Australian Government

Rural Industries Research and
Development Corporation

Living Wall and Green Roof Plants for Australia

RIRDC Publication No. 11/175

RIRDC Innovation for rural Australia

Australian Government
Rural Industries Research and
Development Corporation

Living Wall and Green Roof Plants for Australia

by Melinda Perkins and Daryl Joyce

May 2012

RIRDC Publication No. 11/175
RIRDC Project No. PRJ-005130

© 2012 Rural Industries Research and Development Corporation.
All rights reserved.

ISBN 978-1-74254-352-9
ISSN 1440-6845

Living Wall and Green Roof Plants for Australia
Publication No. 11/175
Project No. PRJ-005130

The information contained in this publication is intended for general use to assist public knowledge and discussion and to help improve the development of sustainable regions. You must not rely on any information contained in this publication without taking specialist advice relevant to your particular circumstances.

While reasonable care has been taken in preparing this publication to ensure that information is true and correct, the Commonwealth of Australia gives no assurance as to the accuracy of any information in this publication.

The Commonwealth of Australia, the Rural Industries Research and Development Corporation (RIRDC), the authors or contributors expressly disclaim, to the maximum extent permitted by law, all responsibility and liability to any person, arising directly or indirectly from any act or omission, or for any consequences of any such act or omission, made in reliance on the contents of this publication, whether or not caused by any negligence on the part of the Commonwealth of Australia, RIRDC, the authors or contributors.

The Commonwealth of Australia does not necessarily endorse the views in this publication.

This publication is copyright. Apart from any use as permitted under the *Copyright Act 1968*, all other rights are reserved. However, wide dissemination is encouraged. Requests and inquiries concerning reproduction and rights should be addressed to the RIRDC Publications Manager on phone 02 6271 4165.

Researcher Contact Details

Daryl Joyce
School of Agriculture and Food Sciences
The University of Queensland
Gatton QLD 4343

Phone: 61 (0)7 5460 1725
Fax: 61 (0)7 5460 1112
Email: d.joyce@uq.edu.au

In submitting this report, the researcher has agreed to RIRDC publishing this material in its edited form.

RIRDC Contact Details

Rural Industries Research and Development Corporation
Level 2, 15 National Circuit
BARTON ACT 2600

PO Box 4776
KINGSTON ACT 2604

Phone: 02 6271 4100
Fax: 02 6271 4199
Email: rirdc@rirdc.gov.au.
Web: http://www.rirdc.gov.au

Electronically published by RIRDC in May 2012
Print-on-demand by Union Offset Printing, Canberra at www.rirdc.gov.au
or phone 1300 634 313

Foreword

Green roofs and living walls in the built environment offer significant environmental, economic and social benefits. Contemporary systems use innovative materials and technology to create a plant-building interface that is optimal for growing plants while maintaining the structural integrity of the building. Such systems have been widely adopted overseas. A lack of proven plant species suited to Australia's harsh climate is one barrier to the uptake of green infrastructure in this country.

This project has overviewed green roofs and living walls literature, developed a 'plant selection matrix' tool, identified plant species suitable for extensive green roofs and exterior living walls in subtropical Australia, and reported on a workshop aimed at conveying findings to industry and identifying consensus priorities for future work. In the research context, it has also demonstrated that substantial temperature reductions can be achieved with green infrastructure in this climate.

The information in this report will be of use to growers in the nursery industry and to green infrastructure suppliers and design professionals. It also provides industries and their clients with greater ability to implement green wall and extensive green roof projects, growing this industry in Australia.

This project was funded from RIRDC, the core funds for which are provided by the Australian Government.

This report is an addition to RIRDC's diverse range of over 2000 research publications and forms part of our New Plant Products R&D program, which aims to facilitate the development of new industries based on plants or plant products that have commercial potential for Australia.

Most of RIRDC's publications are available for viewing, free downloading or purchasing online at www.rirdc.gov.au. Purchases can also be made by phoning 1300 634 313.

