basis for valuation now or in the future.

Stormwater

Flooding

Green roofs have two economic indicators commonly used to measure reduced flood risk: water volume and peak flow. Note that flood risk in this context deals with flash flooding from extreme rainfall. Riverine flooding and storm surge in the Yarra River is not materially affected by runoff from the City of Melbourne. The exception is when heavy rainfall within the city area coincides with a storm surge/riverine flood within the Yarra River and backs up through the city. In that case, limiting flooding from within the city will be at a premium, but it is a complex event with no recent analogue, so is not part of standard flood modelling that calculates potential damages. However, it remains a plausible scenario.

Values for urban flooding are generally calculated through the following relationships:

- Water volume: reduced flood damages, often calculated through annual average damage (AAD) curves related to specific levels of damage.
- Peak flow: avoided infrastructure upgrades.

This separation is somewhat artificial, as floods are a combination of rate and volume of flow, but damages within local urban catchments are most suitably scaled by volume (flood frequency and size) and infrastructure needs by peak flow. Because catchments differ the world over, local damage estimates are greatly preferred to benefit transfer from elsewhere.

Flood damages can be costed in too many ways to detail here but having some kind of flood frequency/severity relationship with accompanying damages is the ideal baseline economic data for assessment. Most green roof studies use a value per volume relationship as seen in this report's section on the Benefits of green roofs, walls and façades. These are costed in two ways:

1. Through explicitly costed damage on infrastructure, activities and people, or
2. Through flood offset schemes where a charge per volume generated or area of development/ hard surface is set. This is the case for new developments in mid to outer Melbourne, but not for established suburbs, despite ongoing catchment modification.

Flood average return intervals (ARI) have been calculated for all catchments in the City of Melbourne by Melbourne Water. These extend from return periods of less than a year to a rated probable maximum flood. From these relationships, Melbourne Water has calculated AAD rates. Damage rates depend on the condition of the catchment, its hard surfaces and stormwater infrastructure, beginning to accrue costs when water affects services or damages people or property. In the most vulnerable catchments this may start at ARIs of <5 years. Melbourne Water is in the process of building AAD tools for all Melbourne catchments. They contribute to plans for removing damages for ARIs of ~10 years and longer, which will reduce AAD substantially.

The Integrated Climate Adaptation Model (ICAM) has been constructed to assess the benefits of a wide range of interventions within the City of Melbourne (Kunapo et al. 2016). The potential for the addition of green roofs as an adaptation has been included in the model. It measures flood depth velocity and hazard, on a 1%, 2%, 10% and 20% annual exceedance probability. For interventions such as green roofs, ICAM uses flood volume as a measure, having determined volumetric reductions for key subcatchments within Melbourne. Model input is a 100-year record of climate from the Bureau of Meteorology's (BoM) Melbourne Office and, on an event basis, the BoM's Intensity Frequency Duration (IFD) data for Melbourne.

Reducing flood volume by intercepting precipitation and/or stormwater either directly or indirectly (e.g. by tanks used to irrigate green roofs or walls) will reduce the AAD across much of the flood damage curve. The reduction in AAD can be measured in volume where flood studies have been undertaken. This will provide a value for intercepted water of dollars/volume/time, often $ per kL per yr. Total AAD in Pt Phillip region is $399 million (from Melbourne Water).

In a sensitivity test for indicative benefits for stormwater interception from green roofs in Melbourne, we used previous work on the Elizabeth St catchment, combining data from GHD (2014) and Melbourne Water. GHD studied the Elizabeth St catchment as part of their green roofs survey for the City of Melbourne (GHD 2015). An earlier study had modelled 6.8 ML storage needs to take flood ARIs from 2 to 5 years at Therry Street and 10 to 20 years at Bourke St (GHD 2014). Total retention needed in catchment from the CoM 2015 Elizabeth St catchment management plan is 25.4 ML.

GHD (2015) modelled two sets of nominal interception rates: 0.035 kL per m² (0.35 ML per ha) for extensive roofs and 0.18 kL per m² (1.8 ML per ha) for intensive roofs. They also modelled suitability gradings of available rooftops for extensive and intensive green roof instalment. The Elizabeth St catchment contains 40.5 ha of rooftops suitable for extensive green roofs with no constraints and 25 ha with low constraints. Added together, these would intercept 23 ML stormwater per yr. This is close to the catchment plan target reduction of 25.4 ML.

For example, if the Elizabeth St catchment AAD is assumed to be $1.5 million and stormwater management reduces it to $0.5 million, then the value of the water would be $1.38 kL and $7.09 kL for extensive and intensive roofs respectively, assuming that 23 ML is sufficient to reduce AAD by $1 million pa (This is assumption is made to test sensitivity). For a 40-year green roof life cycle, discounted at 2.5%, the value becomes $35.53 per m² for extensive roofs and $182.43 per m² for intensive roofs. City of Melbourne's current valuation for stormwater interception is $2.12 per kL, so that would convert into a lifetime benefit of $44.05 per m². It is likely that this value of $2.12 per kL is on the low side, so a readjustment would probably result in a higher benefit. However, to come up with a more accurate assessment, the catchment AAD needs to be known, in addition to the volumes needing to be intercepted to reduce flood damage. This would need to be carried out for each catchment within the city. Given that the damage costs for Elizabeth Street are likely to be higher than in most other catchments, stormwater interception in those catchments would produce lower returns.

A more accurate assessment would require assessing standard physical attributes of intensive and extensive roofs that would be installed and assessing field capacity of the substrate and typical LAI of vegetation (see Part 1). Seasonal estimates of field capacity, given antecedent soil moisture and interception by vegetation will then provide an estimate of interception rates. These can be calculated using a simple moisture balance model using inputs of rainfall and evapotranspiration. Each catchment within the council area will need to have reduction in AAD calculated as a function of reduced flood volume.

For green walls and façades, there would be no rating for stormwater interception. Although they will both intercept some rainfall, this depends strongly on wind speed and direction and is difficult to quantify on a routine basis.

Peak flow

To value peak flow, it is important to ensure there is no double counting with any value calculated for reduced flooding volume. The aim of managing peak flow is to reduce the speed and height of the flood, and the conventional measure is to build larger stormwater drains. One way to value peak flow is to calculate the avoided costs of drainage upgrades. By valuing peak flow according to avoided infrastructure upgrade costs and flood volume is valued according to avoided flood damages double counting can be avoided. Peak flow can be measured through percentage change (simplest) to delay in peak volume (most accurate).

Peak flow is calculated using rainfall-intensity duration data and design floods. If flood modelling has been carried within a subcatchment, the point where infrastructure capacity is exceeded by the size of flood peak is an important threshold. There may be several such thresholds if street intakes and larger pipe systems provide different levels of capacity. Flood modelling in selected catchments was carried out for the ICAM work, but data is not available for the whole city area. Other than that, peak flow is not being explicitly measured at present within any applications for flood management as far as we can determine, although it is used for infrastructure design.

Water quality

As described in Part 1, green roofs can be a nutrient source or a sink depending on a range of variables including medium composition, depth and structure, vegetation composition, rainfall rates and fertiliser levels. The baseline level is provided by cyclic salts contained in rainfall, with nitrogen (N) being the major pollutant. Roofs can also be sources of pollutants from deposited aerosols due to human activity, so removing these will be an added benefit, but currently such contributions are not being measured, so are hard to cost.

Although green roofs can take up a wide range of pollutants, generally N and phosphorus (P) are the only two that are routinely costed. N interception valued at $6,645 per kg by Melbourne Water based on the cost of extracting N as part of water purification, preventing its entry into streams and Port Phillip Bay. In most cases, rates and standards will need to be set for green roofs in Melbourne so that positives and negatives can addressed.

- A key aim of water quality policy for Melbourne's waterways is to prevent additional sources of N and P entering into the stream and river system. If other green infrastructure that has been installed with the purpose of removing nutrients then has to deal with extra nutrients, the investments in nutrient removal would have been wasted.
- If water coming off green roof is carrying pollutants sourced from fertilisers present in the growing media or provided through 'fertigation' (water containing fertilisers as in hydroponic systems), and enters the stream system, then this will count as a negative. If it removes pollutants deposited as aerosols contained in rainfall and from human-generated sources, this is a positive.
- Runoff from green roofs, if managed appropriately, may be suitable for irrigation of other areas, such as green walls, façades and ground-based irrigation. This could be a net benefit if substituting other water. Likewise, runoff from green walls can also run into ground-based systems, such as raingardens.
- As detailed in Part 1 careful selection of fertilisers, additives such as biochar and vegetation can ensure that N and P deposited in rainfall and as dry deposition from pollutants are absorbed and/or used by vegetation. Closed nutrient cycles and interception of pollutants that otherwise would enter waterways will remove this from the water cycle. Using the interception value of N above on deposition rates estimated for Port Phillip Bay (Carnovale et al. 1992), suggests a range of \$2.75 to \$4.50 per m^2 per yr. Using deposition rates from the Dandenong Ranges (Lansdown 2009), this figure would be \$4.00 per m^2 per yr. Any pollutants from urban sources (e.g. vehicle exhausts) would be additional to this, so these estimates can be considered a minimum.

Water supply

Water supply from green roofs and walls can be valued if it substitutes for an alternative supply. Additional storage to supply a green roof should be costed into the roof itself as should all ongoing maintenance to keep the roof, wall and façade in good condition. This is an essential part of life cycle cost assessment. However, if the water captured genuinely substitutes for water that would have been supplied from a different source (e.g. potable water), then it will provide a net benefit.

Substituted water can be costed according to retail price for water of a similar quality (i.e. not costing non-potable water by potable water prices), or by calculating the cost of storage and distribution. This would contribute to the life cycle analysis of a single roof, wall and façade project. The choice for the first would be if the water is being supplied by a retailer, and for the second, if it was used to supply nearby green infrastructure being as an additional measure (which is at-cost delivery). More complex systems may require the use of electric pumps, which may then need greenhouse gas emissions to be factored in if the power is generated by fossil fuels.

Urban heat modification

Heat modification through increased shade, changed albedo and increased evapotranspiration has a local effect in the vicinity of the roof, wall or façade. The physical benefit of heat modification on the UHI is that buildings and surfaces do not warm so much during the day or radiate so much heat at night. The literature suggests this effect is small during the daytime (perhaps up to about 0.8°C) but can be widespread if green roofs, walls and façades cover a large area. Green walls and façades can significantly reduce temperatures at street level and in courtyard settings.

Widespread evapotranspirative cooling can occur when green roofs and walls, and the tree canopy connect to the point where the plants dominate over the gaps between them. At that stage, vegetation will begin to influence the urban climate more than buildings and roads. Taleghani (2017) cites one study for Los Angeles that modelled green roofs on two-storey buildings over a 0.3 km^2 area that produced no street level change in heat and another for Chicago in summer that modelled an area of 606 km^2 reducing temperatures during 19:00 to 23:00 hours by 2–3°C.

Although white roofs can be more efficient from private returns on investment at the building scale, green roofs provide a much wider range of benefits, including areal cooling. However, increasing the albedo of dark pavements on the ground will provide a cumulative benefit where green roofs are being added to buildings.

Some simple rules of thumb and energy balance models can provide a back of the envelope difference in temperature using straightforward environmental models. For example, Acks (2006) used a simple linear scale to estimate the benefits of urban heat modification – most costing models have used similar techniques. The study by Sun et al. (2016) for greater Beijing shows this to be a reasonable first-order approximation. However, for the best results and to provide data that can be used for other purposes, such as calculating human comfort indices and pollution loads in a changing climate, initialising and running an urban climate model would provide the greatest long-term investment. Melbourne's environmental and resilience strategies are designed to have a cumulative effect, and in the long-run, only an integrated model will be able to simulate that effect.

Heat stress and mortality models used to project future deaths within the municipal and Melbourne-wide context under a changing climate are still deficient, underestimating the potential for statistical anomalies such as the February 2009 heatwave, for instance. Recent research into heatwave effects in Melbourne and elsewhere suggest that building an improved relationship between daily heat and comfort indices modelled by the excess heat factor recently developed by the Bureau of Meteorology (BoM) can provide data for estimating mortality, emergency presentations and general levels of comfort (Nairn and Fawcett 2014, Scalley et al. 2015). Currently, a scoping study on the economics of changing health due to climate change is being conducted for the Victorian Department of Health and Human Services.

A comprehensive valuation of benefits for human health and wellbeing arising from urban heat modification would cover:

1. Avoided mortality.
   Benefits can be assessed through value of statistical life methods and quality-adjusted life year methods (Abelson 2008, Access Economics 2008).
2. Avoided emergency admissions and hospital stays that can be assessed as money saved, and
3. Reduced hours over a given threshold of human comfort in:
   a. Unairconditioned buildings where hours of discomfort can be estimated by energy star or building quality ratings
   b. Time spent at street level.

One the technical side, the following methods can be applied to model levels of exposure to heat or discomfort:

1. Microclimate models that work at the fine scale – street level and at elevation using a very fine scale climate model and building surface data base.
   - This is best for yielding detailed results on modelling walls and façades.
2. Urban climate models, which are not as high resolution and can use surface and roughness or building databases with surface characteristics, but may omit microclimate in street canyons, etc.
   - These can also estimate air pollutant distribution and loads.
3. Surface energy balance modelling uses simplified relationships to measure changes in albedo and transpiration rates.
4. Simple rules of thumb derived from any of the above.

Additionally, the City of Melbourne's ICAM model also includes a shade function that can modify ground temperature, which is suitable for intensive green roofs and roof gardens, but not walls or façades.

Energy savings for heating and cooling

Green roofs and walls add insulation to buildings by preventing heat loss/gain. This can be measured to lost heat per area but is ideally converted to change in kWh per day or a similar measure. In addition to direct monetary savings via reduced power bills, monetary savings would also occur, should a levy or tax for emitting carbon be introduced.

Green roof and wall insulation can be converted into the standard R system and/or used to alter a building's energy star ratings if the addition is large enough and the greening asset is appropriately maintained to ensure the ongoing survival of plant species. Note though that they can have different effects to standard insulation, which is sometimes an advantage, mostly in summer, but occasionally not.

Commercial buildings are recorded by the Valuer General Victoria and also in the council database CLUE (Davis Langdon Australia Pty Ltd 2013). These generally have construction dates recorded and are graded from premium through to D, but only those over 2,000 m^2 in area are subject to mandatory disclosure. The average life cycle of services is given as 20 years and for fit-outs are 5–10 years, which provides an idea of potential retrofitting timescales. Most office buildings rated B through to D were built between 1960 and 1999 (Davis Langdon Australia Pty Ltd 2013), and we can reasonably assume these will gain the largest energy savings from green roof retrofitting, provided they are structurally suitable.

