This paper examines the benefits of green roofs, walls and facades that have been established by research. In most cases, experimental testing, and/or computer modelling based on experimental data are used. In this overview, green roofs receive the most coverage because more research has been carried out and firm conclusions can be drawn from it. Research into the most effective uses of green walls and facades is underway in many parts of the world.

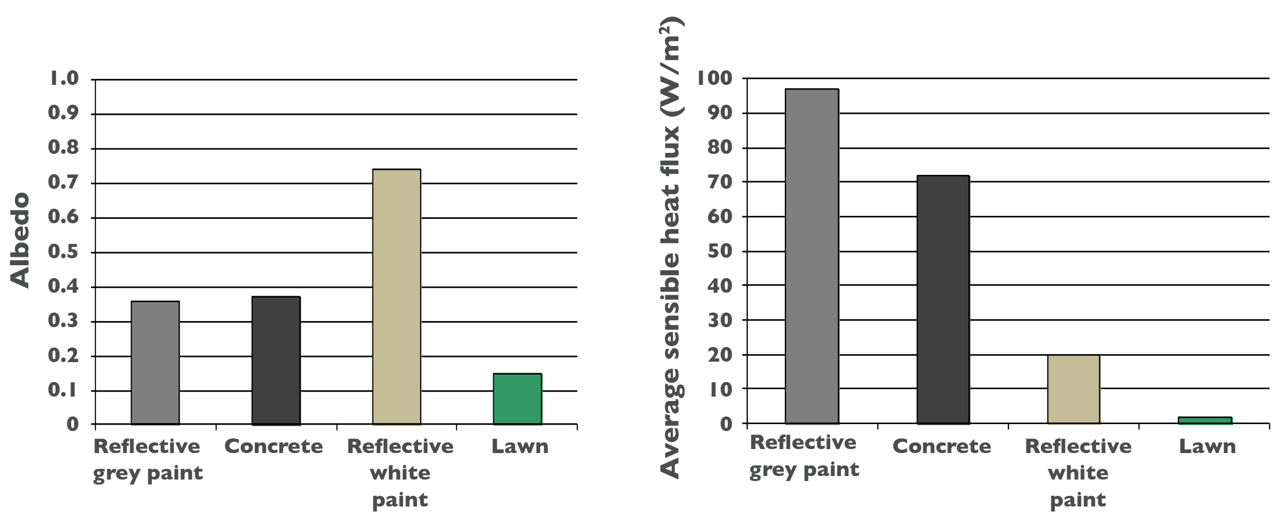
The information provided here is from peer-reviewed scientific, architecture and engineering research journals, technical reports and books. References and links are provided to the original articles but some of these will be accessible only through journal subscriptions. Data used here have been summarised or re-plotted to demonstrate key points.

Reducing the energy budget of a building

Green roofs, walls and facades can reduce cooling and heating costs, by reducing heat gain or loss across the building surface.

Figure 1 shows the results of a study at Kobe University, Japan, where a green roof performed best out of four different roof treatments in reducing heat flux from the outside to the inside of the building. The roofs differed in albedo (the ability to reflect, rather than absorb, solar energy). A high albedo value means that more light is reflected and less is absorbed. A green roof planted with lawn grass had the lowest albedo, but was most effective at reducing heat flux into the building. Heat flux across the "cool roof" treatment using reflective white paint was 10 times higher than for the green roof, although its albedo was almost 5 times greater. The sensible heat flux across the white roof surface is small because most solar radiation is reflected, and little is absorbed. Across the green roof, although the amount of solar radiation absorbed is high, sensible heat flux is small because of loss of latent heat, from evaporation of water from plants and the growing substrate. Grey paint and concrete had similar reflectance, but heat flux with alternative cool roof paint (reflective grey) was greater than the bare concrete roof alone.

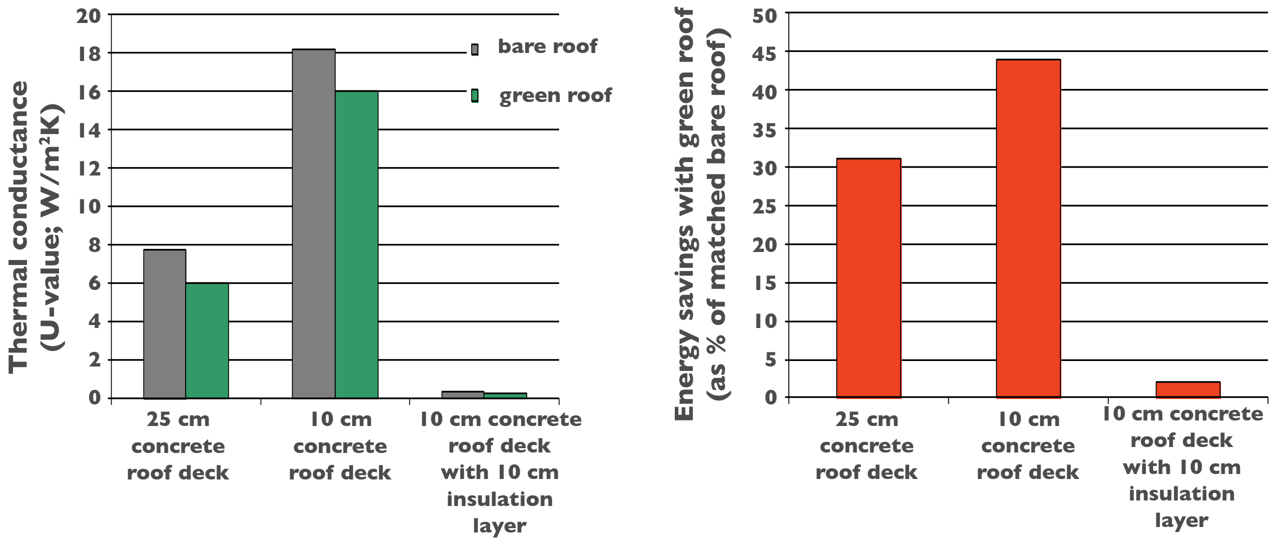
Figure 1. Albedo (ability to reflect solar radiation) and sensible heat flux under different roof treatments.



Source: Takebayashi H, Moriyama M (2007) ***Surface heat budget on green roof and high reflection roof for mitigation of urban heat island,*** *Building and Environment 42: 2971-2979.*

A green roof provides significant cooling benefits compared to a bare roof, although the most effective cooling comes from inclusion of an insulation layer. Modelling comparisons suggest that green roofs could be useful on poorly insulated buildings, to reduce the thermal conductance across the roof deck. Thermal conductance (U-value) is the inverse of the resistance to transfer of heat (R-value). A study conducted in Athens modelled the effect of adding a green roof to concrete roofs of different construction. Figure 2 (left panel) shows that a green roof lowers heat transfer across a 25 cm thick concrete roof and a 10 cm concrete roof, and that the energy savings provided by installing a green roof on an otherwise uninsulated roof may be significant (right panel).