Craig Burns
Managing Director
Rural Industries Research and Development Corporation

About the Author

Melinda Perkins has been involved in green roof research since 2009. She has presented seminars on the horticultural aspects of green roofs and walls at various university lectures, industry meetings, workshops and conferences. Daryl Joyce was recently Principal Investigator on two serial projects investigating the horticultural potential of the fruit tree Red Bayberry (*Myrica rubra*) in Australia.

Acknowledgments

The authors recognise with thanks the input of colleagues, industry partners and support staff that helped to progress this project from a concept to a reality. Particular mention is made of substantial contributions provided by Brad Walker, Ryan Folkard and Frank Cover in the supply and construction of the green roof and living wall demonstration structures. We would also like to express our gratitude to Arno King and David Simons for their expertise, hospitality and the donation of germplasm material. Our thanks go too, to the following people for their involvement in the Living Wall and Green Roof Workshop held as part of this project: Margaret Cover, Cameron Turner, Brad Walker, John Daly, Mark Thomson, Sid Dyer, Geoff Wilson and Jose Florenciano. We also gratefully acknowledge organisational support from the RIRDC and Aussie Colours Pty Ltd.

Abbreviations

CAM	crassulacean acid metabolism
CBD	central business district
EGR	extensive green roof
UHI	urban heat island
VGM	vertical green module

Plant Species

Green Roof Plants

Calandrinia balonensis	Broad Leaf Parakeelya
Calandrinia eremea	Twining Purslane
Eremophila debilis	Winter Apple, Amulla
Myoporum parvifolium	Creeping Boobialla, Creeping Myoporum
Sedum sexangulare	Tasteless Stonecrop
Thelionema umbellatum	Lemon Flax Lily

Green wall plants

Bulbine vagans	Bulbine Lily*
Calandrinia remota	Round Leaf Parakeelya
Dianella tasmanica	Tasman Flax Lily
Hardenbergia violacea	Native Sarsaparilla, Purple Coral Pea
Plectranthus argentatus	Silver Plectranthus
Plectranthus parviflorus	Cockspur Flower
Ricinocarpos pinifolius	Wedding Bush

*not to be confused with *Bulbine bulbosa* which also shares this name

Contents

Tables

Figures

Executive Summary

What the report is about

This report provides the Australian green infrastructure industry with greater knowledge of plant selection for extensive green roofs and living walls in Australia's challenging climate. The many environmental, economic and social benefits of green infrastructure have resulted in its increasing adoption overseas. However, a lack of proven plant species suited to Australian conditions has deterred growth of the industry in this country.

Who is the report targeted at?

This report is targeted at horticulturalists, landscape architects and commercial suppliers of green infrastructure components. This work is intended to provide their clients with greater confidence to invest in green wall and extensive green roof projects, thereby growing the industry in Australia. It is also trusted that local and state government authorities will find this report useful in developing guidelines and policies that promote the implementation of green infrastructure.

Where are the relevant industries located in Australia?

The green infrastructure industry is concentrated in urban centres around Australia, particularly in the southern capital cities of Melbourne, Adelaide and Sydney. A gradual progression of the industry further north is now occurring. It is the growers, suppliers and design professionals in this subtropical to tropical region who will benefit the most from this research.

Background

Green roofs and living walls in the built environment offer very significant triple bottom line benefits. These benefits include ameliorating urban heat island effects, reducing energy demands and attendant CO2 emissions (e.g. from air conditioning) as well as improving the wellbeing and productivity of citizens, and providing habitat for micro- and macro-organisms. Although novel in Australia, green roofs and living walls are becoming increasingly widespread throughout Europe, Asia and North America. They represent a tangible opportunity for industry in Australia. However, plant products proven suitable for use in harsh Australian environments are needed. This is particularly so for outdoor green walls and extensive green roofs versus intensive roof gardens. In these two situations, areas are usually expansive, maintenance is ideally low and the growing medium (viz. water storage capacity) is typically shallow; for example, extensive green roofs on large factory roof tops. With careful planning and maintenance, green infrastructure can be a useful element of sustainable building design in this country.