Australian housing stock has traditionally been poorly adapted to climate. In Victoria, insulation was only mandated from 1991, 5-star ratings were mandated from 2005 and 6-star ratings from 2011 (Sustainability Victoria 2014). Of the total Victorian housing stock, 1.9 million houses had been built before 2005, and 0.3 million after. From a sample of 60 stand-alone pre-2005 houses, the average star rating was 1.8. The pre-1990 star rating was 1.6 and the 1990–2005 average 3.1 (Sustainability Victoria 2014). Year of construction from the City of Melbourne CLUE database can therefore stand as a useful proxy for estimating potential gains from green roofs, walls and façades.

One the technical side, the following methods can be applied to model levels of exposure to heat or discomfort:

- Changes to a building's energy star rating and average energy consumption as a function of building type. Green roofs and walls can perform as well as or better than conventional insulation at cooling but more poorly for heat retention in cooler months.
- If a building data base is available, changes to roof/wall material can be used to estimate power consumption, often using heating (<18°C) and cooling (>18°C) degree days and building type to estimate energy consumption relationships.

Depending on the data available, these can range from general estimates with low accuracy to fairly accurate estimates if individual building data is available. Building energy use models can also be adapted to assess interior comfort levels and thus human health and welfare. If air conditioning is limited or unavailable they can also be used to assess heat stress.

Greenhouse gas mitigation and offsetting

Greenhouse gases will be embedded in the construction and operation of green infrastructure, will be sequestered in permanent biomass stored in vegetation or growth media and avoided through saved fossil fuel-generated energy. The benefits of avoided CO_2 emissions can be calculated through the following means (Baranzini et al. 2017):

1. A shadow price of CO_2 calculated by the costs of abatement and permit schemes within the economy.
2. Direct costs of carbon permits, levy or tax tied to specific activities (e.g. fossil fuel power generation). Tradeable permits are generally low compared other estimates.
3. The social cost of carbon, which estimates the future loss and damage of one tonne of CO_2 emitted at any given time into the future. This is calculated by integrated assessment models, often over the period of several hundred years. In the US, the SCC for regulatory analysis was put in place by the Obama administration (Table 2) (Interagency Working Group on Social Cost of Carbon 2015) and later rescinded by the Trump administration.
4. Capping the amount of emissions that lead to unacceptable climate change and costing the efforts required to avoid that level.

Only the first three options in this list have been estimated to date, but as can be seen by Table 2, estimates remain highly uncertain.

Table 2: Revised Social Cost of CO_2, 2010–2050 (in US 2007 dollars per tonne of CO_2) (Interagency Working Group on Social Cost of Carbon 2015).

DISCOUNT RATE	5.0% AVERAGE	3.0% AVERAGE	2.5% AVERAGE	3.0% 95TH PERCENTILE
2010	10	31	50	86
2010	11	36	56	105
2010	12	42	62	123
2010	14	46	68	138
2010	16	50	73	152
2010	18	55	78	168
2010	21	60	84	183
2010	23	64	89	197
2010	26	69	95	212

For Melbourne, offsets based on avoided power consumption would need to take into account the power source being used to generate electricity used for heating and cooling, in addition to accurate heating and cooling data for buildings. For example, if a building sources renewable power, there will be no offsetting, but if it consumes conventional electricity and gas, there will be. The current emission factor for power not delivered from a specific source is 1.08 CO_2-e per kWh (Department of the Environment and Energy 2017).

Biodiversity

Potential ecological and biodiversity benefits have been surveyed by Williams et al. (2014), who show there is little evidence to support six hypotheses that largely compare rooftop biodiversity with extant ecosystems. The one obvious hypothesis is that green roofs are likely to be more biodiverse than conventional rooftops. But there is little sound evidence that they can compete ecologically with extant ecosystems, although they can supplement existing biodiversity. There is little evidence to support connectivity, particularly in Mediterranean ecosystems.

However, the recent bioblitzes held in the City of Melbourne indicate surprisingly high biodiversity in city parks – of insects and bats in particular. Green roofs, walls and façades will increase the presence of arthropods that will benefit bats and insectivorous birds. Additionally, Melbourne borders the eastern edge of the western Victorian Basalt Plains bioregion; temperate plains grasslands have been reduced to less than 1% of their original extent and many once-common species are now rare and endangered. There is considerable potential for conservation of such species, particularly those predated by rabbits, including daisies (e.g. *Rutidosis, Microseris*), peas (e.g. *Swainsona, Glycine*), ground orchids (*Diuris, Thelymitra*) and lilies (*Bulbine, Arthropodium, Caesia*). The issues to be overcome are mainly technical before such strategies can become commercialised (e.g. mass propagation, grazing and fire effects promoting regeneration).

One way of valuing biodiverse rooftops that do have ecological value is to peg them to market instruments for biodiversity such as BushTender and EcoTender, which are both auction systems. If it could be shown that biodiverse rooftops carried biodiversity benefits similar to sites being funded under those schemes (by addressing hypotheses such as those mentioned above), they could either take part in those schemes or be given equivalent or proportional value through shadow pricing. If they do not meet these criteria, then strategies for the conservation of individual species or groups can be pursued. Willingness to pay estimates can be used for biodiverse garden-like areas with high aesthetic and conservation values. Green walls and especially façades will also provide extra habitat for birds and insect. Addressing Council or state or federal biodiversity strategies can be listed as addressing an institutional value without any monetary costing.

Health and wellbeing

Pollution interception

The methodology for valuing improvements in air quality are based on avoided medical and nonmedical costs and loss of wellbeing. Barnes et al. (1996) and Akobundu et al. (2006) outline the three components of costing health outcomes:

1. *Direct medical costs* cover medical resources consumed, like consultations (specialists, general and hospital practitioners), drugs, in-patient and out-patient hospitalizations, emergency room stays and cost of rehabilitation.
2. *Direct non-medical costs* cover non-medical resources consumed in direct connection with the health outcome: i.e. cost of social support (such as home help), transportation and major home modifications.
3. *Indirect costs* cover different types of resources lost:
    a. Loss of productive work by patient (either due to time off work or a poorer access to employment due to poorer health).
    b. Loss of productive work by patient's family and friends (e.g. parent taking time off work).
    c. Loss of productive work due to patient's early retirement or premature death.
    d. Intangible costs such as unhappiness and stress.

Avoided health costs for PM10, PM2.5, nitrates, ozone and black carbon can be calculated using the World Health Organisation (WHO) AirQ+ model with local demographic and air quality data. This model calculates mortality and shortened life span but does not calculate illness, such as air quality-related asthma attacks. These can be linked to Australian data for avoided health costs, and statistical valuations of premature death and shortened life spans. This also holds for the health and welfare aspects of heat stress.

Jones and Ooi (2014) calculated lost welfare for PM10 for people downwind of pollution from the Brooklyn Industrial Precinct (PM10 and PM2.5), west of Melbourne based on the benefit transfer of the US studies on welfare in this report's section on Health and Wellbeing. This was a point-source pollution problem where it was possible to isolate specific damage, with up to 18 daily exceedances of regulated limits of PM10 each year. For PM10, they calculated an annual range of \$0.16 to \$0.86 per m2 health and welfare benefits based on deposition rates of 3 to 8 g per m2 on trees. For PM2.5, direct health benefits were \$0.35 to \$2.89 for deposition rates of 0.13 to 0.36 g per m2 per yr. The PM2.5 levels of capture were what would be expected close to major traffic routes. Intensive green roofs would be expected to capture half to most of the amount intercepted by trees and extensive green roofs about one-third to one-half.

Within the City of Melbourne, background pollution mainly occurs at fairly low levels and combines with elevated PM2.5 along traffic routes, although these will rarely breach safety limits. Health standards are usually only breached is when atmospheric inversions trap pollution close to the ground and when bushfires/cool burns affect air quality, usually in spring and autumn. Note that health effects are considered to occur even if pollution is within regulated safety limits, but at much lower levels. Usually only residents are included in such estimates and not workers, because of the duration of exposure. Any health study focusing on the benefits of green infrastructure would need to be repeated using the demographic and health data of City of Melbourne residents.

Green roofs and walls have a small ambient effect on general air quality but may ameliorate pooling or poor air in specific locations; e.g. poorly circulating air in street canyons. There will be a small health effect but given that bad-air days are externally-driven, this will be local and marginal. Using PM10 as a marker for all pollution species, the marginal benefits of removing pollutants by green roofs and walls will provide a benefit to people within the airshed over which the removal has an effect. This is the most difficult aspect of these calculations, to measure who benefits, as the impact of a single wall may be very local. More broadly, pollutants will be highest in the mornings as the air mass is relatively stable. As the day warms, convection and mixing occur and wind speeds generally increase and the air will generally be more well mixed.

Elevated levels of pollutants due to traffic will be close to roads, declining away from roadways. From short-term surveys undertaken by the EPA on some of Melbourne's roadways, the main effect is dissipated in a few hundred metres. Further complications arise amongst tall buildings and street canyons where mixing can be reduced. Green walls and façades along busy roadways will have a beneficial effect, less so adjacent green roofs. These effects can be modelled. Currently, the Clean Air and Urban Landscapes Hub has a project currently looking at dose rates of pollution within complex urban topographies (P. Perez, pers. comm.). City-wide aspects can be investigated through the development and application of urban atmospheric models.

It is possible using the current literature, along with deposition rates similar to those above or new site specific estimates calculated by I-Tree ECO as assessed by Jayasooriya et al. (2017), and the benefit-transfer approach used by Jones and Ooi (2014), for a catchment of a few hundred metres with typical population densities and demographics for different zones to estimate the benefits of pollutant removal for PM10, PM2.5 and nitrates. Reducing PM2.5 offers the greatest benefits, but vegetation can remove a range of pollutants. Expanding the range of pollutants tested to O_3, NO_2, SO_2, black carbon in addition to PM10 and PM2.5 for green roofs, walls and façades would add to the benefits that can be valued, in particular if their greenhouse effects were included (positive for O_3, NO_2 and black carbon, negative for SO_2).

Because of the much lower residential exposures much of the City of Melbourne, lifecycle benefits could range from a few hundreds of dollars per green hectare to four figure estimates, but some modelling and sensitivity analysis would be required to narrow this range.

Visual and physical contact

Benefits can be divided according to public and private benefits, proximate and remote benefits and health and wellbeing benefits. We assume that except for specific instances (e.g. outdoor gyms, horticultural therapy) there is limited scope for direct health benefits from active living apart from gyms and active therapy. There is a clear benefit for both when they are present.

The following activities have all been mentioned in the literature – details are provided in the technical sections.

Proximate benefits

- Roof gardens (modular, walls and façades) on **residential premises with private access** – private benefits wellbeing and property benefits (building owner).
- Roof gardens (modular, walls and façades) on **commercial premises with public access** – private benefits income and property benefits (building owner), food production (if restaurant or café).
- Roof gardens (modular, walls and façades) on **business premises with private access** – productivity and property (if owner), wellbeing (employees), and property benefits (building owner), food production (if restaurant or café).
- Roof gardens (modular, walls and façades) on **community premises with public access** – health and wellbeing, food production (supply and personal), and property benefits (building owner).

Remote benefits

- View of green roofs, walls and façades from business premises – productivity for employer and wellbeing for the viewer, property benefit (building owner).
- View of green roofs, walls and façades from public space – wellbeing for the viewer.
- View of green roofs, walls and façades from residential premises – wellbeing for the viewer, property benefit (building owner).
- View of multiple roofs, walls and façades enhancing views also add value to airspace for adjacent tall buildings.

Assessing proximate benefits requires information about the number of people receiving the benefit and what the benefit is. This is complicated by how well that benefit can be measured. Proportional benefits go to vulnerable people: the young, the old and the ill. These affects are positive for childhood development, aged care and therapy, respectively. The quality of the space available is important for proximate benefits, but quality for small spaces is hard to gauge. The quality of views is also not easy to value but depends on scale and complexity (e.g. 'scenicness' (Seresinhe et al. 2015)), favouring longer sight lines, intensive compared to extensive developments, and species diversity rather than monocultures.

City of Melbourne has an existing building database and maps of future buildings. Many of the criteria for assessing amenity – who can see green roofs, and to a lesser extent, walls and façades can be estimated.

The public value of health and wellbeing can be calculated in the following ways:

- For direct and therapy benefits, percent reduction in treatment time until discharge (if whole treatment costed per patient) or number of days if cost per day figures are available – saved health costs. Needs data – the effect is limited to health care and therapy centres.
- Self-reported wellbeing as a determinant of mortality, estimated disability adjusted life years. Although these relationships exist, confidence is not high enough to do benefit-transfer from elsewhere and local calculation would need controls.
- Self-reported wellbeing within a broader number of socio-economic determinants, could potentially be scaled against household income, further research needs to be done. This would be data-intensive and time consuming (major study).
- Even though improved productivity from remote viewing may benefit private businesses, this is generally considered a public benefit, but is usually not monetised due to high uncertainties as to its effect. This may be possible in future.

Most are too complex to be assessed at present. Two compromises can be made:

1. To assess stated preference in willingness to pay for views/access
2. To assess revealed preference using hedonic valuation techniques

The second method was applied by Nurmi et al. (2016) who used apartment values in Helsinki to calculate the hedonic value of small parks within a specific viewing radius. This was measured as realised willingness to pay. We suggest that instead of using per m^2, a percentage linked to household income of residents might be preferable. However, this does not cover workers and commercial buildings. Views over large parks around Melbourne result in premium property prices for commercial buildings, and some owners will purchase air space to preserve those views. If green roofs and walls create new, more appealing visual landscapes these may also have an effect on building values.

Building premiums

The premium that buildings gain for green infrastructure can be obtained by survey data, which ideally should be filtered for other factors. GSA (2011) found that for the US, the premium on rents for commercial buildings with green roofs was 5.7% nationally and 7.4% in Washington DC. After they factored in the cost of green roofs as part of the overall green component of construction, the rental premium was 2.5% and 3.3%, respectively. Their real estate market valuation figures (from real estate survey data) were US$130 m^2 of green roof nationally and US$108 m^2 in Washington DC.

Similar data would need to be gathered for Australia to obtain a meaningful value for buildings. Obviously commercial, industrial, high-rise apartment and low-rise housing would all attract different premiums.

KNOWLEDGE GAPS AND RESEARCH NEEDS

Green roofs

- Development and validation of a model of stormwater retention and plant survival/irrigation demands for different green roof designs (substrate depth, plant type, retention layers) in Melbourne and other climate regions of Australia. This includes investigating the trade-offs between irrigation and stormwater retention, and whether by using harvested rainfall the stormwater retention on an annual basis can be increased.
- Investigate how combinations of plants with different water use strategies and drought tolerance affect stormwater retention and survival on green roofs.
- Investigate how combinations of different substrates and retention layers on green roofs influence rainfall retention and plant performance.
- Determine whether increasing the diversity of hydrological niches increase overall retention and performance of green roofs.
- Understand the thermal properties of different types of green roof, their relationship with building type and building insulation, soil properties and moisture content.
- Identify the effects of plant communities on green roofs over time on cooling, thermal properties and internal building temperatures.