Figure 2. Effect of a green roof on heat transfer (thermal conductance; left panel) and energy savings (right panel) modelled for different types of roof construction.

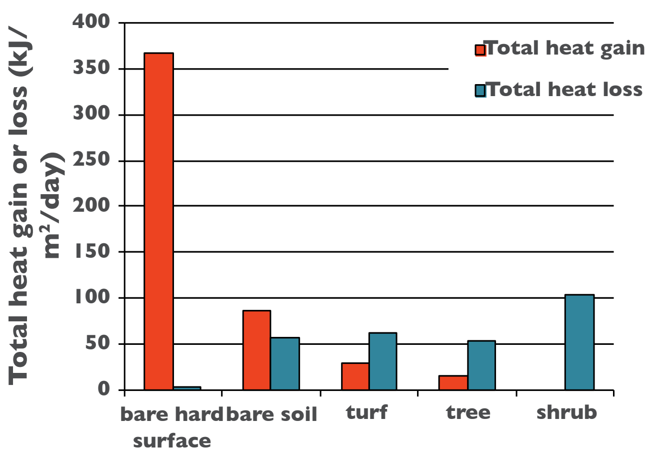


Source: Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A, Mihalakakou G, (2001) Analysis of the green roof thermal properties and investigation of its energy performance, Energy and Buildings 33: 719-729.

Insulation of a building translates into energy savings both for heating and cooling. In Melbourne, with a well-insulated building, winter heating is likely to dominate total energy costs although this will depend on heating and cooling set points preferred by the building's occupants. The 'R' value of an insulation material is a measure of its resistance to transfer of heat. Establishing the R value offered by a green roof, wall and façade is not straightforward as it depends on a complex interaction of all the materials used, the depth of the growing substrate and the amount of water it holds, as well as the plant selection, degree of coverage by plants and whether that coverage is present year-round. The following studies investigated the effect of green roofs compared to bare roofs on the thermal performance of buildings.

A study carried out in Singapore that compared the effect of different vegetation types on a green roof with 40 cm deep soil, showed that heat gain was prevented, and heat loss was greatest under vegetation with the largest and densest foliage cover (*Raphis* palm used as a shrub) – see Figure 3. The bare hard roof surface accumulated and retained the most heat. Turf, and trees with an open canopy, provided less cooling benefit, with similar heat loss to that of bare soil. The reduction of heat gain and increased heat loss from soil, compared to the hard roof surface, is most likely due to evaporation of water held in the soil.

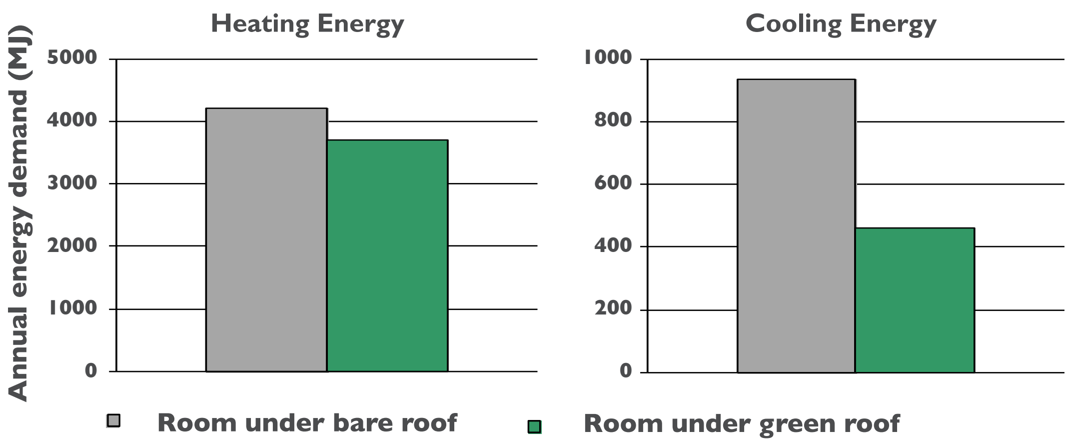
Figure 3. A comparison of heat gain and loss on a green roof covered with different types of vegetation.



Source: Wong NH, Chen Y, Ong CL, Sia A, Investigation of thermal benefits of rooftop garden in the tropical environment, Building and Environment 38 (2003) 261-270.

Figure 4 shows the results of a study on energy demand under a green roof and bare roof in Melbourne. Temperature measurements were made between September 2008 and July 2009, in a room with a conventional waterproofed concrete bare roof, and a room with a green roof installed over the roof deck. These measurements were used in a simulation to predict the effect of a green roof on annual energy costs. Parameters used in the model included cooling and heating set points of 24 °C and 18 °C, respectively, and an assumption that the space was heated or cooled between 8 am and 6 pm. Results showed that cooling and heating costs for the room covered with a vegetated roof would be 50% and 12% lower, respectively, than for the same room with a conventional bare concrete roof. For a building constructed from less strongly insulating materials, although winter heating and summer cooling requirements would be higher, the green roof would achieve comparable energy savings.

Figure 4. Heating and cooling energy demand in a room under a bare roof and a green roof.

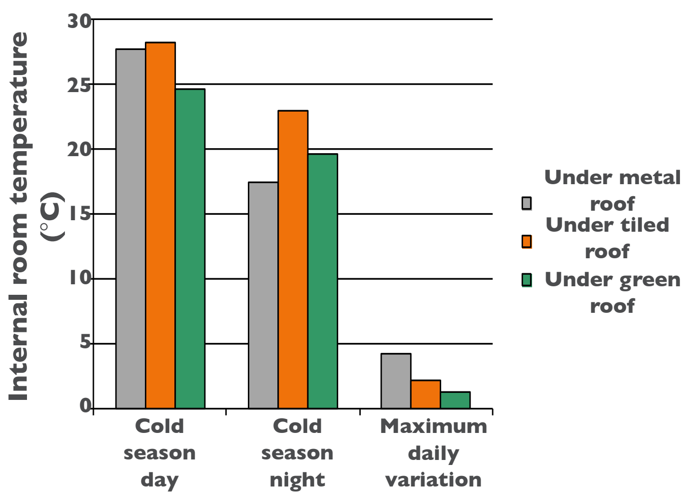


Source: Chen and Williams (2009) Green roofs as an adaptation to climate change: modelling the green roof at the Burnley Campus, The University of Melbourne, Research Report for CSIRO Climate Adaptation Flagship.

One of the major benefits of the insulation provided by a green roof is in reducing heat fluctuations between the inside and outside of the building. The stability of internal temperatures under a green roof is increased, and contributes to thermal comfort year-round: heat gain from the outside to inside is prevented in summer, and heat loss from inside to outside is reduced in winter. The construction of the roof deck and other building components plays a major role in determining the extent of heat gain or loss from a building.