Aims/objectives

The overall aim of this research was to provide those wishing to develop an Australian green infrastructure industry with a greater knowledge of plant species selection for extensive green roofs and external green walls. Specific objectives were to: (1) review existing knowledge of plant selection and performance for extensive green roofs and living walls; (2) use this to generate plant species selection matrices for identifying putatively suitable plants for such situations in Australia; and (3) conduct trials to evaluate the *in situ* performance of these plants. A final objective (4) was to then communicate the project outcomes with key stakeholders via a workshop.

Methods used

An overview of available literature, internet sources and industry/research contacts identified green roof and living wall plant selection criteria used overseas and critically analysed their relevance in the context of Australia's climate. From this information selection, matrices for two different green infrastructure applications of extensive green roofs and exterior living walls were generated and applied to a number of Australian native plant species to identify at least five species putatively suited to each application. Uniform plants of each species were propagated from stock plants already on hand or which had been sourced from native seed suppliers, native plant nurseries or private collections. Plants were transplanted as plugs or tubestock into the living wall and extensive green roof areas of two custom-built steel structures located at The University of Queensland's Gatton Campus. An additional two identical structures without green infrastructure were also located at the trial site. Monthly evaluations of plant survival, plant growth as measured by dimensions (e.g. plant height and width, canopy area/density) and digital photography, plant development stages of flowering and seed set, pest and disease symptoms and canopy temperature were conducted. Internal roof and wall temperatures were monitored throughout the trial period for both the vegetated and un-vegetated (control treatment) structures. The experiment was designed and analysed in consultation with a University of Queensland biometrician. Outcomes were showcased at a workshop on green infrastructure species for Australia which included a forum to address the issues affecting growth of the industry.

Results/key findings

An overview of the literature (Objective 1) revealed that plant species for green infrastructure in Australia ideally need to withstand stresses of high temperature, wind and water deficit while providing good vegetation cover. Perennial species with mat-forming or dense clumping growth habits were considered best for long-term coverage. From these and other important traits, 16-point selection matrices were developed for extensive green roofs and external living walls (Objective 2). Identification of six species putatively suited to extensive green roofs and seven species for green walls was achieved using the selection matrices (Objective 3). In terms of actual performance (Objective 4), the native *Myoporum parvifolium* (Creeping Myoporum) and *Eremophila debilis* (Winter Apple), and the exotic *Sedum sexangulare* (Tasteless Stonecrop) displayed the greatest survival and coverage on an extensive green roof. Growth rates of the three species were higher than expected with full coverage achieved 21 weeks after transplanting. For the green wall *Bulbine vagans* (Bulbine Lily), *Plectranthus parviflorus* (Cockspur Flower) and *Plectranthus argentatus* (Silver Plectranthus) performed well in terms of growth and survival. However, the fast-growing *B. vagans* caused overcrowding of neighbouring plants. The workshop held towards the end of this project (Objective 5) highlighted the need for 'real' local data to demonstrate the feasibility of green infrastructure to potential clients. In particular, industry would like to see quantitative data on the cooling effect of green roofs and walls being used as a basis for their more accurate inclusion in building sustainability incentive schemes such as the Green Building Council's 'Green Star' rating. Additional findings of this report show that covering roofs and walls with greenery greatly reduces maximum temperatures of the internal roof / wall surface. The daily maximum temperature under an extensive green roof was up to 24°C lower than that for a conventional steel roof. For the green wall, temperature differences of up to 17°C were observed.

Implications for relevant stakeholders for:

Until now there has been limited information available on the suitability of Australian native plant species for extensive green roofs and external green walls in Australia's northern regions. This general limitation plus a specific lack of 'local' data to quantify the claimed benefits of green infrastructure have hindered its uptake in these regions. The research presented in this project report is an initial step forward. It has identified select Australian native plant species that can be successfully used for extensive green roofs and external living walls in a subtropical climate. It has also demonstrated that both applications can provide substantial thermal benefits, particularly during warmer months. An important issue is that industry specifications of green infrastructure in the subtropics should account for the consideration that a warmer climate is conducive to rapid plant growth, which may add to maintenance costs. This phenomenon may be countered by limiting the organic fraction of the growing medium and / or minimising the use of fertilisers and supplementary irrigation. Greater uptake of green infrastructure is likely to occur as the tangible benefits of green roofs and walls become increasingly well understood in Australian applications, including subtropical and tropical climate contexts.