Substrates

- Determine the suitability of the FLL guidelines (FLL 2008) and other standards for green roof substrates in Australian cities – particularly around water retention, permeability and air-filled porosity.
- Continue to investigate the use of demolition and other waste materials in green roof substrates to improve sustainability.
- Identify the substrate properties required to sustain different green roof, wall and façade outcomes and planting types, with need for reference values and performance criteria.
- Determine how rates and types of organic matter influence performance of green roof substrates over time (e.g. is 20% organic matter by volume optimal?)
- Investigate the role of substrate structure and composition on nutrient cycling.

Green façades

- Obtain growth and water use requirements of different façade species in Melbourne.
- Investigate response of façade plants to grey water irrigation.
- Research that integrates green façade systems with stormwater and greywater-capture and reuse systems.
- How environmental gradients on buildings affect plant performance – particularly light and wind – and the implications for plant selection at different heights and orientations, light and wind conditions.
- How much cooling do green façades contribute to both the building and the human thermal comfort of pedestrians in Melbourne? Quantify shade and evapotranspirative cooling of green façade species and diversify plant palettes.
- Modelling of benefits of green façades at a city-wide scale, particularly for cooling.
- There are knowledge gaps around sustaining green façades in containers. Determine the container specifications needed to sustain green façade plants, and importantly the minimum substrate volume for a range of species to achieve plant growth outcomes and design requirements.
- Information is required on suitable substrate composition and plant tolerances.
- Establish the hierarchy of street orientation to achieve maximum benefits.

Green walls

- Determine the extent and quantity of the ecosystem services provided by different green wall systems in Melbourne and other climate regions of Australia.
- How much cooling do external green walls contribute to both the building and the human thermal comfort of pedestrians in Melbourne? Examine and quantify shade and evapotranspirative cooling of wall species and diversify plant palettes.

Plants

- What are the rooting traits of different plants in green roof, walls and façades and their implications for plant performance?
- Observations of the effect of elevated heat on plant performance are largely anecdotal, and more research is required to quantify plant response.
- Better understand the role of plants in pollutant interception and take-up.

Biodiversity

- Plant selection research to diversify green roof, green façade and green wall plant palettes with an emphasis on species that will survive the difficult conditions and enhance local biodiversity.
- Vegetation dynamics of green roofs in SE Australia. Which plant species are able to recruit and form self-sustaining populations and hence lower maintenance green roofs? The influence of plant completion and facilitation on vegetation dynamics.
- Development of cost effective techniques of installing vegetation conducive to biodiversity on green roofs; i.e. direct seeding, vegetated mats.
- How can green roofs function to support metapopulation persistence? How much do they need to be connected to other green roofs/ground-level habitats?
- How high is too high for animal species likely to use green roofs in Melbourne?
- What plant species and other design features are required on green roofs to support desired/target species and avoid green roofs becoming an ecological trap?
- Are Melbourne green roofs able to act as sources of seed, spores and other propagules for other areas?
- What fauna species, particularly birds and microbats, utilise green roofs, façades and walls in Melbourne?
- Research into the biodiversity associated with existing green façades and green walls.

Installation and maintenance

- Evaluation of planting design against maintenance inputs over time – what are the likely maintenance inputs, resources and other costs to sustain the planned design outcomes?
    - This should involve both long-term, latitudinal studies of full scale green roofs along with experimental green roofs designed to answer specific questions around maintenance.
- Identify and install a system of non-potable water sources for irrigation.
- Understand nutrient cycling and take-up through a variety of different systems.

Urban heat island and cooling

- What is the peak temperature UHI across the City of Melbourne for measuring UHI effect on heat stress and cooling demands?
- What is the areal effect on UHI of increasing coverage of green roofs, walls and façades?

Health and wellbeing

- Evaluating the effects of green roofs and walls in the workplace – what are the likely outcomes for businesses and employees?
- Developing a better understanding of the role of micro-breaks in the presence of green roofs and walls – how does frequency, duration, and time of break affect outcomes?
- How do characteristics and perceptions of green roofs and walls influence health and wellbeing outcomes? Are different characteristics important for different kinds of experiences/breaks?
- What are the range of different outcomes associated with experiences in the presence of green roofs and walls?
- Developing a better understanding of the mechanisms through which green roofs and walls influence health and wellbeing.
- Understanding the role of green roof, wall and façade structure and placement in mitigating air pollution in built-up urban environments.

Economics

- Understand the relationship between green infrastructure and property values in the Melbourne context.
- Have standard values for stormwater volume for all subcatchments within the City of Melbourne.
- Have standard installation costs for major types of green roofs, walls and façades for Melbourne.
- Agree on appropriate public and private discount rates for all life cycle analysis within the City if Melbourne.
- Understand demographic characteristics and vulnerabilities of Melbourne resident, worker and visitor populations in order to assess and track health benefits.

GREEN ROOFS, WALLS AND FAÇADES: STATE OF THE SCIENCE AND PRACTICAL APPLICATION

The refereed and grey literature describes a wide range of services and economic benefits provided by green roofs, walls and façades. However, there is also a great deal of uncertainty about how they can be reliably quantified, especially for economic benefits.

This especially difficult for regions with climates similar to Melbourne's, which are characterised by high summer temperatures and large climatic variability. The main technical skills and cultural acceptance of green roofs, walls and façades have been developed in temperate climates where moisture supply is plentiful. In climates with variable moisture supply, the technical challenges are much greater.

In Australia and globally, the practice of urban horticulture is proceeding faster than the science is able to document. Technical skills in developing and managing of green infrastructure within urban environments is expanding rapidly. This includes knowledge on container growth and growth media, urban food production, integrated urban water management and urban biodiversity.

This is shown by a number of recent major projects in Melbourne and Australia involving hospitals and other public buildings, where green roofs, walls and façades are a major part of the building purpose and design. This highlights the scientific and technical knowledge needs relevant to this effort. Scientific monitoring and analysis conducted within a controlled environment is necessary but time consuming. Practical knowledge is also increasing. Innovation and learning on the job, where knowledge gained in other areas of practice such as engineering, urban horticulture and design, is being brought into green infrastructure projects, expanding the skill base and contributing to technological learning. Following this pathway, technologies move from the phase of early adoption into diffusion and mainstream take-up. Installation costs will also decrease over time, something that has not been highlighted in this survey, but has been integrated into some of the economic assessments summarised here (e.g. Acks 2006, Ulubeyli and Arslan 2017).

It is important that the gaps in the science identified above do not become a barrier to practical action in a situation where generally, there is sufficient knowledge to act, a willingness by policy makers and investors to take action, increasing consumer demand and suppliers who are willing to innovate, take risks and learn by doing. The literature survey shows that green roofs and walls will usually provide a positive return if both public and private benefits are combined but not in every case or every situation. In some situations, positive private returns are also possible, but we currently cannot predict whether this would be the case in any particular instance.

The most useful measure of value for a green roof, wall or façade is an estimate of the private and public returns per square metre. These returns need to be quantifiable and scalable, so that they work in a similar way from small to large roofs, walls or façades. For some benefits, such as improved biodiversity, this cannot be achieved because the cumulative effect of providing suitable habitat is nonlinear. For example, one square metre of green roof may attract one bee but 2,400 m^2 may attract a hive (with 50,000 bees). For most other measures, particularly those dealing with water, energy, pollutants and even health and wellbeing, some level of scalability is possible.

However, even if benefits are scalable, they will also be context-specific, tied to a particular physical environment. The people who benefit will also be specific to a place, requiring both an environmental and demographic analysis covering who they are and where they live and/or work. The expense and difficulty of measuring environmental effects also means that they are usually modelled. Most of the papers reviewed were based on modelling. Only a minority incorporated direct measurement because of its expense and the time needed to gather reliable data.

The review has identified a wide range of benefits, but more work needs to be done before they can be routinely included into cost-benefit life cycle analyses. Case studies are a useful step on the way to conducting more comprehensive analyses. Enough studies on the performance of green infrastructure in and around Melbourne have been done to which economic analyses can be added.

Uncertainty analysis can then be used to explore the likely bounds of benefits, asking questions like "What is the balance between public and private returns?" and "What is the effect of declining installation costs on the feasibility of future projects?"

There is an advantage in using case studies to set a minimum level of performance for green roofs, walls and façades for the main types likely to be applied in practice along. These will help to set standards by which that performance can be measured. Beyond that, it would be up to industry to sort out the technical aspects and cost to help ensure that returns on investment, both public and private, are maximised. Future work would ideally be highly collaborative, involving researchers, policy makers and planners, practitioners and the community to better integrate experience and research, overcoming the current gap between what is happening on the ground and what is being published in the formal literature. This would speed up the time taken for research to by carried out, evaluated for quality and rigour and feed into practice.

APPENDIX I: TABLES OF BENEFITS FROM THE LITERATURE

Table A1.1 Summary of evidence for benefits for green roofs for Melbourne and cities with comparable climates

STORMWATER			
Detail	**Result**	**Authors/year**	**City/region, country**
Rainfall retention. Modelling of 100 mm scoria extensive green roof for 30-year Melbourne climate scenario, based on species response experiments for 16 native plant species.	Rainfall retention 66–81% for low water use plants and 72–90% retention for other plants, but more drought stress in latter group which use more water.	Szota et al. (2017)	Melbourne, Australia
Rainfall retention. Modelling of theoretical 300 m2 green roof in Melbourne CBD.	93 kL reduction in rainfall runoff (roughly 50%).	Jayasooriya and Ng (2013)	Melbourne, Australia
Rainfall retention. Substrate depth and vegetation on extensive and intensive experimental green roofs.	Deeper substrates hold more stormwater. Runoff retention 51–96%, greater in deeper, flatter, vegetated roofs.	Beecham and Razzaghmanesh (2015)	Adelaide, Australia
Rainfall retention. Experimental extensive green roofs.	Cumulative stormwater retention up to 67%.	Sims et al. (2016)	Calgary, Canada
Rainfall retention. Experimental 150 mm green roof over 6-month autumn-winter + modelling of potential green roofs.	Rainfall retention 55–100%. 69 of 184 rain events did not produce runoff. Modelling suggests 75% green roof cover in city could retain 166K–224 Kl m^3 rainwater.	Brandão et al. (2017)	Lisbon, Portugal
Rainfall retention. Modelling of extensive green roof potential for a Greek city.	17% roofs have retrofit potential, with capacity to retain 45% of rainfall.	Karteris et al. (2016)	Thessaloniki, Greece
Rainfall retention. Modelling based on experimental 100 mm green roof under Melbourne climatic conditions.	Most rainfall events in Melbourne are small (<3.7 mm) and would be completely retained in 100 mm scoria green roof.	Szota et al. (In prep)	Melbourne, Australia
Rainfall retention. Water holding capacity (WHC) and plant available water (PAW) for 3 green roof substrates, nursery experiment.	Substrates with higher WHC perform better than low WHC substrates. High PAW substrates provide more water to plants with positive effects for plant survival and transpiration (and therefore improved stormwater and cooling).	Szota et al. (In prep)	Melbourne, Australia
Delay in peak runoff. Model simulation of potential green roofs in Melbourne CBD.	Peak flow reduced by 10.9–52.2% depending on area of green roof coverage.	Meek et al. (2015)	Melbourne, Australia

STORMWATER (Continued)			
Detail	**Result**	**Authors/year**	**City/region, country**
Plant transpiration. Comparison of 2 native and 2 exotic succulent species for experimental green roofs.	Plant coverage increased ET by 13% compared to bare substrates. 3 substrates varied in amount of ET.	Szota et al. (2017) Szota et al. (In prep)	Melbourne, Australia
Plant transpiration. Exotic and native succulent species drought response and transpiration function.	Succulents can withstand periods of drought because they are low-water users, but this makes them suboptimal for stormwater control.	Williams et al. (2010) Farrell et al. (2012) Rayner et al. (2016)	Melbourne, Australia
Plant transpiration. Identification of native Victorian plant species that can regulate their water use and improve stormwater retention on green roofs.	Four species from granite outcrops particularly good at withstanding both high and low water conditions, and good green roof candidates.	Farrell et al. (2013b)	Melbourne, Australia
Soil additives. Tested hydrogel, silicates and biochar on water-holding properties of substrates.	Lightweight biochar greatly increased substrate water holding capacity and plant available water.	Farrell et al. (2016)	Melbourne, Australia
Soil additives. Tested addition of hydrogel on plant performance.	Hydrogel increased amount of water available for plants for 5 months.	Savi et al. (2014)	Trieste, Italy
Runoff water quality. Extensive and intensive experimental green roofs – vegetated and unvegetated.	Vegetated beds of both depths removed more nitrogen and phosphate than bare substrate roofs.	Beecham and Razzaghmanesh (2015)	Adelaide, Australia
Other modifiers of green roof stormwater performance – studies that have identified factors influencing rainfall retention.	Time between rainfall (drier roofs have greater water storage capacity), rainfall depth and % retention, season (summer increased retention), roof age, slope, orientation, shading from surrounding buildings and trees.	Elliott et al. (2016 Getter et al. (2007 Berndtsson (2010) Mentens et al. (2003) Carter and Rasmussen (2006)	Various