Figure 5 shows the results of a study in Brazil that compared external roof temperatures with internal ceiling temperatures in a single storey building, with rooms covered by a green roof, metal roof or a ceramic tile roof. Measurements were made over a week in both warm and cold seasons. Heat flux was recorded between the three roof types and the internal surface of the ceiling inside each room, and internal air temperature was measured 1.5 m above the floor in the three rooms. The green roof was planted with a monoculture of a low-growing succulent herb (*Bulbine frutescens*) in a substrate 140 mm deep. The graph shows that the room under the green roof showed the smallest variation in daily temperature during the day during the cold season: this was also the case during the warm season, with a maximum daily variation of 1.2°C.

Figure 5. Internal temperature effects of different roof types.



Source: Parizotto S & Lamberts R (2011) Investigation of green roof thermal performance in a temperate climate: a case study of an experimental building in Florianópolis city, Southern Brazil, Energy and Buildings 43:1712-1722.

Green roofs in a hot, dry climate

In Adelaide, between 2009 and 2012, the properties of different green roof systems were monitored to determine the extent to which a green roof can enhance the thermal properties of a building in a hot and dry climate. Green roofs were installed on ANZ House, a 22-storey building in Adelaide's central business district.

Two plots were had profiles of 300 mm deep growing substrate. The other four plots were shallow green roof profiles of 125 mm thick substrate. Two of the shallow depth plots had a trafficable aluminium grating installed 150 mm above the surface of substrate, to create an air gap above (Figure 6). The aluminium grating treatment was tested to investigate the effect of shading of the vegetation.

The substrates used were either a lightweight growing medium or a heavier substrate made from recycled brick and other inorganic materials. Each green roof plot contained the same number, species and arrangement of Australian ground covering and grass-like species: Carpobrotus rossii (Karkalla), Myoporum parvifolium (Creeping Boobialla), Dianella 'Tasred' and Lomandra 'Nyalla'. All species were able to grow vertically through the aluminium grating.

Figure 6. Experimental green roof systems on the roof of ANZ House, Adelaide.

Table 2 shows the variation in temperature measured across a single day (3 February 2012). On this day, the air temperature variation was 19.8°C.

Table 2. Variation in temperature measured below the growing substrate on 3 February 2012, of 6 green roof test plots with lightweight or inorganic growing substrate, and with or without an aluminium grating installed over the vegetation.

	Lightweight	Lightweight + grating	Lightweight	Inorganic	Inorganic + grating	Inorganic
Variation in temperature (°C)	15.5	12.6	5.4	16.8	8.1	2.0
Depth (mm)	125	125	300	125	125	300

At both substrate depths, temperature fluctuations of the underlying surface were smaller for the inorganic growing substrate with its higher thermal mass, than for the lightweight growing substrate. The variation in temperature across the whole day was halved with the aluminium grating installed over the substrate and vegetation. The grating contributes to this increased insulation effect by a combination of shading, and from the creation of an unstirred air layer.

Source: Clay R, Wild N, Hopkins G, Goodwin C (2012) Determining and understanding thermal characteristics of green roofs in the City of Adelaide, Appendix 1 of Green Roof Trials Monitoring Report by Fifth Creek Studio for SA Government's Building Innovation Fund and Aspen Development Fund No. 1.

http://www.sa.gov.au/upload/franchise/Water,%20energy%20and%20environment/climate_change/documents/BIF/Appendix%201%20Thermal%20characteristics%20of%20green%20roofs.pdf

Experimental studies on green walls and facades focus on the shading (and cooling) benefits that facade greening provides. Even though a broad range of factors influence how much shading a green facade offers (including the presence and type of a support structure, facade orientation and whether the climber is deciduous or evergreen); decreases in wall surface temperature of 5-10°C are common. The most useful assessments come from data collected throughout the year: in future, longitudinal studies could provide additional value, as outcomes are likely to change as the facade matures.

Table 3 shows the results of a Spanish study on green facades. Temperature measurements were made over a year on the north-east, south-east and south-west sides of a building in Golmés, Spain that was covered with the deciduous climber *Wisteria sinensis* (Chinese Wisteria). The climber was grown on a steel mesh support system. Shading of the south-west face of the building provided the greatest cooling effect.

Table 3. Effect of a green facade on building thermal performance.

Parameter measured	Outcome	Effect of the green facade
Difference in temperature in front of and behind the facade	1.4°C cooler in summer 3.8°C warmer in winter	Absorption of light and heat energy by foliage keeps the cavity temperature lower Facade support system creates a microclimate/unstirred air layer next to the wall even when stems are bare
Difference in surface temperature between bare wall and vegetated wall (summer)	Average bare wall temperature is 5.5 °C higher Maximum temperature is 15.2 °C higher	Full leaf cover provides effective shading and prevents heat gain by the building
Difference in relative humidity in front of and behind the facade	7% higher in summer 8% lower in winter	Evapotranspiration from leaves causes a local increase in humidity (and cooling) in summer which is not apparent when stems are bare

Source: Pérez G, Rincón L, Vila A, González JM, Cabeza LF (2011) Behaviour of green facades in Mediterranean Continental climate, Energy Conversion and Management 52:1861–1867.

Hybrid living walls

Research from Adelaide investigated a vertical greening system that combines elements of green facades and living walls. A hybrid living wall system was installed on the west-facing wall of the former Telephone Exchange building, and monitored for 12 months. It was made up of prefabricated panels on a steel frame that was attached to the building. This enables maintenance of the building facade to be carried out behind the system. The system incorporates green walls of approximately 0.5 m^2, planted out with herbaceous species ***Dianella*** 'Tasred', ***Lomandra*** 'Nyalla', ***Ficinia nodosa*** (Knobby Club-rush), and ***Myoporum parvifolium*** (Creeping Boobialla). The green facades are trellis systems that support climbing species grown in planter boxes at height up the building facade. Climbing species used on the green facades were ***Hardenbergia violacea*** (False Sarsaparilla), ***Pandorea pandorana*** (Wonga Wonga Vine), ***Trachelospermum jasminoides*** (Star Jasmine). The choice of mainly native species that use water efficiently keeps water consumption low: in winter, 0.34 litres/m^2/day, while in summer it rose to 3.69 litres/m^2/day.

Air temperature and solar radiation were measured in front

Figure 7. A hybrid living wall in Adelaide incorporates green wall modules and green facades grown in containers.

of, and behind the green facade. Table 3 shows that although there was little reduction in air temperature in front of the green facade (relative to the adjacent bare brick wall), the wall surface temperature was considerably lower. The green facade significantly reduced the amount of solar radiation detected behind the living wall system.

Table 3. Comparison of temperature and solar radiation for bare brick wall (control) and green facade panels of the hybrid living wall.