Recommendations

From the indicative progress reported here, it is clear that long-term evaluation of a wider range of plant species, substrate formulations and irrigation regimes is required to support increasing confidence in green infrastructure for Australia. This is particularly so for the warmer northern regions where little information is publicly available at present. Attendant climate-specific modelling of environmental benefits such as thermal buffering and mitigation of stormwater flows is vitally important to ensure their accurate representation in building sustainability indicators such as the Green Building Council's 'Green Star' rating. This would offer greater incentive for implementation of green infrastructure.

While there are currently few investors in this new and emerging industry, its growth in the subtropics will likely continue to generate greater interest and needs in the medium to long term. In this regard, the industry should seek further investment in research and development.

Introduction

Green infrastructure involves the use of plants on the roofs and walls of buildings. Although the concept is not new (e.g. sod roofs and ivy-clad walls have been around for centuries), contemporary systems are using innovative materials and technology to create a plant-building interface that is optimal for the plant whilst maintaining the structural integrity of the building. Two such systems are extensive green roofs and living walls. Extensive green roofs are characterised by expansive areas of typically low growing, drought resistant and fire retardant vegetation grown in shallow substrates (e.g. 2-15 cm thick) underlain with a series of drainage and barrier materials to protect the roof from water and root penetration. These green roofs are designed for limited maintenance: for example, on factory rooftops. Living walls comprise plants rooted in a vertical structure attached to a building, as opposed to traditional façade greening. In the façade greening configuration, plants are rooted in the ground and trained to grow up a wall.

Contemporary green infrastructure has been widely adopted in central Europe, particularly Germany. More recently, it has been adopted in countries including the USA and Singapore. Overseas experience has shown that green roofs and living walls provide a myriad of social, environmental and economic benefits. Perhaps of most importance is the thermal buffer effect—during warm weather, evapo-transpiration and shading provided by the plants can markedly reduce temperatures inside the building. This, in turn, can lead to significant reductions in energy demand for air conditioning. Implementation of green roofs and walls on a large scale can reduce the urban heat island effect that many cities experience, thereby creating more liveable urban environments with less energy inputs.

In Australia, rapidly growing awareness of green infrastructure and its benefits has generated widespread recent interest among potential stakeholders at all levels, including government policy makers, property developers, architects, landscapers, horticulturalists and the general public. However, implementation of this technology in Australia is limited largely due to a lack of detailed knowledge regarding climate specific soft and hard green infrastructure performance. Overseas experience indicates that climate specific plant selection is critical to green infrastructure success. In North America, for example, *Sedum* species that are the primary choice for green roofs in cool temperate regions are unable to cope with the warm humid summer conditions of subtropical regions.

Australia’s climate is relatively harsh and perhaps destined to become progressively more so in the face of climate change. Experts predict reduced rainfall overall and increasingly extreme climate events, such as droughts, storms and cyclones. In this context, the ‘Achilles heel’ of a potentially vibrant green infrastructure industry in Australia is the lack of proven performance for appropriate plant species. Some green roof research has been initiated in temperate Victoria (Melbourne). However, such research needs extension to other climatic regions of Australia, especially subtropical regions experiencing continuing high growth in urban populations, as in south east Queensland. Without reliable information, plant selection is based on guesswork and / or potentially misguiding information from different climatic zones.

Objectives

The objectives of this project were as follows:

1. Review existing knowledge of plant selection and performance for extensive green roofs and living walls.
2. Develop regionally specific plant species selection matrices for extensive green roofs and living walls in Australia.
3. Use selection matrix criteria to generate lists of plant species, including ornamental and productive natives, putatively suited to regions and applications.
4. Establish and evaluate plants on a proof-of-concept demonstration living wall and extensive green roof.
5. Communicate outcomes with key stakeholders via an application focused plant improvement workshop.