COOLING			
Detail	**Result**	**Authors/year**	**City/region, country**
UHI. Modelling potential benefits of retrofitting green roofs in Melbourne	UHI temperature lowered by 0.7–1.5°C depending on extent of retrofitting.	Meek et al. (2015)	Melbourne, Australia
UHI. Review of effects of increased albedo of green roofs at city scale, based on data from multiple cities.	Reduce ambient temperature by 0.3–3°C per 0.1 rise in albedo.	Santamouris (2014)	Studies from multiple countries
UHI. Modelling of potential green roofs in city.	50% coverage of green roofs across city – decrease ambient air temperature by average 1.29°C.	Sahnoune and Benhassine (2017)	Constantine, Algeria
Temperature of underlying structural roof. Experiment of extensive green roof compared to black bituminous roof.	12°C cooler in summer, 4°C warmer in winter. Negative heat fluxes over observation period. Thermal energy transfer -100% reduction in thermal energy entering building in summer, 30–37% reduction thermal energy exiting indoor environment in winter.	Bevilacqua et al. (2016)	Calabria, Italy
Energy savings. Modelling of extensive green roof potential.	17% green roof cover reduces heating (5%) and cooling (16%) energy requirements across city.	Karteris et al. (2016)	Thessaloniki, Greece
Energy savings. Modelling of extensive green roof potential.	Addition of 30% green roof in area of CBD could reduce summer cooling electricity consumption by 2.57 ($W/m^2/day$)	Razzaghmanesh et al. (2016)	Adelaide, Australia
Energy savings. Substrate depth and thermal performance of green roofs with no insulation, compared to black roofs.	Extensive green roofs reduced energy demand by 20%, intensive: 45–60%, semi-intensive: 60–70%.	Silva et al. (2016)	Lisbon, Portugal
Heat gain. Experiments + modelling heat gain of large retail spaces with extensive green roofs.	Vegetated roofs had heat losses during the day, compared to uninsulated concrete slab roof (heat gain 10 Wh/m^2).	Vera et al. (2017)	Melbourne, Australia Albuquerque, USA Santiago, Chile
Internal building temperature. Experimental house modules, green roofs (+ green walls).	Average/maximum temperature inside vegetated house 23.4/33°C and non-vegetated house 26.1/42°C.	Wilkinson et al. (2017)	Sydney, Australia
Thermal gain of underlying building, extensive green roof.	Dense vegetation lowered thermal gain entering building by 60%.	Olivieri et al. (2013)	Southern Spain
Human thermal comfort and health. Prioritisation framework for green infrastructure implementation in Melbourne	Recommendation for green roofs on large, low areas to maximise human health benefits.	Norton et al. (2015)	Melbourne, Australia
Human thermal comfort, modelling to investigate effects of Plan Melbourne.	Adding green roofs in CBD did not show any improvement in human thermal comfort at ground level.	Jamei and Rajagopalan (2017)	Melbourne, Australia
Irrigation of green roofs.	Irrigation (particularly at establishment and drier/hotter months) enhances cooling benefits and ensures plant survival.	Coutts et al. (2013) Van Mechelen et al. (2015a)	Melbourne, Australia Regions that have hot, dry, climates or that are seasonally hot and/or dry
Air temperature above plant canopy.	Air above foliage 1°C cooler cf. bare substrate.	Klein and Coffman (2015)	Oklahoma, USA

BIODIVERSITY			
Detail	**Result**	**Authors/year**	**City/region, country**
Study of invertebrate biodiversity on Melbourne green roofs (<300 mm, unirrigated)	2,194 invertebrates found on 6 green roofs comprised of 13 orders. Abundance significantly lower on green roof compared to similar ground habitats, but no difference in community composition. Diversity and abundance strongly influenced by % cover of green space surrounding the roof. Roof height influenced community composition. Older roofs had greater biodiversity.	Murphy (2013) Murphy et al. (in review)	Melbourne, Australia
Study of invertebrate biodiversity on Sydney green roofs.	Winged insects the most common invertebrates, Roof height affected connectivity. Biodiversity conservation more effective on green roofs closer to the ground.	(Berthon 2015)	Sydney, Australia
Testing suitability of native species from habitat 'analogues' for Melbourne green roofs.	Species from Victorian granite outcrops all showed suitable attributes, but variation in performance amongst species.	Farrell et al. (2013b)	Melbourne, Australia
Testing suitability of native species for Melbourne green roofs.	Plant species from Australian native dry grasslands on Melbourne green roof – 75% survival at 3 years.	Williams, unpublished	Melbourne, Australia

HEALTH AND WELLBEING			
Detail	**Result**	**Authors/year**	**City/region, country**
Psychological study on effect of virtual green roofs on attention and cognitive function of Melbourne university students.	40 second micro-breaks looking at green roof scenes had a restorative effect and boosted concentration levels.	Lee (2015)	Melbourne, Australia
Psychological study on effect of real green roofs on attention and cognitive function of Melbourne university students.	Reduced observer stress associated with performing tasks, improving performance and lowering tension.	Lee et al. (2017)	Melbourne, Australia
Study on the preference for green roof types using images of virtual roofs	Highly diverse roofs were more preferred, as well as roofs with flowers.	Lee et al. (2014)	Melbourne, Australia
Study on the preference of green roof types in Spain	More highly designed, intensive roofs preferred over extensive roofs.	Fernandez-Cañero et al. (2013)	Southern Spain

Table A1.2 Summary of evidence for benefits for **green walls and green façades** for Melbourne and cities with comparable climates.

STORMWATER

No climate-relevant studies for green façades and stormwater mitigation found. Preliminary study into pollutant-removal capacity of green façade species from greywater for Melbourne (Barron et al. 2016, Fowdar et al. 2017). Recommendation for irrigation with non-potable water e.g. harvest water from downpipes for Melbourne (Croeser 2016).

No climate-relevant studies for green walls and stormwater mitigation found. Melbourne study into pollutant-removal capacity of green wall media (Prodanovic et al. 2017). Recommendation for irrigation from harvested stormwater - Adelaide (Razzaghmanesh 2017).

COOLING

Detail	Result	Authors/year	City/region, country
Prioritisation framework for green infrastructure implementation in Melbourne.	Green façades most beneficial on walls with high solar exposure and where space at ground level is limited; on darker walls and near pedestrians, and on westerly (and to a lesser extent east) walls.	Norton et al. (2015) Hunter et al. (2014)	Melbourne, Australia
GIS and microclimate modelling to determine green façade potential for Melbourne CBD.	16 ha of walls up to 7 m high have potential – 1.9 ha had optimal conditions in terms of light and wind.	Croeser (2016)	Melbourne, Australia
Energy savings, double-skin façade on experimental houses.	Cooling related energy savings 33.8% compared to bare wall.	Coma et al. (2017)	Leida, Spain
Review of existing studies on cooling benefits green walls and façades.	Green façades can reduce external wall temperatures of buildings in hot, dry climates by 6°C (direct façade) and 15.8°C (double-skin façade). Higher heating/cooling performance for green walls compared to green façades.	Coma et al. (2017)	Various, including Spain, Greece, UAE
Building cooling under façade, experiment.	Reduction in exterior surface temperature of building 1.7-13°C depending on orientation and foliage thickness. West and east orientations had greatest temperature reduction.	Pérez et al. (2014)	Spain
Building cooling under façade, experiment.	Reduction in exterior surface temperature average 5.5°C, maximum 15.2°C SW orientation in September.	Pérez et al. (2011)	Spain
Building cooling under façade, experiment.	6°C reduction of external wall temperature.	Haggag et al. (2014)	UAE
Cooling under horizontal façade – human thermal comfort.	Planting 100% of pergola reduced mean radiant temperature by 29.4°C and PET by 17.9°C.	Katsoulas et al. (2017)	Arta, Greece
Cooling building walls and internal rooms under green façade	Surface temperatures reduced by average 5.7°C, internal rooms 0.9°C cooler.	Eumorfopoulou and Kontoleon (2009)	Thessaloniki, Greece

COOLING (Continued)			
Detail	**Result**	**Authors/year**	**City/region, country**
Cooling building and internal rooms under green façade – model simulation	External west walls had 16.85°C temperature reductions, internal walls 3.27°C.	(Kontoleon and Eumorfopoulou 2010)	Thessaloniki, Greece
Cooling building walls under green walls	Exterior wall temperature reduction in summer, 12–20.8°C daytime, 2–6°C night time.	Pérez et al. (2014)	Spain
Experimental green wall overlying brick wall	External wall temperature decreases 14.9°C, slight decrease in heat exchange into building for green wall compared to bare wall.	Razzaghmanesh (2017)	Adelaide, Australia
External wall surface reduction under green wall	15.1–31.9°C for south facing green walls.	Olivieri et al. (2013)	Southern Spain
Cooling energy benefits for green walls	Savings of 58.9% when compared to bare walls, external wall temperature reduction 12–31.9°C depending on orientation.	Coma et al. (2017)	Lleida, Spain
Experiment to test effect of air gap width under green wall	Heat flux reduction 90 W/m^2 for 5 cm air gap, and 1.5 W/m^2 for 3 cm air gap.	Mazzali et al. (2013)	Pisa, Italy

BIODIVERSITY
No climate-relevant studies on biodiversity of green walls and façades (Melbourne or comparable regions).

HEALTH AND WELLBEING
No climate-relevant studies on health and well-being benefits of green walls and façades (Melbourne or comparable regions)

APPENDIX II: ABBREVIATIONS

AAD – Average annualised damage

ADWP – Antecedent dry weather period

ARI – Average return interval

BoM – Bureau of Meteorology

CAUL – Hub for Clean Atmosphere and Urban Landscapes

CBA – Cost benefit analysis

CBD – Central Business District

DPBP – Discounted payback period

ET – Evapotranspiration

ICAM – Integrated climate adaptation model

IRR – Internal rate of return

EGR – Extensive green roof

IGR – Intensive green roof

LAI – Leaf area index

N - Nitrogen

NPV – Net present value

P - Phosphate

PAW – Plant available water

PET – Potential evapotranspiration

PBP – Payback Period

ROI – Return on investment

TEEB – The Economics of Ecosystems and Biodiversity

UHI – Urban heat island

WHC – Water-holding capacity

WHO – World Health Organisation

APPENDIX III: ACKNOWLEDGEMENTS

Thanks to Robyn Mitchell, Gail Hall and Ben Nicholson from the City of Melbourne for project management and review. Thanks to Brod Street from the Victorian Department of Environment, Land Water and Planning for review comments. Thanks also to John Rayner, Claire Farrell, Stephen Livesley, Kate Lee, Chris Szota and Andrew Pianella from the University of Melbourne Green Infrastructure Research Group for discussions. This review is supported by funding from the City of Melbourne.

Citation: Jones, R. N., Bathgate, R.S., Symons, J. and Williams, N. S. G. (2018) Quantifying the Benefits of Green Infrastructure: Literature Review and Gap Analysis. A report to the City of Melbourne. Institute of Sustainable Industries and Liveable Cities, Victoria University, Melbourne and Green Infrastructure Research Group, School of Ecosystem and Forest Sciences, University of Melbourne.

REFERENCES

Abelson, P. (2008) *Establishing a Monetary Value for Lives Saved: Issues and Controversies.* Working papers in cost-benefit analysis. Canberra: Office of Best Practice Regulation, Department of Finance and Deregulation.

Abhijith, K., Kumar, P., Gallagher, J., McNabola, A., Baldauf, R., Pilla, F., Broderick, B., Di Sabatino, S. and Pulvirenti, B. (2017) Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments–A review. *Atmospheric Environment,* 162, pp. 71-86.

Access Economics (2008) *The Health of Nations: The Value of a Statistical Life,* Canberra: Office of the Australian Safety and Compensation Council.

Acks, K. (2006) A Framework for Cost-Benefit Analysis of Green Roofs: Initial Estimates. in Rosenzweig, C., Gaffin, S. and Parshall, L., (eds.) *Green Roofs in the New York Metropolitan Region Research Report:* Columbia University Center for Climate Systems Research NASA Goddard Institute for Space Studies. pp. 41-52.

Agra, H. e., Klein, T., Vasl, A., Kadas, G. and Blaustein, L. (2017) Measuring the effect of plant-community composition on carbon fixation on green roofs. *Urban Forestry & Urban Greening,* 24, pp. 1-4.

Akobundu, E., Ju, J., Blatt, L. and Mullins, C. D. (2006) Cost-of-illness studies. *Pharmacoeconomics,* 24(9), pp. 869-890.

Alam, M., Sanjayan, J., Zou, P. X. W., Stewart, M. G. and Wilson, J. (2016) Modelling the correlation between building energy ratings and heat-related mortality and morbidity. *Sustainable Cities and Society,* 22, pp. 29-39.

Alexandri, E. and Jones, P. (2008) Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment,* 43(4), pp. 480-493.

Anwar, M., Rasul, M. and Khan, M. (2013) Air conditioning energy saving by rooftop greenery system in subtropical climate in Australia. *International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering,* 7(7), pp. 427-433.

Arnell, N. and Lloyd-Hughes, B. (2014) The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. *Climatic Change,* 122: 127.

Azkorra, Z., Pérez, G., Coma, J., Cabeza, L. F., Bures, S., Álvaro, J. E., Erkoreka, A. and Urrestarazu, M. (2015) Evaluation of green walls as a passive acoustic insulation system for buildings. *Applied Acoustics,* 89, pp. 46-56.

Baik, J.-J., Kwak, K.-H., Park, S.-B. and Ryu, Y.-H. (2012) Effects of building roof greening on air quality in street canyons. *Atmospheric Environment,* 61, pp. 48-55.

Bambrick, H., Dear, K., Woodruff, R., Hanigan, I. and McMichael, A. (2008) *The impacts of climate change on three health outcomes: temperature-related mortality and hospitalisations, salmonellosis and other bacterial gastroenteritis, and population at risk from dengue* Garnaut Climate Change Review Technical Paper. Melbourne: Garnaut Climate Change Review.

Banting, D., Doshi, H., Li, L., Missios, P., Au, A., Currie, B. A. and Verrati, M. (2005) *Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto.* Toronto: City of Toronto and Ontario Centres of Excellence - Earth and Environmental Technologies (OCE-ETech).

Baranzini, A., van den Bergh, J. C. J. M., Carattini, S., Howarth, R. B., Padilla, E. and Roca, J. (2017) Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations. *Wiley Interdisciplinary Reviews: Climate Change,* 8(4), pp. e462.

Barnes, P., Jonsson, B. and Klim, J. (1996) The costs of asthma. *European Respiratory Journal,* 9(4), pp. 636-642.

Barnett, G., Beaty, M., Chen, D., McFallan, S., Meyers, J., Nguyen, M., Ren, Z., Spinks, A. and Wang, X. (2013) *Pathways to climate adapted and healthy low income housing,* Gold Coast: National Climate Change Adaptation Research Facility.

Barron, N., Fowdar, H., Jung, J., Deletic, A., Farrelly, M. and Hatt, B. (2016) Dual-mode stormwater-greywater biofilters: Interactions between inflow dynamics, plant selection and treatment performance. In Paper Presented to the China-Australia Water Sensitive City Summit, Kunshan, China.

Bassuk, N., Grabosky, J. and Trowbridge, P. (2005) *Using CU-Structural Soil™ in the Urban Environment.* Urban Horticulture Institute, Department of Landscape Architecture, Cornell University: Department of Landscape Architecture, Cornell University.

Bateman, I., Lovett, A. and Brainard, J. (2004) *Applied Environmental Economics: A GIS Approach to Cost-Benefit Analysis,* Cambridge University Press, Cambridge.

Baumann, N. (2006) Ground-nesting birds on green roofs in Switzerland: preliminary observations. *Urban Habitats,* 4, pp. 37-50.

Bayer, P., Keohane, N. and Timmins, C. (2009) Migration and hedonic valuation: The case of air quality. *Journal of Environmental Economics and Management,* 58(1), pp. 1-14.