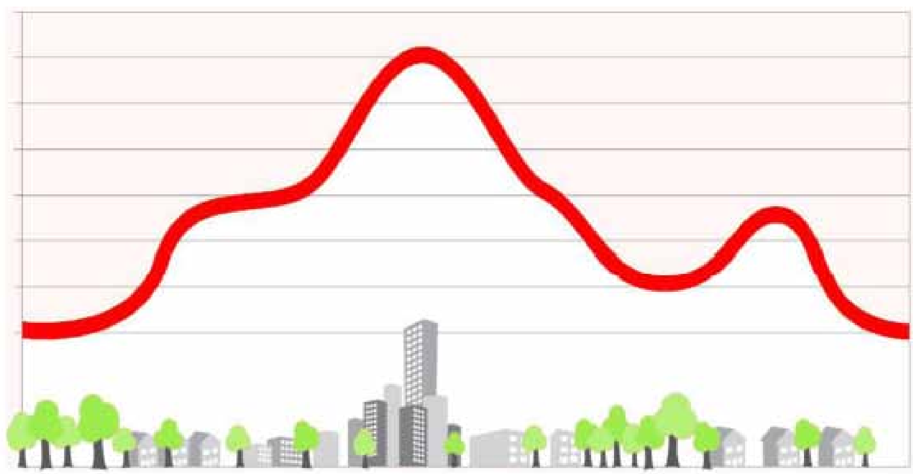
	Air temperature 600 mm in front of wall (°C)	Wall surface temperature (°C)	Gross solar radiation measured in front of wall (W/m^2)	Gross solar radiation measured behind green facade panels (W/m^2)
Control - adjacent brick wall	40.9	45.8	804	-
Green facade - **range over 5 panels**	39.5 - 39.8	37.2 – 38.0	646 - 758	37.3 – 38.1

Source: Hopkins G, Goodwin C, Milutinovic M, Andrew M (2012) Post-construction monitoring report: Living wall system for multi-storey buildings in the Adelaide climate, prepared for The Government of South Australia.

Contribution to urban cooling

Concrete, bricks, glass and large areas of impervious paved footpaths and roads contribute to heat gain in urban areas. This, and the loss of shading and cooling from vegetation in high density urban development, contributes to the formation of urban heat islands: increased ambient temperatures that arise when warm stable air masses develop above cities, particularly during periods of calm weather and low wind speeds (Figure 8).

Figure 8. The urban heat island effect in Melbourne is greatest over the most heavily built up CBD and inner suburbs.



A modelling study conducted by CSIRO and the Nursery and Garden Industry of Australia investigated the likely effect of increasing vegetation cover in Melbourne's CBD on average summer daily maximum (ASDM) temperatures over the period of December through February. Remote sensing imagery from the 2009 summer was analysed, and showed that daytime land surface temperatures were significantly reduced by vegetation. An urban climate model was then used to predict temperature changes under different vegetation schemes for the 2009 climate, and for projected future climates in 2050 and 2090.

Comparisons were made using the CBD in its present form as a reference (with respect to urban boundary and density of vegetation), and the CBD with increased densities of vegetation. Vegetation density was doubled at ground level, installed on green roofs, or both.

Green roof vegetation was 0.5 m high and covered 50% of building rooftops completely. In all models, it was assumed that vegetation was irrigated, so that evapotranspiration rates did not vary significantly between different years. In the 2009 scenario, ASDM temperatures were reduced by 0.3 °C by doubling the density of vegetation in the CBD, or by 0.4°C with green roofs. Increasing vegetation density both at ground level and with green roofs reduced ASDM temperatures by 0.7°C. In comparison, the creation of large urban parklands reduced ASDM temperatures by 2°C. For reference, suburban areas were 0.5 to 0.7°C cooler than the CBD.

The same relative effect of vegetation on ASDM temperatures was predicted for 2050 and 2090. Green roofs, in conjunction with cooling from an increased density of street trees and park vegetation at ground level, could help to decrease urban temperatures, reduce summer heat stress and the peak electricity requirements for air conditioning.

Source: Chen D, Wang X, Khoo YB, Thatcher M, Lin BB, Ren Z, Wang C-H, Barnett G (2013) Assessment of Urban Heat Island and Mitigation by Urban Green Coverage, in Mitigating climate change: the emerging face of modern cities, Khare A, Beckman T (eds), Springer, Berlin, New York.

A 2005 study in Toronto, Canada modelled the effect of implementing green roofs on low-rise buildings with low slope and

An Australian report outlines principles for choosing the green roofs, walls, facades, and other more traditional uses of vegetation to cool urban areas (collectively known as green infrastructure) for cooling of urban spaces in the Greater Melbourne area.

The report is available at http://www.vcccar.org.au/publications.

Source: Coutts A, Livesley S, Norton B, and Williams N (2013) Urban Heat Island Report: Decision principles for the selection and placement of Green Infrastructure, Victorian Centre for Climate Change Adaptation Research.

flat roofs of areas greater than 350 m^2, and concluded that green roofs, implemented as a city-wide strategy, could mitigate the heat island effect, by reducing local ambient temperatures by 0.5 to 2°C. It was calculated that this could save Toronto homeowners and businesses $21 million annually by reducing the energy demand for mechanical cooling.

Source: Banting, D., Doshi, H., Li, J. & Missios, P. 2005, 'Report on the environmental benefits and costs of green roof technology for the City of Toronto', Prepared for City of Toronto and Ontario Centres of Excellence – Earth and Environmental Technologies, Ryerson University, <http://www.toronto.ca/greenroofs/pdf/executivesummary.pdf>

Managing stormwater volume

Green roofs absorb and retain water and can be an effective strategy for reducing stormwater runoff in urban environments. When rain falls on a bare roof, runoff water flows into drains very rapidly. The rate of runoff depends on the slope of the roof as well as the volume of the rain event. When the rain stops, runoff continues until the roof is drained: any water remaining on the surface will evaporate.

On a green roof, plants and growing substrate intercept rainfall. Some water will evaporate directly off plant foliage, but rain that falls directly onto the substrate, or drips off the foliage, percolates downwards. Some water is absorbed by substrate particles, and some drains down into underlying layers where it can be stored if these have the capacity to hold it (typically the drainage and protection/water retention layers). Excess water drains onto the roof and out into the stormwater system, ultimately ending up in our waterways (Figure 9).

Figure 9. Extreme stormwater on the Yarra at Dights Falls.

Source: Dr. Geoff Vietz.

On a green roof, both the time to onset and the time to peak flow of stormwater entry are delayed, and the overall time taken to drain the roof is increased, as shown in Figure 10. The overall volume of stormwater is reduced because of the retention by the substrate and other layers of the green roof.

Published studies suggest that on average, green roofs can capture 50-80% of rainfall (see breakout box on New Zealand green roofs research). Analysis of Bureau of Meteorology rainfall data for Melbourne between 1991-2010 shows that most daily rainfalls are in the range of 1 to 5 mm, summer or winter, but there is usually at least one fall of 10 mm or more each month, even in summer (see Figure 11). This means that in many years, stormwater runoff from large rain events could be collected for irrigation of the green roof itself.

On average, rain fell in Melbourne every 2 days in winter (August) and every 4 days in summer (February). However, the length of dry periods was very variable: about 9% of dry periods lasted 1 week or more, and 1% lasted 2 weeks or more. (The lengthiest dry spell was 36 days, ending in a February.) About 80% of the dry spells that lasted 2 weeks or more occurred in January, February or March. The corresponding high average and maximum temperatures experienced during these months adds to the challenge of maintaining vegetation.