Beecham, S. and Razzaghmanesh, M. (2015) Water quality and quantity investigation of green roofs in a dry climate. *Water Research,* 70, pp. 370-384.

Bendict, M. and McMahon, E. (2006) *Green Infrastructure: Linking Landscapes and Communities,* Washington, DC: Island Press.

APPENDIX IV: REFERENCES

Bengtsson, L., Grahn, L. and Olsson, J. (2005) Hydrological function of a thin extensive green roof in southern Sweden. *Nordic Hydrology,* 36(3), pp. 259-268.

Berardi, U. (2016) The outdoor microclimate benefits and energy saving resulting from green roofs retrofits. *Energy and Buildings,* 121(1), pp. 217-229.

Berghage, R., Beattie, D., Jarrett, A., Thuring, C. and Rezaei, F. (2009) *Green roofs for stormwater runoff control.* National Risk Management Research Laboratory Office of Research and Development.

Berndtsson, J. (2010) Green roof performance towards management of runoff water quantity and quality: A review. *Ecological Engineering,* 36(4), pp. 351-360.

Berthon, K. (2015) *Invertebrates on Green Roofs in Sydney* Unpublished Masters, Macquarie University.

Bevilacqua, P., Coma, J., Pérez, G., Chocarro, C., Juárez, A., Solé, C., De Simone, M. and Cabeza, L. F. (2015) Plant cover and floristic composition effect on thermal behaviour of extensive green roofs. *Building and Environment,* 92, pp. 305-316.

Bevilacqua, P., Mazzeo, D., Bruno, R. and Arcuri, N. (2016) Experimental investigation of the thermal performances of an extensive green roof in the Mediterranean area. *Energy & Buildings,* 122, pp. 63-79.

Bianchini, F. and Hewage, K. (2012) How “green” are the green roofs? Lifecycle analysis of green roof materials. *Building and Environment,* 48 pp. 57-65.

Bierman, H. (2007) *The Capital Budgeting Decision: Economic Analysis of Investment Projects,* 9th ed., New York: Routledge.

Blackhurst, M., Hendrickson, C. and Matthews, H. (2010) Cost-effectiveness of green roofs. *Journal of Architectural Engineering,* 16(4), pp. 136-143.

Blanchard, B. S. and Fabrycky, W. J. (2011) *Systems engineering and analysis, Prentice-Hall international series in industrial and systems engineering,* Fifth ed., Boston, MA: Prentice Hall.

Bowen, K. and Parry, M. (2015) *The evidence for linkages between green infrastructure, public health and economic benefit. Paper prepared for the project Assessing the Economic Value of Green Infrastructure.* Melbourne: City of Melbourne.

Braaker, S., Ghazoul, J., Obrist, M. and Moretti, M. (2014) Habitat connectivity shapes urban Arthropod communities: the key role of green roofs. *Ecology,* 95(4), pp. 1010-1021.

Brandão, C., Cameira, M. d. R., Valente, F., Cruz de Carvalho, R. and Paço, T. A. (2017) Wet season hydrological performance of green roofs using native species under Mediterranean climate. *Ecological Engineering,* 102, pp. 596-611.

Bratman, G., Hamilton, J. and Daily, G. (2012) The impacts of nature experience on human cognitive function and mental health. *Annals of the New York Academy of Sciences,* 1249, pp. 118–136.

Brenneisen, S. (2005) *The Natural Roof (NADA) - Research Project Report on the Use of Extensive Green Roofs by Wild Bees:* University of Wädenswil.

Brenneisen, S. (2006) Space for urban wildlife: designing green roofs as habitats in Switzerland. *Urban Habitats,* 4, pp. 27-36.

Cameron, R. W. F., Taylor, J. and Emmett, M. (2015) A Hedera green façade – Energy performance and saving under different maritime-temperate, winter weather conditions. *Building and Environment,* 92, pp. 111-121.

Cao, C. T. N., Farrell, C., Kristiansen, P. E. and Rayner, J. P. (2014) Biochar makes green roof substrates lighter and improves water supply to plants. *Ecological Engineering,* 71, pp. 368-374.

Carnovale, F., Carvalho, C. and Cope, M. E. (1992) *Literature review of aeolian and atmospheric inputs of toxicants to Port Phillip Bay.* Technical Report No. 5. CSIRO Port Phillip Bay Environmental Study. Melbourne: CSIRO.

Carson, T., Marasco, D., Culligan, P. and McGillis, W. (2013) Hydrological performance of extensive green roofs in New York City: observations and multi-year modeling of three full-scale systems. *Environmental Research Letters,* 8, pp. 13.

Carter, T. and Keeler, A. (2008) Life-cycle cost-benefit analysis of extensive vegetated roof systems. *Journal of Environmental Management,* 87, pp. 350- 363.

Carter, T. and Rasmussen, T. (2006) Hydrologic behaviour of vegetated roofs. *JAWRA Journal of the American Water Resources Association,* 42(5), pp. 1261-1274.

Castleton, H. F., Stovin, V., Beck, S. B. M. and Davison, J. B. (2010) Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings,* 42, pp. 1582–1591.

Celik, S., Morgan, S. and Retzlaff, W. (2010) Energy conservation analysis of various green roof systems. In Paper Presented to the In Green Technologies Conference, 2010 IEEE, Grapevine, Texas.

Champ, P., Boyle, K. and Brown, T. (2003) *A Primer on Non-market Valuation.* Dordrecht, Netherlands, Kluwer Academic Publishers.

Chan, A. and Chow, T. (2013) Energy and economic performance of green roofsystem under future climatic conditions in Hong Kong. *Energy and Buildings,* 64, pp. 182-198.

Cheng, C., Cheung, K. and Chu, L. (2010) Thermal performance of vegetated cladding system on façade walls. *Built Environment,* 45, pp. 1779-87.

Cipolla, S., Maglionico, M. and Stojkov, I. (2016) A long-term hydrological modelling of an extensive green roof by means of SWMM. *Ecological Engineering,* 95, pp. 876-887.

City of Waterloo (2005) *Green Roof Feasibility Study and City Wide Implementation Plan.* Waterloo, Canada: City of Waterloo.

Clark, C., Adrieans, P. and Talbot, F. B. (2008) Green Roof Valuation: A probabilistic economic analysis of environmental benefits. *Environmental Science Technology,* 42(6), pp. 2155 -2161.

Clements, J. and St Juliana, A. (2013) *The Green Edge: how commercial property investment in green infrastructure creates value.* New York City: Natural Resources Defence Council.

Cline, W. (1992) *The Economics of Global Warming:* Institute for International Economics, Washington, DC.

Collins, R., Schaasfma, M. and Hudson, M. (2017) Value of green walls to biodiversity. *Land Use Policy,* 64, pp. 114-123.

CoM (2017) *Nature in the City: Thriving biodiversity and healthy ecosystems.* Melbourne: City of Melbourne.

Coma, J., Pérez, G., de Gracia, A., Burés, S., Urrestarazu, M. and Cabeza, L. F. (2017) Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green façades. *Building and Environment,* 111, pp. 228-237.

Cook-Patton, S. and Bauerle, T. (2012) Potential benefits of plant diversity on vegetated roofs: A literature review. *Journal of Environmental Management,* 106, pp. 85-92.

Coutts, A. M., Daly, E., Beringer, J. and Tapper, N. J. (2013) Assessing practical measures to reduce urban heat: Green and cool roofs. *Building and Environment,* 70, pp. 266-276.

Croeser, T. (2016) Biological potential in cities: An estimate from Melbourne. *Urban Forestry & Urban Greening,* 16, pp. 84-94.

Crompton, J. (2005) The impact of parks on property values: empirical evidence from the past two decades in the United States. *Managing leisure,* 10(4), pp. 203-21.

Currie, B. A. and Bass, B. (2008) Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. *Urban Ecosystems,* 11, pp. 409-422.

Davies, R., Simcock, R. and Toft, R. (2010) Islands in the sky: Urban biodiversity enhancement in NZ on indigenous living roof landscapes. in *44th Annual Conference of the Architectural Science Association, ANZAScA 2010, Unitec Institute of Technology.*

Davis Langdon Australia Pty Ltd (2013) *The Next Wave: Retrofitting Victoria's Office Buildings. Summary Report.* Melbourne: Sustainability Victoria.

de Groot, R., Fisher, B., Christie, M., Aronson, J., Braat, L., Gowdy, J., Haines-Young, R., Maltby, E. and Neuville, A. (2010) Integrating the ecological and economic dimensions in biodiversity and ecosystem service valuation. in Kumar, P., (ed.) *The Economics of Ecosystems and Biodiversity Ecological and Economic Foundations,*London and Washington: Earthscan. pp. 9-40.

De Groot, R. S. (1992) *Functions of nature: Evaluation of nature in environmental planning,* I n Groningen , Netherlands: Wolters-Noordhoff.

Deeproot (2014) *Soil Volume Recommendations for Vines, Hedges, and Palms,* Available: http://www.deeproot.com/blog/blog-entries/soil-volume-recommendations-for-vines-hedges-and-palms [Accessed 16/07/2017].

DeNardo, J. C., Jarrett, A. R., Manbeck, H. B., Beattie, D. J. and Berghage, R. D. (2005) Stormwater mitigation and surface temperature reduction by green roofs. *Transactions of the ASAE,* 48(4), pp. 1491-1496.

Department of the Environment and Energy (2017) *National Greenhouse Accounts Factors.* Canberra: Commonwealth of Australia.

Department of the Environment, Land, Water and Planning (2017) *Metropolitan Planning Strategy - Plan Melbourne 2017 -2050.* Victoria: Commonwealth of Australia.

DEPI (2014) *Growing Green Guide: A guide to green roofs, walls and façades in Melbourne and Victoria, Australia.* Melbourne: Inner Melbourne Action Plan, Goverment of Victoria.

Des Rosiers, F., Thériault, M., Kestens, Y. and Villeneuve, P. (2002) Landscaping and house values: an empirical investigation. *Journal of real estate research,* 23(1-2), pp. 139-162.

DHS (2009) *January 2009 heatwave in Victoria: An assessment of health impacts.* Melbourne, Victoria: Department of Human Services.

Dobes, L., Argyrous, G. and Leung, J. (2016) *Social cost-benefit analysis in Australia and New Zealand. The state of current practice and what needs to be done,* ANU Press.

Downtown, P. (2013) *Green roofs and walls,* Available: http://www.yourhome.gov.au/materials/green-roofs-and-walls [Accessed 17/07/2017 2017].

Dunnett, N. and Kingsbury, N. (2004) Planting options for extensive and semi-extensive green roofs. in *Greening Rooftops for Sustainable Communities,* Portland, Oregon.

Dvorak, B. and Volder, A. (2013) Rooftop temperature reduction from unirrigated modular green roofs in south-central Texas. *Urban Forestry & Urban Greening,* 12(1), pp. 28-35.

Editorial Desk AAU (2018) "World's most sustainable" shopping centre to feature 2,000-square-metre rooftop farm. *Architecture Australia.*

Edwards, K. (2007) *Do Parks Make Cents?: An Analysis of the Economic Value of Parks in San Francisco:* UC Berkeley, Richard and Rhoda School of Public Policy.

Elliott, R., Gibson, R., Carson, T., Marasco, D., Culligan, P. and McGillis, W. (2016) Green roof seasonal variation: comparison of the hydrologic behavior of a thick and a thin extensive system in New York City. *Environmental Research Letters,* 11(7), pp. 1.

Escobedo, F. J. and Nowak, D. J. (2009) Spatial heterogeneity and air pollution removal by an urban forest. *Landscape and Urban Planning,* 90(3–4), pp. 102-110.

Eumorfopoulou, E. A. and Kontoleon, K. J. (2009) Experimental approach to the contribution of plant-covered walls to the thermal behaviour of building envelopes. *Building and Environment,* 44(5), pp. 1024-1038.

Farrell, C., Ang, X. and Rayner, J. P. (2013a) Water-retention additives increase plant available water in green roof substrates. *Ecological Engineering,* 52, pp. 112-118.

Farrell, C., Cao, C. T. N., Ang, X. Q. and Rayner, J. P. (2016) Use of water-retention additives to improve performance of green roof substrates. *Acta Horticulturae,* (1108), pp. 271-277.

Farrell, C., Mitchell, R. E., Szota, C., Rayner, J. P. and Williams, N. S. G. (2012) Green roofs for hot and dry climates: Interacting effects of plant water use, succulence and substrate. *Ecological Engineering,* 49, pp. 270-276.

Farrell, C., Szota, C., Williams, N. S. G. and Arndt, S. K. (2013b) High water users can be drought tolerant: using physiological traits for green roof plant selection. *Plant and Soil,* 372(1/2), pp. 177-193.

Fassman-Beck, E., Voyde, E., Simcock, R. and Hong, Y. S. (2013) 4 Living roofs in 3 locations: Does configuration affect runoff mitigation? *Journal of Hydrology,* 490, pp. 11-20.

Fassman, E. and Simcock, R. (2012) Moisture measurements as performance criteria for extensive living roof substrates. *Journal of Environmental Engineering,* 138(8), pp. 841-851.

Fernandez-Cañero, R., Emilsson, T., Fernandez-Barba, C. and Machuca, M. Á. H. (2013) Green roof systems: A study of public attitudes and preferences in southern Spain. *Journal of Environmental Management,* 128, pp. 106-115.

Fernandez-Cañero, R. and Gonzalez-Redondo, P. (2010) Green Roofs as a Habitat for Birds: A Review. *Journal of Animal and Veterinary Advances,* 9, pp. 2041-2052.

Fletcher, T., Shuster, W., Hunt, W., Ashley, R., Butlere, D., Arthur, S., Trowsdale, S., Barraud, C., Semadeni-Davies, A., Bertrand-Krajewski, J.-P., Mikkelsen, P., Rivard, G., Uhl, M., Dagenais, D. and Viklander, M. (2015) SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal,* 12(7), pp. 525–542.

FLL (2008) *Guidelines for the Planning, Construction and Maintenance of Green Roofing: Green Roofing Guideline,* Forschungsgesellschaft Landschaftsentwickung Landschaftsbau.

Fowdar, H. S., Hatt, B. E., Breen, P., Cook, P. L. M. and Deletic, A. (2017) Designing living walls for greywater treatment. *Water Research,* 110, pp. 218-232.

Fromm, O. (2000) Ecological structure and functions of biodiversity as elements of its total economic value. *Environmental & Resource Economics,* 16(3), pp. 303-328.

Gagliano, A., Detommaso, M., Nocera, F. and Evola, G. (2015) A multi-criteria methodology for comparing the energy and environmental behavior of cool, green and traditional roofs. *Building and Environment,* 90, pp. 71-81.