Figure 10. Theoretical graph comparing stormwater runoff from a bare roof and green roof.

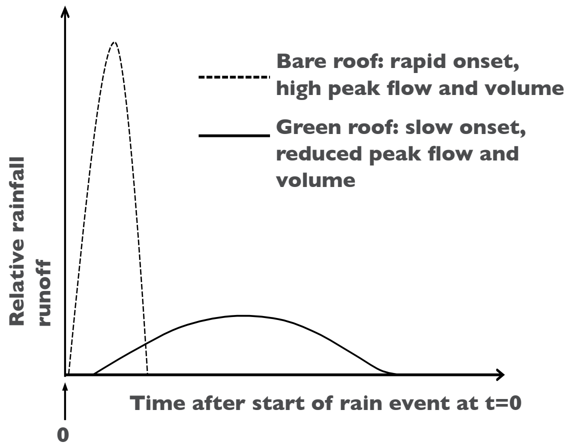
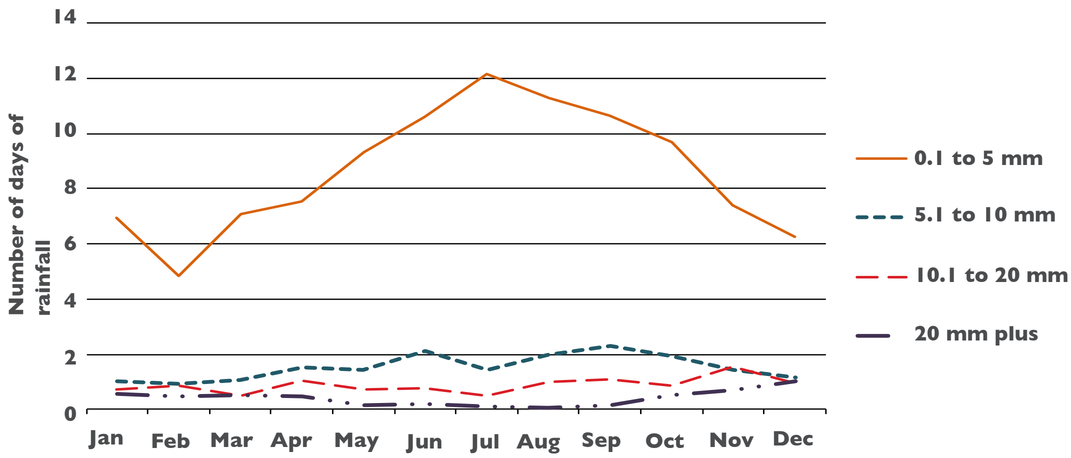


Figure 11. Average number of rain episodes per month for Melbourne between 1991-2010.



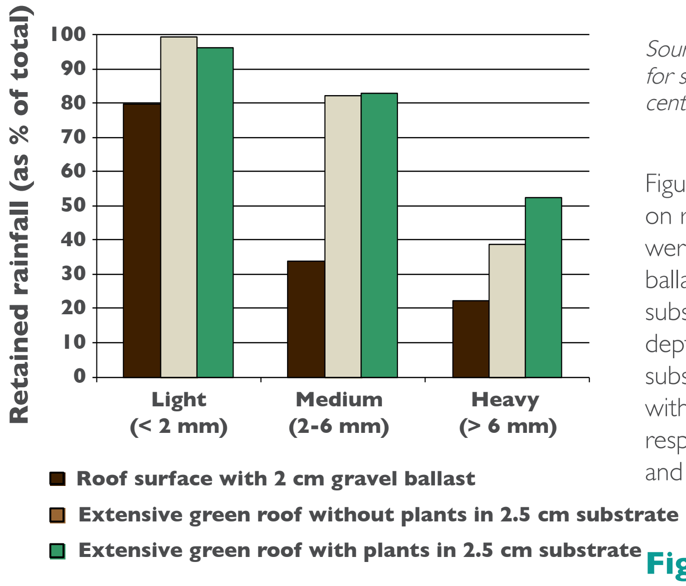
Source: Bureau of Meteorology Climate Data Online, for Melbourne Regional Office weather station 086071.

The advantage of using vegetation to manage stormwater runoff is that it increases the surface area available for rainfall capture, and thus contributes to slow the rate of entry and reduce the volume of stormwater. The height and spread of vegetation, as well as the type and diversity of species used affects how much rainfall plants can capture on their leaves, and how much water they release back into the environment through transpiration. Evaporation of water from the substrate also reduces the overall volume of runoff entering the stormwater system.

Note: When considering international research results, remember that the climate may differ to Australia's. Many European and North American green roofs have very shallow substrates, such as the 2.5 cm deep substrates described in Figure 9. In Melbourne conditions, a minimum depth of 10 cm is recommended for a green roof substrate. Shallower substrates are likely to dry out too quickly, and plants will not survive.

Figure 12 shows data from an experimental green roof study in Michigan, where rainfall retention was measured over 14 months. The three treatments were: a roof with gravel ballast only, an unplanted green roof, and a green roof planted with succulents (*Sedum* species). All roofs had a 2% slope. Runoff was measured for rain events of different intensity. The green roof with plants retained the highest proportion of water from heavy rain events. For smaller rainfall volumes, the substrate-only roof was as effective as the green roof in retaining water. Both captured more water than the ballasted roof.

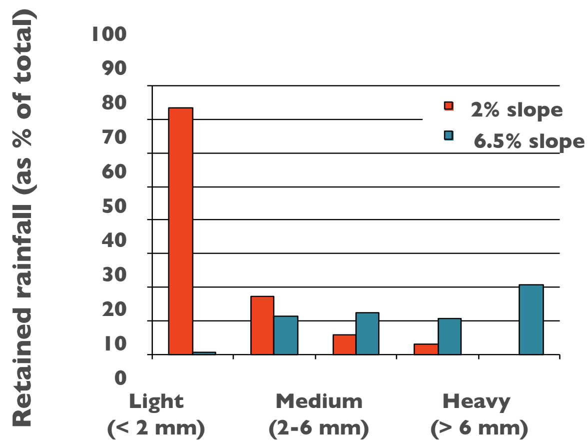
Figure 12. Rainfall retention under three roof treatments for rain events of different intensity.



Source: Van Woert ND, Rowe DB, Andresen JA, Rugh CL, Fernandez RT, Xiao L (2005) Green roof stormwater retention: effects of roof surface, slope and media depth, Journal of Environmental Quality 34:1036-1044.

Figure 13 shows how slope affects stormwater retention. Green roofs with 2% and 6.5% slope were planted with succulents (*Sedum* species) in 4 cm deep growing substrate. Runoff was measured for rain events of different intensity. The difference in percentage runoff between the two slopes was greatest in heavy rain events, with the highest runoff observed from the more steeply sloped roof.