Gao, X. and Asami, Y. (2007) Effect of urban landscapes on land prices in two Japanese cities. *Landscape and Urban Planning,* 81(1), pp. 155-166.

Garrison, N. and Hobbs, K. (2011) *Rooftops to Rivers II: Green Strategies for Controlling Stormwater and Combined Sewer Overflows.* New York: Natural Resources Defence Council.

Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Tobias, A., Tong, S., Rocklöv, J., Forsberg, B., Leone, M., De Sario, M., Bell, M. L., Guo, Y.-L. L., Wu, C.-f., Kan, H., Yi, S.-M., de Sousa Zanotti Stagliorio Coelho, M., Saldiva, P. H. N., Honda, Y., Kim, H. and Armstrong, B. (2015) Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *The Lancet,* 386(9991), pp. 369-375.

Gedge, D., Grant, G., Kadas, G. and Dinham, C. (2014) *Creating green roofs for invertebrates: a best practice guide.* Peterborough: Buglife - The Invertebrate Conservation Trust.

Georgescu, M., Morefield, P. E., Bierwagen, B. G. and Weaver, C. P. (2014) Urban adaptation can roll back warming of emerging megapolitan regions. *Proceedings of the National Academy of Sciences of the United States of America,* 111(8), pp. 2909.

Getter, K. L., Rowe, D. B. and Andresen, J. A. (2007) Quantifying the effect of slope on extensive green roof stormwater retention. *Ecological Engineering,* 31(4), pp. 225-231.

GHD (2014) *Elizabeth Street Flooding: Flood Reduction Benefits of WSUD Initiatives.* Melbourne: City of Melbourne.

GHD (2015) *Rooftop Adaptation Study: Green Roofs, Cool Roofs and Solar Panels Final Report.* Melbourne: City of Melbourne

Gill, S., Handley, J., Ennos, A. and Pauleit, S. (2007) Adapting cities for climate change: the role of the green infrastructure. *Built Environment,* pp. 115-133.

greenscreen (2015) *Considerations for Advanced Green Façade Design,* greenscreen [online], available: http://greenscreen.com/docs/Education/greenscreen_Advanced%20Green%20Façade%20Design_White%20Paper.pdf and http://greenscreen.com/docs/Education/greenscreen_Advanced%20Green%20Façade%20Design_CEU.pdf [accessed 15/06/2017].

GSA (2011) *The Benefits and Challenges of Green Roofs on Public and Commercial Buildings,* Washington DC: United States General Services Administration.

Haggag, M., Hassan, A. and Elmasry, S. (2014) Experimental study on reduced heat gain through green façades using free-standing walls. *Building & Environment,* 82, pp. 668-674.

Haines-Young, R. and Potschin, M. (2010) The links between biodiversity, ecosystem services and human well-being in Raffaelli, D. and Frid, C., (eds.) *Ecosystem Ecology: a new synthesis,* Cambridge, UK: Cambridge University Press. pp. 110-139.

Hale, R. and Swearer, S. E. (2016) Ecological traps: current evidence and future directions. in *Proceedings of the Royal Society B:* The Royal Society. 283, pp. 20152647.

Hallegatte, S. (2011) Uncertainties in the Cost-Benefit Analysis of Adaptation Measures, and Consequences for Decision Making. in Linkov, I. and Bridges, T. S., (eds.) *Climate:* Springer Netherlands. pp. 169-192.

Hallegatte, S., Shah, A., Lempert, R., Brown, C. and Gill, S. (2012) *Investment decision making under deep uncertainty -- application to climate change.* Policy Research Working Paper Series No. 6193: The World Bank.

Hartig, T., Mitchell, R., De Vries, S. and Frumkin, H. (2014) Nature and health. in *Annual Review of Public Health.* pp. 207-228.

Hidano, N. (2002) *The Economic Valuation of the Environment and Public Policy,* Cheltenham, UK: Edward Elgar Publishing.

HM Treasury (2011) *The Green Book: Appraisal and Evaluation in Central Government, Treasury Guidance,* London: HM Treasury.

Holm, D. (1989) Thermal improvement by means of leaf cover on external walls – a simulation model. *Energy and Buildings,* 14, pp. 19–30.

Hong, T., Kim, J. and Koo, C. (2012) LCC and LCCO 2 analysis of green roofs in elementary schools with energy saving measures. *Energy and Buildings,* 45, pp. 229-239.

Hop, M. E. C. M. and Hiemstra, J. A. (2013) Contribution of green roofs and green walls to ecosystem services of urban green. *Acta Horticulturae,* (No.990), pp. 475-480.

Hoyano, A. (1988) Climatological uses of plants for solar control and the effects on the thermal environment of a building. *Energy and Buildings,* 11(1-3), pp. 181-199.

Hunt, H. D. (2008) Green house values. *Tierra Grande,* 15(2).

Hunter, A. M., Williams, N. S. G., Rayner, J. P., Aye, L., Hes, D. and Livesley, S. J. (2014) Quantifying the thermal performance of green façades: a critical review. *Ecological Engineering,* 63, pp. 102-113.

Ichihara, K. and Cohen, J. P. (2011) New York City property values: what is the impact of green roofs on rental pricing? *Letters in spatial and resource sciences,* 4(1), pp. 21-30.

Interagency Working Group on Social Cost of Carbon, U. S. G. (2015) *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* Washington DC: Whitehouse.

Jamei, E. and Rajagopalan, P. (2017) Urban development and pedestrian thermal comfort in Melbourne. *Solar Energy,* pp. 681.

Jayasooriya, V. M. and Ng, A. W. M. (2013) Development of a framework for the valuation of Eco-System Services of Green Infrastructure. *20th International Congress on Modelling and Simulation (Modsim2013),* pp. 3155-3161.

Jayasooriya, V. M., Ng, A. W. M., Muthukumaran, S. and Perera, B. J. C. (2017) Green infrastructure practices for improvement of urban air quality. *Urban Forestry & Urban Greening,* 21, pp. 34-47.

Jim, C. Y. (2001) Managing urban trees and their soil envelopes in a contiguously developed city environment. *Environmental Management,* 28(6), pp. 819–832.

Jones, R. (2002) *Tecticolous invertebrates: a preliminary investigation of the invertebrate fauna on green roofs in urban London.* English Nature, London.

Jones, R. N. and Ooi, D. (2014) Living Brooklyn: Baseline Report on the Economics of the Urban Water Cycle in the Brooklyn Industrial Precinct. in,Melbourne: Victoria Institute of Strategic Economic Studies. pp. 42.

Jones, R. N., Young, C. K. and Symons, J. (2015) *Assessing the Economic Value of Green Infrastructure. Green Paper.* Melbourne: Victoria Institute of Strategic Economic Studies, Victoria University.

Joshi, S. V. and Ghosh, S. (2014) On the air cleansing efficiency of an extended green wall: A CFD analysis of mechanistic details of transport processes. *Journal of theoretical biology,* 361, pp. 101-110.

Kadas, G. (2006) Rare invertebrates colonizing green roofs in London. *Urban Habitats,* 4.

Karteris, M., Theodoridou, I., Mallinis, G., Tsiros, E. and Karteris, A. (2016) Towards a green sustainable strategy for Mediterranean cities: Assessing the benefits of large-scale green roofs implementation in Thessaloniki, Northern Greece, using environmental modelling, GIS and very high spatial resolution remote sensing data. *Renewable and sustainable energy reviews,* 58, pp. 510-525.

Kats, G. (2013) *Greening Our Built World: Costs, Benefits, and Strategies,* Washington DC: Island Press.

Katsoulas, N., Antoniadis, D., Tsirogiannis, I. L., Labraki, E., Bartzanas, T. and Kittas, C. (2017) Microclimatic effects of planted hydroponic structures in urban environment: measurements and simulations. *International Journal of Biometeorology,* 61(5), pp. 943-956.

Keniger, M. and Bennetts, P. (2014) Fiona Stanley Hospital. *Architecture Australia,* 103(5), pp. 86-94.

Kew, B., Pennypacker, E. and Stuart Echols, S. (2014) Can greenwalls contribute to stormwater management? A study of cistern storage greenwalls first flush capture. *Journal of Green Building,* 9, pp. 85-99.

Kim, J., Hong, T. and Koo, C. (2012) Economic and environmental evaluation model for selecting the optimum design of green roof systems in elementary schools. *Environmental Science & Technology,* 46(15), pp. 8475-8483.

Klein, P. M. and Coffman, R. (2015) Establishment and performance of an experimental green roof under extreme climatic conditions. *Science of the Total Environment,* pp. 82-93.

Köhler, M. (2008) Green façades—a view back and some visions. *Urban Ecosystems,* 11(4), pp. 423.

Kolb, W. and Schwarz, T. (1986) New habitats on the roof: the possibilities for the provision of extensive verdure. *Anthos,* 1, pp. 4-10.

Kontoleon, K. J. and Eumorfopoulou, E. A. (2010) The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. *Building and Environment,* 45(5), pp. 1287-1303.

Korpela, K. and Kinnunen, U. (2011) How is leisure time interacting with nature related to the need for recovery from work demands? Testing multiple mediators. *Leisure Sciences,* 33, pp. 1-14.

Kotsiris, G., Androutsopoulos, A., Polychroni, E. and Nektarios, P. (2012) Dynamic U-value estimation and energy simulation for green roofs. *Energy and Buildings,* 45, pp. 240-249.

Kowal, C. (2008) Measuring Urban Green. *The New Planner, Winter.*

Koyama, T., Yoshinaga, M., H., H., Maeda, K. and Yamauchi, A. (2013) Identification of key plant traits contributing to the cooling effects of green façades using freestanding walls. *Building and Environment,* 66, pp. 96-103.

Kunapo, J., Fletcher, T., Burns, M. and Ladson, T. (2016) *Integrated Climate Adaptation Model.* Melbourne: Melbourne City Council.

Lansdown, K. P.-M. (2009) *Biogeochemistry of nitrate in headwater streams and atmospheric deposition of the Dandenong Ranges.* Unpublished Ph D, Monash University Clayton, Vic.

Latty, T. (2016) Biodiversity and Green Roof Retrofit. in Wilkinson, S. and Dixon, T., (eds.) *Green Roof Retrofit: Building Urban Resilience,* Chichester: John Wiley & Sons. pp. 106-117.

Lee, J. G., Borst, M., Brown, R. A., Rossman, L. and Simon, M. A. (2015) Modeling the hydrologic processes of a permeable pavement system. *Journal of Hydrologic Engineering*, 20(5).

Lee, K. E. (2015) Gazing at Nature makes you more productive. Defend your research. *Harvard Business Review, September,* pp. 32-33.

Lee, K. E., Sargent, L., Williams, K., Johnson, K. and Williams, N. (2017) Green micro-breaks: Viewing workplace nature improves mood and performance. in *Proceedings of the Seventy-seventh Annual Meeting of the Academy of Management.* pp. Online ISSN: 2151-6561.

Lee, K. E., Williams, K. J. H., Sargent, L. D., Farrell, C. and Williams, N. S. (2014) Living roof preference is influenced by plant characteristics and diversity. *Landscape and Urban Planning,* 122, pp. 152-159.

Levinson, A. (2012) Valuing public goods using happiness data: The case of air quality. *Journal of Public Economics,* 96(9), pp. 869-880.

Lin, P. J., Cangelosi, M. J., Lee, D. W. and Neumann, P. J. (2013) Willingness to pay for diagnostic technologies: a review of the contingent valuation literature. *Value In Health,* 16(5), pp. 797-805.

Lindsey, P. and Bassuk, N. (1992) Redesigning the urban forest from the ground below: a new approach to specifying adequate soil volumes for street trees. *Arboricultural Journal,* 16(1), pp. 25-39.

Lo, A. Y. and Jim, C. Y. (2015) Protest response and willingness to pay for culturally significant urban trees: Implications for Contingent Valuation Method. *Ecological Economics,* 114, pp. 58-66.

Loder, A. (2014) 'There's a meadow outside my workplace': a phenomenological exploration of aesthetics and green roofs in Chicago and Toronto. *Landscape and Urban Planning,* 126, pp. 94-106.

Loh, S. (2008) *Living walls - a way to green the built environment.* BEDP Environment Design Guide 1 (TEC 26).

Loughnan, M., Nicholls, N. and Tapper, N. J. (2012) Mapping heat health risks in urban areas. *International Journal of Population Research,* 2012.

Loughnan, M. E., Tapper, N. J., Phan, T., Lynch, K. and McInnes, J. A. (2013) *A spatial vulnerability analysis of urban populations during extreme heat events in Australian capital cities,* Gold Coast: National Climate Change Adaptation Research Facility.

Lundholm, J. (2006) Green Roofs and Façades: A Habitat Template Approach. *Urban Habitats,* 4, pp. 87-101.

Lundholm, J., MacIvor, J. S., MacDougall, Z. and Ranalli, M. (2010) Plant Species and Functional Group Combinations Affect Green Roof Ecosystem Functions. *PLoS ONE,* (3).

MacIvor, J. S. (2016) Building height matters: nesting activity of bees and wasps on vegetated roofs. *Israel Journal of Ecology & Evolution,* 62(1-2), pp. 88-96.

MacMullan, E., Reich, S., Puttman, T. and Rodgers, K. (2008) *Cost Benefit Evaluation of Ecoroofs:* ECONorthwest, David Evans and Associates, Inc.

Madre, F., Clergeau, P., Machon, N. and Vergnes, A. (2015) Building biodiversity: Vegetated façades as habitats for spider and beetle assemblages. *Global Ecology and Conservation,* 3, pp. 222-233.

Madre, F., Vergnes, A., Machon, N. and Clergeau, P. (2013) A comparison of 3 types of green roof as habitats for arthropods. *Ecological Engineering,* 57, pp. 109-117.

Madre, F., Vergnes, A., Machon, N. and Clergeau, P. (2014) Green roofs as habitats for wild plant species in urban landscapes: First insights from a large-scale sampling. *Landscape and Urban Planning,* 122, pp. 100-107.

Mahdiyar, A., Tabatabaee, S., Sadeghifam, A., Mohandes, S., Abdullah, A. and Meynagh, M. (2016) Probabilistic private cost-benefit analysis for green roof installation: A Monte Carlo simulation approach. *Urban Forestry & Urban Greening,* 20, pp. 317-327.

Mahmoud, A., Asif, M., Hassanain, M., Babsail, M. and Sanni-Anibire, M. (2017) Energy and economic evaluation of green roofs for residential buildings in hot-humid climates. *Buildings,* 7(2), pp. 30.

Mahmoudi, P., Hatton MacDonald, D., Crossman, N. D., Summers, D. M. and van der Hoek, J. (2013) Space matters: the importance of amenity in planning metropolitan growth. *Australian Journal of Agricultural and Resource Economics,* 57(1), pp. 38-59.

Malpezzi, S. (2003) Hedonic pricing models: a selective and applied review. in O'Sullivan, T. and Gibb, K., (eds.) *Housing economics and public policy,* Oxford, UK: Blackwell Science. pp. 67-89.

Maltby, E. (2009) *Functional Assessment of Wetlands: Towards evaluation of ecosystem services,* Abington Hall Cambridge: Woodhead Publishing Limited.

Malys, L., Musy, M. and Inard, C. (2016) Direct and indirect impacts of vegetation on building comfort: A comparative study of lawns, green walls and green roofs. *Energies,* 9, pp. 20.

Manso, M. and Castro-Gomes, J. (2015) Green wall systems: a review of their characteristics. *Renewable and sustainable energy reviews,* 41, pp. 863-871.

Mazzali, U., Peron, F., Romagnoni, P., Pulselli, R. and Bastianoni, S. (2013) Experimental investigation on the energy performance of Living Walls in a temperate climate. *Building and Environment,* 64, pp. 57-66.

Meek, A., Jayasuriya, N., Horan, E. and Adams, R. (2015) Environmental benefits of retrofitting green roofs to a city block. *Journal of Hydrologic Engineering,* 20(4), pp. 05014020.

Meierhofer, D. (2013) Ground beetles (Carabidae) on San Francisco green roofs. in *11th Annual CitiesAlive Green Roof and Wall Conference: October 23-26,* 2013, San Francisco: CitiesAlive.

Melbourne Water (2018) Stormwater offsets explained. Available: https://www.melbournewater.com.au/planning-and-building/developer-guides-and-resources/drainage-schemes-and-contribution-rates-1-1 [Accessed: 3/07/2019].

Mentens, J., Raes, D. and Hermy, M. (2003) The effect of orientation on the water balance of green roofs In Paper Presented to the Greening Rooftops for Sustainable Communities: the first North American green roof infrastructure conference, awards and trade show, Chicago.

Mentens, J., Raes, D. and Hermy, M. (2006) Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape Urban Plan,* 77, pp. 217-226.

Morgan, S., Celik, S. and Retzlaff, W. (2013) Green roof storm-water runoff quantity and quality. *Journal of Environmental Engineering,* 139(4), pp. 471-478.

Morikawa, H., Takahasi, M. and Kawamura, Y. (1998) More than a 600-fold variation in nitrogen dioxide assimilation among 217 plant taxa. *Plant, Cell & Environment,* 21, pp. 180-190.

Murphy, J. (2013) *Insect Diversity on Extensive Green Roofs in Melbourne.* Unpublished Masters Thesis, University of Melbourne.

Murphy, J., Threlfall, C., Norton, B. A. and Williams, N. S. G. (in review) Location, location, location! Landscape context structures green roof invertebrate communities. *Urban Forestry and Urban Greening.*

Nagase, A. and Nomura, M. (2014) An evaluation of one example of biotope roof in Japan: Plant development and invertebrate colonisation after 8 years. *Urban Forestry & Urban Greening,* 13(4), pp. 714-724.

Nairn, J. R. and Fawcett, R. J. (2014) The excess heat factor: a metric for heatwave intensity and its use in classifying heatwave severity. *International Journal of Environmental Research and Public Health,* 12(1), pp. 227-253.

Nardini, A., Andri, S. and Crasso, M. (2012) Influence of substrate depth and vegetation type on temperature and water runoff mitigation by extensive green roofs: Shrubs versus herbaceous plants. *Urban Ecosystems,* 15(3), pp. 697-708.

National Parks Service (2017) *Green Roof Benefits,* Available: https://www.nps.gov/tps/sustainability/new-technology/green-roofs/benefits.htm [Accessed July 16 2017].

Niachou, A., Papakonstantinou, K., Santamouris, M., Tsangrassoulis, A. and Mihalakakou, G. (2001) Analysis of the green roof thermal properties and investigation of its energy performance. *Energy and Buildings,* 33, pp. 719-29.

Niu, H., Clark, C., Zhou, J. and Adriaens, P. (2010) Scaling of economic benefits from green roof implementation in Washington, DC. *Environmental Science & Technology,* 44(11), pp. 4302-4308.

Norton, B. A., Coutts, A. M., Livesley, S. J., Harris, R. J., Hunter, A. M. and Williams, N. S. G. (2015) Planning for cooler cities: a framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landscape and Urban Planning,* 134, pp. 127-138.

Nowak, D. and Crane, D. (1998) The Urban Forest Effects (UFORE) model: quantifying urban forest structure and functions. in *Integrated Tools Proceedings,* http://www.nrs.fs.fed.us.

Nowak, D. J., Crane, D. E. and Stevens, J. C. (2006) Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening,* 4(3–4), pp. 115-123.

Nowak, D. J., Hirabayashi, S., Bodine, A. and Hoehn, R. (2013) Modeled PM2.5 removal by trees in ten U.S. cities and associated health effects. *Environmental Pollution,* 178(0), pp. 395-402.

Nurmi, V., Votsis, A., Perrels, A. and Lehvävirta, S. (2016) Green roof cost-benefit analysis: special emphasis on scenic benefits. *Journal of Benefit-Cost Analysis,* 7(3), pp. 488-522.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R. R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K. K. Y. and Rowe, B. (2007) Green roofs as urban ecosystems: ecological structures, functions, and services. *Bioscience,* 57(10), pp. 823.

Okvat, H. A. and Zautra, A. J. (2011) Community Gardening: A Parsimonious Path to Individual, Community, and Environmental Resilience. *American Journal of Community Psychology,* 47(3-4), pp. 374-387.

Olivieri, F., Di Perna, C., D'Orazio, M., Olivieri, L. and Neila, J. (2013) Experimental measurements and numerical model for the summer performance assessment of extensive green roofs in a Mediterranean coastal climate. *Energy and Buildings,* 63, pp. 1-14.

Olmsted, F. (1865) *The value and care of parks:* In Report to the Congress of the State of California (Reprinted in Landscape Architecture, 17: 20-23).

Ondoño, S., Martínez-Sánchez, J. J. and Moreno, J. L. (2016) Research article: The composition and depth of green roof substrates affect the growth of Silene vulgaris and Lagurus ovatus species and the C and N sequestration under two irrigation conditions. *Journal of Environmental Management,* 166, pp. 330-340.

Orsini, F., Gasperi, D., Marchetti, L., Piovene, C., Draghetti, S., Ramazzotti, S., Bazzocchi, G. and Gianquinto, G. (2014) Exploring the production capacity of rooftop gardens (RTGs) in urban agriculture: the potential impact on food and nutrition security, biodiversity and other ecosystem services in the city of Bologna. *Food Security,* 6(6), pp. 781-792.

Page, J. L., Winston, R. J. and Hunt Iii, W. F. (2015) Soils beneath suspended pavements: An opportunity for stormwater control and treatment. *Ecological Engineering,* 82, pp. 40-48.

Parkins, K. L. and Clark, J. A. (2015) Green roofs provide habitat for urban bats. *Global Ecology and Conservation,* 4, pp. 349-357.

Pearce, D. and Ulph, D. (1998) A social discount rate for the United Kingdom. in Pearce, D., (ed.) *Economics and Environment: Essays on Ecological Economics and Sustainable Development,* Cheltenham: Edward Elgar. pp. 268-85.

Pearce, H. and Walters, C. L. (2012) Do green roofs provide habitat for bats in urban areas? *Acta Chiropterologica*, 14(2), pp. 469.

Peck, S., Callaghan, M., Kuhn, M. and Bass, B. (1999) *Greenbacks from Green Roofs: Forging A New Industry In Canada. Status Report on Benefits, Barriers and Opportunities for Green Roof and Vertical Garden Technology Diffusion.* Ottowa: Canada Mortgage and Housing Corporation.

Peng, L. and Jim, C. (2015) Economic evaluation of green-roof environmental benefits in the context of climate change: the case of Hong Kong. *Urban Forestry & Urban Greening,* 14(3), pp. 554-561.

Pérez, G., Coma, J., Martorell, I. and Cabeza, L. F. (2014) Vertical Greenery Systems (VGS) for energy savings in buildings: A review. *Renewable and sustainable energy reviews,* 39, pp. 139-165.

Pérez, G., Coma, J., Sol, S. and Cabeza, L. F. (2017) Green façade for energy savings in buildings: The influence of leaf area index and façade orientation on the shadow effect. *Applied Energy,* 187, pp. 424-437.

Pérez, G., R. L.,, Vila, A., González, J. M. and Cabeza, L. F. (2011) Green vertical systems forbuildings as passive systems for energy savings. *Appl Energy,* 88, pp. 4854–9.

Perini, K., Bazzocchi, F., Croci, L., Magliocco, A. and Cattaneo, E. (2017) The use of vertical greening systems to reduce the energy demand for air conditioning. Field monitoring in Mediterranean climate. *Energy & Buildings,* 143, pp. 35-42.

Perini, K., Ottelé, M., Fraaij, A. L. A., Haas, E. M. and Raiteri, R. (2011) Vertical greening systems and the effect on air flow and temperature on the building envelope. *Building and Environment,* 46(11), pp. 2287-2294.

Perini, K. and Rosasco, P. (2013) Cost–benefit analysis for green façades and living wall systems. *Building and Environment,* 70, pp. 110-121.

Pianella, A., Bush, J., Chen, Z., Williams, N. and Aye, L. (2016a) Green roofs in Australia: review of thermal performance and associated policy development. in Zuo, J., Daniel, L. and Soebarto, V., (eds.) *Fifty years later: Revisiting the role of architectural science in design and practice: 50th International Conference of the Architectural Science Association* Adelaide: Architectural Science Association and The University of Adelaide. pp. 795–804.

Pianella, A., Clarke, R., Williams, N., Chen, Z. and Aye, L. (2016b) Steady-state and transient thermal measurements of green roof substrates. *Energy & Buildings,* pp. 123.

Poë, S., Stovin, V. and Berretta, C. (2015) Parameters influencing the regeneration of a green roof's retention capacity via evapotranspiration. *Journal of Hydrology,* 523, pp. 356-367.

Prodanovic, V., Hatt, B., McCarthy, D., Zhang, K. and Deletic, A. (2017) Green walls for greywater reuse: Understanding the role of media on pollutant removal. *Ecological Engineering,* 102, pp. 625-635.

Pugh, T. A., MacKenzie, A. R., Whyatt, J. D. and Hewitt, C. N. (2012) Effectiveness of green infrastructure for improvement of air quality in urban street canyons. *Environmental Science & Technology,* 46(14), pp. 7692-7699.

Raimondo, F., Trifilo, P., Gullo, M. A. L., Andri, S., Savi, T. and Nardini, A. (2015) Plant performance on Mediterranean green roofs: interaction of species-specific hydraulic strategies and substrate water relations. *AoB Plants,* pp. 1.

Rayner, J. P., Farrell, C., Raynor, K. J., Murphy, S. M. and Williams, N. S. G. (2016) Plant establishment on a green roof under extreme hot and dry conditions: the importance of leaf succulence in plant selection. *Urban Forestry & Urban Greening,* 15, pp. 6-14.

Rayner, J. P., Raynor K.J. and Williams N.S.G. (2010) Façade Greening: a case study from Melbourne, Australia. in Prosdocimi G. and Orsini, F., (ed.) *11th International Conference on Landscape and Urban Horticulture:* ACTA Hort.

Razzaghmanesh, M., Beecham, S. and Salemi, T. (2016) The role of green roofs in mitigating Urban Heat Island effects in the metropolitan area of Adelaide, South Australia. *Urban Forestry & Urban Greening,* 15, pp. 89-102.

Razzaghmanesh, M. (2017) Thermal performance investigation of a living wall in a dry climate of Australia. *Building and Environment,* 112, pp. 45-62.

Ren, Z., Wang, X. and Chen, D. (2014) Heat stress within energy efficient dwellings in Australia. *Architectural Science Review,* 57(3), pp. 227-236.

Riley, B. (2017) The state of the art of living walls: Lessons learned. *Building and Environment,* 114, pp. 219-232.

Rosenzweig, C., Gaffin, S. and Parshall, L. (2006) *Green Roofs in the New York Metropolitan Region Research Report:* Columbia University Center for Climate Systems Research, NASA Goddard Institute for Space Studies.

Russo, A., Escobedo, F. J., Cirella, G. T. and Zerbe, S. (2017) Edible green infrastructure: An approach and review of provisioning ecosystem services and disservices in urban environments. *Agriculture, Ecosystems & Environment,* 242, pp. 53-66.

Sahnoune, S. and Benhassine, N. (2017) Quantifying the impact of green-roofs on urban heat island mitigation. *International Journal of Environmental Science and Development,* 8(2), pp. 116-123.

Sailor, D., Elley, T. and Gibson, M. (2012) Exploring the building energy impacts of green roof design decisions-a modeling study of buildings in four distinct climates. *Journal of Building Physics,* 35(4), pp. 372-391.

Santamouris, M. (2014) Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy,* 103, pp. 682-703.

Santamouris, M., Pavlou, C., Doukas, P., Mihalakakou, G., Synnefa, A., Hatzibiros, A. and Patargias, P. (2007) Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens. *Energy,* 32(9), pp. 1781-1788.

Savi, T., Marin, M., Boldrin, D., Incerti, G., Andri, S. and Nardini, A. (2014) Green roofs for a drier world: effects of hydrogel amendment on substrate and plant water status. *Science of the Total Environment,* 490, pp. 467-76.

Savio, P., Rosenzweig, C., Sokecki, W. D. and Slosberg, R. B. (2006) *Mitigating New York City's Heat Island with Urban Forestry, Living Roof, and Light Surfaces.* New York City Regional Heat Island Initiative. Albany, NY: The New York State Energy Research and Development Authority.

Scalley, B. D., Spicer, T., Jian, L., Xiao, J., Nairn, J., Robertson, A. and Weeramanthri, T. (2015) Responding to heatwave intensity: Excess Heat Factor is a superior predictor of health service utilisation and a trigger for heatwave plans. *Australian and New Zealand Journal of Public Health,* 39(6), pp. 582-587.

Schettinia, E., Blancoa, I., Campiotti, C., Bibbianic, C., Fantozzi, F. and Voxa, G. (2016) Green control of microclimate in buildings. *Agriculture and Agricultural Science Procedia,* 8, pp. 576 – 582.

Seresinhe, C. I., Preis, T. and Moat, H. S. (2015) Quantifying the Impact of Scenic Environments on Health. 5, pp. 16899.

Shanahan, D., Bush, R., Gaston, K., Lin, B., Dean, J., Barber, E. and Fuller, R. (2016) Health benefits from nature experiences depend on dose. *Scientific Reports,* 6, pp. 10.