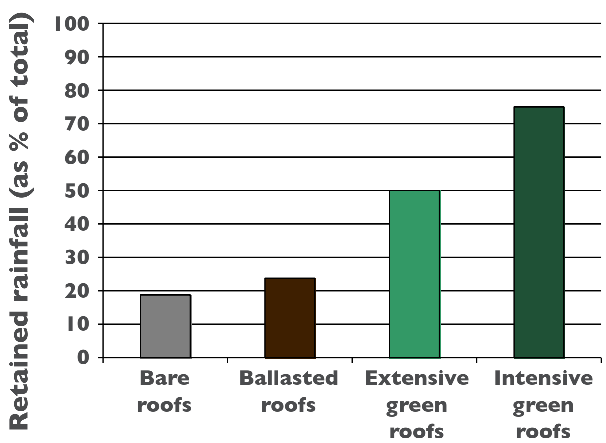
Figure 13. Rainfall retained by different types of green roofs



Source: Mentens J, Raes D, Hermy R (2006) Green roofs as a tool for solving the rainwater runoff problem in the urbanised 21st century? Landscape and Urban Planning 77:217-226.

Figure 14 shows the results of an analysis of published data on rainfall retention across a range of roof types. Data were analysed for 5 bare roofs, 8 roofs covered with gravel ballast, 121 shallow (extensive) green roofs and 11 deeper substrate (intensive) green roofs, with average substrate depths of 0, 50, 100 and 210 mm, respectively. Deeper substrate green roofs retained the most rainfall on average, with minimum and maximum retention of 65 and 85% respectively: for roofs with shallower substrates it was 27 and 81%.

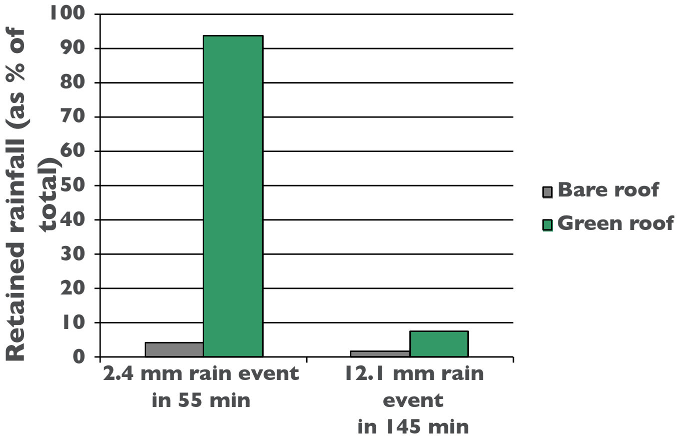
Figure 14. Rainfall retention on green roofs with different slopes.



Source: Van Woert ND, Rowe DB, Andresen JA, Rugh CL, Fernandez RT, Xiao L (2005) Green roof stormwater retention: effects of roof surface, slope and media depth, Journal of Environmental Quality 34:1036-1044.

A green roof captures a higher percentage of rainfall of a light rain event than a heavy one. If the rain event is very small, there may not be any runoff from the green roof, especially if the substrate is dry. During very intense rain events where a large volume of water is delivered in a short time, the substrate may not absorb all the rain that falls, even on a densely vegetated roof. In these situations, the vertical movement of water through the substrate dominates, although vegetated roofs usually still have lower runoff than bare roofs. The runoff from intense or long rain events could be harvested and stored for irrigation. Figure 15 shows how retention varies with different intensities of rainfall. Rainfall runoff was collected from a bare roof, and a green roof with low growing herbaceous and succulent species planted in a growing substrate 10 cm deep. The green roof captures most of the volume of a small rain event. Although the green roof did not capture much of the rainfall from a more intense rain event, it did capture more than the bare roof.

Figure 15. Rainfall retention on a green roof under different rainfall scenarios.



Source: Teemusk A, Mander Ü (2007) Rainwater runoff quantity and quality performance from a green roof: the effects of short-term events, Ecological Engineering 30:271-277.

Rainfall capture by green roofs - New Zealand

Research in Auckland (annual rainfall 1200 mm) compared rainfall retention on four different green roofs and three control (unvegetated) roofs, in relation to the depth and composition of the growing substrates that were used. Control of retention and peak flow are affected by several variables, including the depth, permeability and water holding capacity of the growing substrate, and also by the length of the flow path to perimeter or point drains, and the proportion of the roof that is unvegetated. Rainfall retention can be improved by using a porous granular (ballast) drainage layer, as this increases the porous surface area for water absorption, compared to using cup style drainage sheets. For control roofs, runoff was affected by the roughness of the surface, with steel roofs providing little resistance to runoff compared with bituminous waterproofing membranes with a sandy particulate covering. Despite these many differences in substrate composition and roof design, all green roofs provide control of runoff for events up to 25 mm (Table 4).

Table 4. Range in percentage frequency of rain events of different sizes, along with rainfall retention and reduction in peak flow for four green roofs in Auckland.

Size of rain event (mm)	% Frequency of events (cumulative)
< 2	42 – 52
< 10	72 – 81
< 25	91 – 95

Size of rain event (mm)	% Retention	% Reduction in peak flow
> 2	56 –76	62 – 90
2 – 25	60 – 84	
26 – 69	31 – 58	

Runoff was lower and retention was higher from all living roofs compared with matched control roofs. Retention and reduction of peak flow are likely to be at least 60%, regardless of substrate depth, for the high proportion of rain events that are 25 mm or less. This is true even if only a small proportion of large volume (> 70 mm) rain events is captured: these events are so rare that they make little difference to the overall rainfall total across the year.

For most rain events (those between 2 - 25 mm), the median (mid range) value for runoff is 1.9 mm, while the mode (most common) value is 0.03 mm. These low runoff depths demonstrate that green roofs capture the majority of rainfall, even if the substrate composition and depth vary. The findings of this study underline how stormwater capture can vary with different green roof designs even within a small geographical area. The authors suggest that even in a climate with high rainfall like Auckland, increased substrate depth may yield better plant performance and more effective stormwater capture, with a minimum depth of 100 mm recommended, if supplementary irrigation is not provided.

Source: Fassmand-Beck E, Voyde E, Simcock R, Hong YS (2013) 4 Living roofs in 3 locations: Does configuration affect runoff mitigation? Journal of Hydrology 490:11-20. See also Fassman-Beck EA and Simcock R (2013) Living Roof Review and Design Recommendations for Stormwater Management, prepared by Auckland UniServices for Auckland Council, Auckland Council Technical Report 2013/045.

Improving stormwater quality

In urban environments stormwater collected from surfaces at ground level is usually contaminated. Rainfall runoff carries a mix of litter, organic materials (plant material and animal droppings), dust and soil particles and chemical pollutants such as oils and fertilisers. In contrast, the quality of water arriving at stormwater drains from roofs is relatively high.

Data from two separate experiments (Tables 5 and 6) show the improvement of the quality of runoff from green roofs relative to bare roofs. The higher concentration of nitrogen and phosphorus in runoff from the bare roof is most likely due to the wash down of contaminants in the first flush runoff after rain begins. The greater surface area for potential capture and storage of these contaminants on a green roof (on foliage, in the substrate) reduces the nutrient loading entering stormwater runoff. The green roofs were planted with mixed herbaceous perennials, including succulents, into 10.2 cm deep substrate held in modular boxes that were installed on a roof (Table 5), or succulent species installed as a vegetated mat system on 10 cm deep substrate (Table 6).

Table 5. Comparison of nitrogen (N) and phosphorus (P) content in rainwater and runoff from bare roofs and green roofs.

Nutrient content	Total N (mg/l)	Total P (mg/l)
Rainfall	**0.51**	**0.007**
Bare roof runoff	**0.896**	**0.197**
Green roof runoff	**0.49**	**0.043**

Source: Gregoire BG, Clausen JC (2011) Effect of a modular extensive green roof on stormwater runoff and water quality, Ecological Engineering 37:963-969.

Table 6. Comparison of nitrogen (N) and phosphorus (P) content in rainwater and runoff from bare roofs and green roofs.

Nutrient content	Total N (mg/l)	Total P (mg/l)
Rainfall	0.6 - 1.3	0.012 - 0.019
Bare roof runoff	1.4 - 2.6	0.102 - 0.104
Green roof runoff (vegetated mat)	1.2 - 2.1	0.026 - 0.09

Source: Teemusk A, Mander Ü (2007) Rainwater runoff quantity and quality performance from a green roof: the effects of short-term events, Ecological Engineering 30:271-277.

Most plants grown on a green roof require some fertiliser to be applied for them to grow well in the long term, and leaching of nutrients into roof runoff will reduce water quality to some extent. The nutrients of greatest concern in runoff water quality are phosphorus and nitrogen: high levels of both cause algal blooms in waterways. However, relative to the amount of fertiliser applied to the roof initially, loss of nutrients into runoff can be small. The benefit of a large reduction in stormwater volume probably outweighs the cost of a small increase in nutrient loading. This should be considered in relation to stormwater quantity and quality requirements set by local water authorities.

Table 7 shows the results of an experiment that measured the nutrient concentration of stormwater runoff over a 6-week period. Mid-range starting concentrations of controlled-release fertiliser were applied to bare and vegetated roof areas at 5000 mg/m^2 total nitrogen and 1470 mg/m^2 total phosphorus, respectively. Succulents were pre-grown on a vegetated mat system. Substrates on both bare and green roofs were 4 cm deep. In this study, the concentrations of nutrients released into runoff from the green roof were lower than nutrient release from the bare substrate, but this is not always the case for green roofs. Nutrient concentrations will rise after fertiliser is added, and on a newly planted green roof, leaching of nutrients will likely be high until plants become established.

Table 7. Total nutrient runoff with and without vegetation.

Nutrient	Vegetated green roof	Bare substrate
Total nitrogen	47.35 mg/m^2	849.2 mg/m^2
Total phosphorus	3.27 mg/m^2	28.11 mg/m^2

Source: Emilsson T, Berndtsson JC, Mattsson JE, Rolf K (2007) Effect of using conventional and controlled release fertilizer on nutrient runoff from various vegetated roof systems, Ecological Engineering 29:260-271.

Quality of runoff – Adelaide green roof trials

The water quality from the outflow of green roof systems with shallow or deep substrates was studied over 9 months on the rooftop of ANZ House in Adelaide. Controlled release fertiliser was applied at the same rate to both green roof types.

Using direct and indirect measures of dissolved salt concentration (total dissolved salts, TDS and electrical conductivity, EC), there was a strong trend for runoff from the green roofs areas with deeper substrates to be of higher quality, i.e. have lower TDS and EC. However, there was also a trend for elevated nitrogen (measured as nitrate) and phosphorus concentrations in runoff from the green roofs with deep substrates. These nutrients are highly soluble so their appearance in runoff is not surprising. Given that fertiliser application was the same for both the shallow and deep substrates, it is surprising that the deeper substrate did not provide greater nutrient retention. Sediment levels (measured as turbidity) were higher in runoff from the extensive green roofs. Runoff quality was compared with local, State and national water guidelines suggest that green roof runoff could be recycled for irrigation and other non-potable use. A link to this report is available at:

http://www.sa.gov.au/upload/franchise/Water,%20energy%20and%20environment/climate_change/documents/BIF/Appendix%202%20ANZ%20House%20Green%20Roof%20Trials%20Stormwater%20Quality%20Monitoring.pdf

Urban air quality

Many Australian and international studies show a link between poor air quality and adverse effects on human health. This is particularly evident for people prone to asthma and other respiratory conditions, and those with cardiovascular disease. A study by the Environmental Protection Authority demonstrated an association between elevated nitrogen dioxide , carbon monoxide, ozone and particulate air pollutants (e.g. smoke, dust) and mortality due to cardio-respiratory disease, including asthma, in Melbourne between 1991 and 1996. This association was strongest in warm weather, when ozone levels are high due to increased production at higher temperatures and stable weather conditions that reduce mixing of air (Figure 16).

As urban populations continue to grow, and even with improvements in quality of motor vehicle emissions, it is projected that the concentration of pollutants such as ozone and fine particulate matter (PM2.5) will also rise. Management of pollution requires control of emission sources, and the use of measures that reduce the concentrations of pollutants in the atmosphere. Increasing the amount of vegetation in urban environments is one such measure: plant leaves absorb gaseous pollutants, while particulate matter can fall onto leaves or be washed onto them by rain, and ultimately into the growing medium, where it is degraded or stored.

Sources: EPA (2000) Melbourne Mortality Study: Effects of ambient air pollution on daily mortality in Melbourne 1991-1996, EPA publication 709; EPA (2013) Future Air Quality in Victoria – Final Report, EPA publication 1535.

Figure 16. Summer smog over Melbourne's CBD.

The larger canopies of trees and shrubs offer the biggest surface area for pollution capture, suggesting that green roofs with deeper substrate and the potential to carry a broad range of vegetation types, will be an effective approach to pollution management at height. However as any increase in the surface area available to absorb or adsorb pollutants offers the potential for improvement of air quality, shallower green roofs, or walls and facades planted with herbaceous species may still provide significant benefit. The extent of pollutant capture will vary with the density of foliage cover, and the degree of complexity of the leaf surfaces.

In narrow city streets at ground level (urban canyons; see Figure 17), green walls and facades offer the opportunity for improvement of urban air quality in narrow spaces, by increasing the area that is covered by vegetation and providing more potential surfaces for deposition of pollutants. Not surprisingly, measures of pollution capture in urban canyons (and estimates from modelling studies) vary widely, as so many factors contribute to the outcome, including the dimensions of the urban canyon, and wind speeds through it. A study that modelled the effect of vegetation in London street canyons estimated a reduction of 15% to 40% for nitrogen dioxide and 23% to 60% for particulate matter concentrations, respectively, with the adoption of green walls in an urban canyon that was as wide as it was high.