She, N. and Pang, J. (2010) Physically based green roof model. *Journal of Hydrologic Engineering,* 15(6), pp. 458-464.

Silva, C. M., Gomes, M. G. and Silva, M. (2016) Green roofs energy performance in Mediterranean climate. *Energy and Buildings,* 116, pp. 318-325.

Sims, A., Robinson, C., Smart, C., Voogt, J., Hay, G., Lundholm, J., Powers, B. and O'Carroll, D. (2016) Retention performance of green roofs in three different climate regions. *Journal of Hydrology,* 542, pp. 115-124.

Sirmans, S., Macpherson, D. and Zietz, E. (2005) The composition of hedonic pricing models. *Journal of real estate literature,* 13(1), pp. 1-44.

Sisco, L., Monzer, S., Farajalla, N., Bashour, I. and Saoud, I. P. (2017) Roof top gardens as a means to use recycled waste and A/C condensate and reduce temperature variation in buildings. *Building & Environment,* 117, pp. 127-134.

Speak, A., Rothwell, J., Lindley, S. and Smith, C. (2012) Urban particulate pollution reduction by four species of green roof vegetation in a UK city. *Atmospheric Environment,* 61, pp. 283-293.

Sproul, J., Wan, M., Mandel, B. and Rosenfeld, A. (2014) Economic comparison of white, green, and black flat roofs in the United States. *Energy and Buildings,* 71, pp. 20-27.

Stern, N. (2007) *The Economics of Climate Change: the Stern Review,* Cambridge: Cambridge University Press.

Stern, P. C., Easterling, W. E. and National Research Council (U.S.). Panel on the Human Dimensions of Seasonal-to-Interannual Climate Variability. (1999) *Making climate forecasts matter,* Washington, D.C.: National Academy Press.

Stovin, V., Poë, S., De-Ville, S. and Berretta, C. (2015) The influence of substrate and vegetation configuration on green roof hydrological performance. *Ecological Engineering,* 85, pp. 159-172.

Stovin, V., Vesuviano, G. and Kasmin, H. (2012) The hydrological performance of a green roof test bed under UK climatic conditions. *Journal of Hydrology,* 414, pp. 148-161.

Sun, T., Grimmond, C. S. B. and Ni, G. (2016) How do green roofs mitigate urban thermal stress under heat waves? *Journal of Geophysical Research: Atmospheres,* 121(10), pp. 5320-5335.

Susca, T., Gaffin, S. R. and Dell'osso, G. R. (2011) Positive effects of vegetation: urban heat island and green roofs. *Environmental Pollution,* 159(8-9), pp. 2119-26.

Sustainability Victoria (2014) *Victorian Households Energy Report.* Melbourne: Sustainability Victoria.

Szota, C., Farrell, C., Williams, N., Arndt, S. and Fletcher, T. (2017) Drought-avoiding plants with low water use can achieve high rainfall retention without jeopardising survival on green roofs. *Science of the Total Environment,* 603-604, pp. 340-351.

Szota, C., Fletcher, T., Desbois, C., Rayner, J., Williams, N. and Farrell, C. (In prep) A correction factor to predict in-situ rainfall retention performance of green roof substrates from laboratory measurements. *Water,* 9, pp. 920.

Taleghani, M. (2017) Outdoor thermal comfort by different heat mitigation strategies - A review. *Renewable and sustainable energy reviews,* in press.

TEEB (2012) *The Economics of Ecosystems and Biodiversity: The Ecological and Economic Foundations,* London and Washington: Earthscan.

ten Brink, P. (2011) *The Economics of Ecosystems and Biodiversity in National and International Policy Making,* London and Washington: Earthscan.

Tomalty, R., Komorowski, B. and Doiron, D. (2010) *The monetary value of the soft benefits of green roofs:* Canada Mortgage and Housing Corporation, Ottawa.

Tonietto, R., Fant, J., Ascher, J., Ellis, K. and Larkin, D. (2011) A comparison of bee communities of Chicago green roofs, parks and prairies. *Landscape and Urban Planning,* 103(1), pp. 102-108.

Torrance, S., Bass, B., MacIvor, J. and McGlade, T. (2013) *City of Toronto guidelines for biodiverse green roofs.* Toronto: City of Toronto Planning Division.

Treasury Board of Canada (1998) *Benefit-Cost Analysis Guide,* Ottawa, Canada: Treasury Board of Canada.

Tselekis, K. (2012) Literature Review of the Potential Energy Savings and Retention Water from Green Roofs in Comparison with Conventional Ones. *Scientific Journal of Riga Technical University. Environmental and Climate Technologies,* 9(40), pp. 2012.

Tzachanis, A. D. (2011) The energy efficiency of natural shading with climbing plants *Environmental Engineering & Management Journal,* 10(9), pp. 1379-1385.

Ulrich, R. S. (1993) Biophilia, biophobia, and natural landscapes. in Kellert, S. R. and Wilson, E. O., (eds.) *The biophilia hypothesis*, Washington DC: Island Press. pp. 73-137.

Ulrich, R. S. (2002) Health benefits of gardens in hospitals. in *Plants for People International Exhibition Floriade,* Netherlands. pp. 5.

Ulubeyli, S. and Arslan, V. (2017) Economic viability of extensive green roofs through scenario and sensitivity analyses: Clients' perspective. *Energy and Buildings,* 139, pp. 314-325.

Urban, J. (2008) *Up by Roots: Healthy Soils in the Built Environment,* Champaign, IL, USA: International Society for Arboriculture.

van den Berg, A., Hartig, T. and Staats, H. (2007) Preference for nature in urbanized societies: stress, restoration, and the pursuit of sustainability. *Journal of Social Issues,* 63, pp. 1540-4560.

Van Mechelen, C., Dutoit, T. and Hermy, M. (2015a) Adapting green roof irrigation practices for a sustainable future: A review. *Sustainable Cities and Society,* 19, pp. 74-90.

Van Mechelen, C., Dutoit, T., Kattge, J. and Hermy, M. (2014) Plant trait analysis delivers an extensive list of potential green roof species for Mediterranean France. *Ecological Engineering,* 67, pp. 48-59.

Van Mechelen, C., Van Meerbeek, K., Dutoit, T. and Hermy, M. (2015b) Research Paper: Functional diversity as a framework for novel ecosystem design: The example of extensive green roofs. *Landscape and Urban Planning,* 136, pp. 165-173.

van Raalte, L., Nolan, M., Thakur, P., Xue, S. and Parker, N. (2012) *Economic Assessment of the Urban Heat Island Effect* Melbourne: AECOM Australia Pty Ltd.

Veisten, K., Smyrnova, Y., Klæboe, R., Hornikx, M., Mosslemi, M. and Kang, J. (2012) Valuation of Green Walls and Green Roofs as Soundscape Measures: Including Monetised Amenity Values Together with Noise-attenuation Values in a Cost-benefit Analysis of a Green Wall Affecting Courtyards. *International Journal of Environmental Research and Public Health,* 9(11), pp. 3770.

Venn, S. J., Kotze, D. J., Lassila, T. and Niemelä, J. K. (2013) Urban dry meadows provide valuable habitat for granivorous and xerophylic carabid beetles. *Journal of Insect Conservation,* 17.

Vera, S., Pinto, C., Tabares-Velasco, P. C., Bustamante, W., Victorero, F., Gironás, J. and Bonilla, C. A. (2017) Influence of vegetation, substrate, and thermal insulation of an extensive vegetated roof on the thermal performance of retail stores in semiarid and marine climates. *Energy & Buildings,* 146, pp. 312-321.

Villarreal, E. L. and Bengtsson, L. (2005) Response of a Sedum green-roof to individual rain events. *Ecological Engineering,* 25, pp. 1-7.

Voicu, I. and Been, V. (2008) The Effect of Community Gardens on Neighboring Property Values. *Real Estate Economics*, 36(2), pp. 281-243.

Volder, A. and Dvorak, B. (2014) Event size, substrate water content and vegetation affect storm water retention efficiency of an un-irrigated extensive green roof system in Central Texas. *Sustainable Cities and Society,* 10, pp. 59-64.

Voyde, E., Fassman, E. and Simcock, R. (2010) Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. *Journal of Hydrology,* (3-4), pp. 384.

Wachter, S. (2004) *The Determinants of Neighborhood Transformations in Philadelphia - Identification and Analysis: The New Kensington Pilot Study:* University of Pennsylvania, The Wharton School.

Walsh, C. J., Fletcher, T. D. and Burns, M. J. (2012) Urban Stormwater Runoff: A New Class of Environmental Flow Problem. PLoS ONE, 7(9), pp. e45814.

White, E. and Gatersleben, B. (2011) Greenery on residential buildings: Does it affect preferences and perceptions of beauty? *Journal of Environmental Psychology,* 31, pp. 89-98.

Wilkinson, S. and Castiglia Feitosa, R. (2015) Retrofitting Housing with Lightweight Green Roof Technology in Sydney, Australia, and Rio de Janeiro, Brazil. *Sustainability,* 7(1), pp. 1081-1098.

Wilkinson, S., Feitosa, R., Kaga, I. and Franceschi, I. (2017) Evaluating the Thermal Performance of Retrofitted Lightweight Green Roofs and Walls in Sydney and Rio de Janeiro. *Procedia Engineering,* 180, pp. 231-240.

Wilkinson, S. and Orr, F. (2017) The impact of horticulture therapy on mental health care consumers on a retrofitted roof. in *23rd Annual Pacific Rim Real Estate Society Conference,* Sydney, Australia. pp. 13.

Wilkinson, S. J. and Dixon, T. (2016) *Green Roof Retrofit: building urban resilience,* Chichester: John Wiley & Sons.

Williams, N. S. G., Hughes, R. E., Jones, N. M., Bradbury, D. A. and Rayner, J. P. (2010) The performance of native and exotic species for extensive green roofs in Melbourne, Australia. *Acta Horticulturae,* (No.881), pp. 689-696.

Williams, N. S. G., Lundholm, J. and MacIvor, J. S. (2014) Do green roofs help urban biodiversity conservation? *Journal of Applied Ecology,* 51(6), pp. 1643-1649.

Wolf, K. and Lundholm, J. (2008) Water uptake in green roof microcosms: Effects of plant species and water availability. *Ecological Engineering,* 33, pp. 179-186.

Wolter, A., Wolter, S. and Schroeder, F. G. (2012) Potentials of running a living wall. in *Acta Horticulturae.* pp. 157-164.

Wong, G. K. L. and Jim, C. Y. (2016) Do vegetated rooftops attract more mosquitoes? Monitoring disease vector abundance on urban green roofs. *Science of the Total Environment,* 573, pp. 222-232.

Wong, I. and Baldwin, A. (2016) Investigating the potential of applying vertical green walls to high-rise residential buildings for energy-saving in sub-tropical region. *Building and Environment,* 97, pp. 34-39.

Wong, N. H., Kwang Tan, A. Y., Chen, Y., Sekar, K., Tan, P. Y., Chan, D., Chiang, K. and Wong, N. C. (2010) Thermal evaluation of vertical greenery systems for building walls. *Building and Environment,* 45(3), pp. 663-672.

Yakkundimath, T. (2013) Green buildings; Benefits to our environment. in Nautiyal, S., Rao, K. S., Kaechele, H., Raju, K. V. and Schaldach, R., (eds.) *Knowledge systems of societies for adaptation and mitigation of impacts of climate change,* Berlin Heidelberg: Springer-Verlag. pp. 669-681.

Yang, J., Yu, Q. and Gong, P. (2008) Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment,* 42(31), pp. 7266-7273.

Zheng, Z., Szota, C., Fletcher, T. D., Williams, N. S. G. and Farrell, C. (in review) The storage capacity of substrates can be a more important driver of rainfall retention on green roofs than evapotranspiration. *Water Research.*

Zhou, L., Shen, G., Woodfin, T., Chen, T. and Song, K. (2017) Ecological and economic impacts of green roofs and permeable pavements at the city level: the case of Corvallis, Oregon. *Journal of Environmental Planning and Management,* pp. 1-21.

PHOTO REFERENCES

Cover image: Aspire Melbourne, 299 King Street, Melbourne - Courtesy of Architect: Elenberg Fraser, Developer: ICD Property, and Visualiser: Floodslicer.

The pathway from ecosystem strcuture and processes to human well-being - de Groot, R., Fisher, B., Christie, M., Aronson, J., Braat, L., Gowdy, J., Haines-Young, R., Maltby, E. and Neuville, A. (2010) Integrating the ecological and economic dimensions in biodiversity and ecosystem service valuation. in Kumar, P., (ed.) *The Economics of Ecosystems and Biodiversity Ecological and Economic Foundations*, London and Washington: Earthscan.

Council House 2, Melbourne - David Hannah for City of Melbourne.

Coromandel Place, Melbourne - Paul Custy for City of Melbourne.

Cumulative exposure-response relationship for Melbourne 1998–2009 showing cold and warm relative risk (RR) and average annual number of deaths for each degree °C over the temperature range - Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Tobias, A., Tong, S., Rocklöv, J., Forsberg, B., Leone, M., De Sario, M., Bell, M. L., Guo, Y.-L. L., Wu, C.-f., Kan, H., Yi, S.-M., de Sousa Zanotti Stagliorio Coelho, M., Saldiva, P. H. N., Honda, Y., Kim, H. and Armstrong, B. (2015) Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *The Lancet*, 386(9991).

Rankins Lane, Melbourne - Benjamin Botting for City of Melbourne.

ISBN: 978-1-86272-781-6

Institute of Sustainable Industries and Liveable Cities
Victoria University
PO Box 14428
Melbourne Vic 8001
Ph. 03 9919 1340

How to contact us

Online:
melbourne.vic.gov.au

In person:
Melbourne Town Hall – Administration Building
120 Swanston Street, Melbourne
Business hours, Monday to Friday
(Public holidays excluded)

Telephone:
03 9658 9658
Business hours, Monday to Friday
(Public holidays excluded)

Fax:
03 9654 4854

In writing:
City of Melbourne
GPO Box 1603
Melbourne VIC 3001
Australia

Interpreter services
We cater for people of all backgrounds
Please call 03 9280 0726

03 9280 0717	廣東話
03 9280 0719	Bahasa Indonesia
03 9280 0720	Italiano
03 9280 0721	普通话
03 9280 0722	Soomaali
03 9280 0723	Español
03 9280 0725	Việt Ngữ
03 9280 0726	عربي
03 9280 0726	한국어
03 9280 0726	हिंदी
03 9280 0726	All other languages

National Relay Service:
If you are deaf, hearing impaired or speech-impaired, call us via the National Relay Service: Teletypewriter (TTY) users phone 1300 555 727 then ask for 03 9658 9658
9am to 5pm, Monday to Friday (Public holidays excluded)

melbourne.vic.gov.au

CITY OF MELBOURNE