Major findings are that significant reduction in both gaseous and particulate pollutants are achievable with vegetation on roofs and walls. This is achieved by direct capture of pollutants, and by reducing building heat gain and associated localised warming of the environment. All of these contribute to the creation of urban heat islands and the generation of photochemical smog.

Source: Pugh TAM, Mackenzie AR, Whyatt JD, Hewitt CN (2012) Effectiveness of green infrastructure for improvement of air quality in urban street canyons, Environmental Science and Technology 46:7692-7699.

Figure 17. Urban canyons in our cities can be stark places.

Source of image at right: Edwin Tee.

Human health and well being

Our cities are noisier places to live in: construction noise, vehicular traffic, and the sounds of HVAC (heating, ventilation and air-conditioning) equipment are constant features of Melbourne's aural landscape.

Modelling studies show that though green roofs provide some attenuation of noise, this is small: up to a maximum of 10 dB across most of the frequency ranges that have been tested. Tests on a range of green wall and facade systems in Singapore's HortPark reveal a similar outcome. So far, for green roofs, there is no evidence for increased sound absorption beyond a substrate depth of 20 cm (with depths up to 40 cm tested). Any small decrease in the volume of outside noise is an additional, unsolicited benefit of a green roof, wall or facade.

Sources: Van Renterghem T, Botteldooren D (2008) Numerical evaluation of sound propagating over green roofs, Journal of Sound and Vibration 317:781-799; Wong NH, Tan AYK, Tan PY, Chang K, Wong NC (2010) Acoustics evaluation of vertical greenery systems for building walls, Building and Environment 45:411-420.

Green roofs for sound reduction

At the University of Tasmania, a green roof was one of the practical solutions chosen by JAWS Architects to attenuate noise from the new Union Bar building. Sound levels of 50 dBA reached nearby residents from the old building. The new building incorporated a green roof with 125 mm deep substrate planted with turf, along with other design features incorporated into the building envelope and HVAC systems, to reduce sound transmission to the outside. Internal sound levels of 110 dBA were inaudible outside the new building.

Source: Hopkins G, Goodwin C (2011) Living Architecture, CSIRO Publishing.

During the Melbourne summer, the city often experiences several consecutive days of hot weather. This is associated with higher rates of illness and death: extreme high temperatures add an additional stress to people whose health may already be fragile, particularly the elderly. A report by the Victorian Department of Health quantified the increased incidence of heat-related illness and death during severe heat waves in January 2009. During this time, there were 62% more deaths than would have been expected on average for this time of year, mostly for the age group 75 years or older. Keeping our buildings cooler through increased shading is likely to contribute to reducing the loss of human lives, and the demands on health services associated with extreme hot weather.

Source: Department of Health (2012) January 2009 Heatwave in Victoria: an Assessment of Health Impacts.

Vegetated environments are good for people. Traditional public parks and open spaces provide refreshment and restful views, space for recreation, cool areas of shade in summer, and community gardens offer opportunities for food production. All offer the potential for social interaction and community building. They are good for physical and psychological health and wellbeing and provide relief from the pressures of high-density living. Cost estimates of morbidity and mortality associated with the lack of access to green open space are not easy to dissect as there are usually concurrent, co-dependent factors that limit people's ability to engage with nature. Exposure to nature improves people's ability to focus, cope with stress, generate creative ideas, and decreases volatile, anti social, behaviours.

Source: Townsend M, Weerasuriya R (2010) Beyond Blue to Green: the benefits of contact with nature for mental health and well-being, Beyond Blue Limited: Melbourne.

Property value

There is very little published research on the impacts of green roofs, walls or facades on property value. Research in Canada estimated that buildings with a recreational green roof achieve an 11% increase in property value, and buildings with views onto green roofs have a 4.5% increase in property value.

Source: Tomalty, R. & Komorowski, B. 2010, The Monetary Value of the Soft Benefits of Green Roofs, Smart Cities Research Services, <http://www.greenroofs.org/resources/Monetary_Value_of_Soft_Benefits_of_Green_Roofs.pdf>

Green roofs research at The University of Melbourne

Since 2008, researchers at The University of Melbourne's Burnley Campus have undertaken research evaluating green roofs for Australian conditions, with a focus on plants, substrates, hydrology, energy use and environmental psychology (Figure 18).

Experiments quantified the performance of Australian native and exotic species on roofs and in controlled environments. Of 56 species tested for survival in the absence of irrigation, plants with low water use and high leaf succulence, such as *Sedum pachyphyllum* and *S. xrubrotinctum* proved to be the most successful. However, to reduce stormwater runoff from green roofs, plants also need to dry out substrates between rainfall events, a function that low water use succulents are incapable of. This research showed that plants from specialised natural habitats similar to green roofs, such as rock outcrops, can balance high water use with high drought tolerance. The most successful species included *Dianella revoluta*, *Stypandra glauca* and *Lomandra* spp. An additional benefit was the capacity of these plants to re-sprout following desiccation, further improving survival after drought.

The development and analysis of lightweight growing substrates, based on mineral and waste components, such as scoria, crushed roof-tiles and bottom ash (wastes from coal-powered electricity generation) has led to multiple green roof installations across Melbourne. This work also included testing and evaluating a wide range of substrate components and mixes; and investigating the use of water-retention additives in substrates, such as silicates, hydrogel and biochar. Of these, biochar was the most effective, resulting in lighter substrates that held more water and delaying the onset of permanent wilting in test plants by up to two days. This research also showed that the effectiveness of retention additives varied, depending on substrate and additive properties (e.g. fine silicates were ineffective in coarse-textured substrates).

Hydrology research under natural rainfall conditions found that a 100 mm deep scoria substrate can reduce stormwater runoff in Melbourne by 43 to 88%, depending on the season. Further work evaluated the influence of three different substrates (bottom ash, roof tile and scoria) and succulent vegetation cover (planted vs. bare) on evapotranspiration and retention capacity under simulated rainfall conditions. The results showed that the effect of plant cover was influenced by season with greater evapotranspiration in spring. Planted modules also retained more rainfall than bare modules for medium and large rainfall events and overall the cumulative evapotranspiration was greatest from the bottom ash substrate (bare and planted) and significantly less in scoria. Water retention also differed between substrate types, with scoria retaining at least 20% less rainfall after large events than both bottom ash and roof tile substrates, probably due to lower evapotranspiration from scoria between rainfall events. Results of an energy study completed in 2009 showed that a 125 mm deep scoria substrate green roof reduced building energy use by 38% on a summer day.

Environmental psychology research demonstrated that people prefer 'meadow-like' green roofs, dominated by green strappy or grass-like plants. The addition of flowers on the green roof further increased preference scores. Viewing this type of green roof was also found to improve concentration and could result in improved workplace productivity.

Figure 18. Green roof research at the University of Melbourne includes plant survival experiments in glasshouses and on roofs, and hydrology experiments in controlled environments under cover.