Part 1: Overview of literature

1.1 Extensive green roofs

The use of a shallow growing medium or substrate to support rooftop vegetation constitutes an extensive green roof (EGR). In this situation, plantings are predominantly designed to provide functional benefits whilst requiring minimal maintenance. This is in contrast to intensive green roofs, which involve deep substrates to support larger and more varied plant species. In the latter context, regular access is promoted by greater aesthetics and higher maintenance requirements.

The functional benefits provided by EGRs address a number of environmental, economic and social issues arising from increased urbanisation. EGRs have an insulative effect that reduces the need for air conditioning to cool buildings in summer. In temperate North America, a cost-benefit analysis of an EGR on a retail store found small, but significant, reductions in energy consumption (Kosareo and Ries 2007). In warmer climates, much greater reductions in energy usage are likely to result. Wong et al. (2007) found that in Singapore over 60% of heat gain by a building could be stopped by an EGR. In subtropical southern China, less than 2% of the heat gained by an EGR during a 24 h period in summer was retained by the plants and substrate or transferred to the building below. The remainder was lost through evapo-transpiration, re-radiated to the atmosphere, or used in photosynthesis (Feng et al. 2010). Implementation of EGRs on a large scale has the potential to reduce urban heat island (UHI) effects. Susca et al. (2011) reported an average 2°C temperature difference between areas of New York city that have high and low levels of vegetation. EGRs with their biological activity, high thermal resistance, and low surface albedo compared with traditional bitumen rooftops were considered a useful way of combating this UHI effect.

A review of research into the hydrological performance of EGRs has shown that they can retain between 34 and 69% of precipitation (Gregoire and Clausen 2011). These authors reported that retention capacity is affected by the water holding capacity of the substrate, evapo-transpiration rates, temperature, amount of precipitation, and the number of dry days preceding precipitation. This ability to reduce stormwater volumes is of benefit where expansive areas of impervious surfaces create problems of localised flooding during heavy rainfall events and disturbance of surrounding natural waterways. Improvement in stormwater quality is a commonly touted feature of EGRs. However, research has shown that this greatly depends on the construction of the green roof, particularly the presence of organic material and fertiliser in the substrate (Gregoire and Cluasen 2011).

Other benefits include carbon sequestration (Li et al. 2010; Getter et al. 2009), reductions in air and noise pollution (Yang et al. 2008; Van Renterghem and Botteldooren 2008); habitat provision for wildlife (Coffman and Davis 2005), and extended roof membrane longevity (Köhler and Poll 2010). Socially, a general sense of enhanced well-being is also gained by virtue of the aesthetic value of plants (Maas et al. 2006).

Despite the benefits, there are few examples of EGRs in this country. A recent publication showcasing the current state of Australia’s green infrastructure industry lists only three EGR case studies: the Adelaide Zoo Envirodome, ‘The Venny’ community centre in Melbourne, and Kingston High School in Hobart (Hopkins and Goodwin 2011). Williams et al. (2010a) have identified several barriers to green roof implementation in Australia, most of which relate to a lack of knowledge, expertise, guidelines, and proven examples in a local context. The authors specifically highlight the need to identify plant species that can survive and be aesthetically pleasing in Australia’s climate.

Studies into the selection of plants for extensive green roofs have been conducted, but predominantly in cool temperature regions of the northern hemisphere (e.g. Durhman et al. 2006, 2007; Getter and Rowe 2009; Köhler 2006; Monterusso et al. 2005; Sendo et al. 2007; Van Woert et al. 2005; Wolf and

Lundholm 2008). Sedum species feature recurrently as the primary choice for these regions. Overseas studies are difficult to adapt to Australian situations, since our climate is characterised by low rainfall, high evaporation and high year-to-year rainfall variability (http://www.bom.gov.au/lam/climate/levelthree/ausclim/zones.htm).

This situation, combined with the fact that most of Australia's capital cities receive seasonal rainfall (i.e. winter-dominant in Melbourne, Adelaide and Perth; summer-dominant in Brisbane and Darwin), creates a challenging environment for plants in exposed situations.

A number of text books discuss the issue of plant selection for EGRs (e.g. Dunnett and Kingsbury 2008; Hopkins and Goodwin 2011; Snodgrass and McIntyre 2010; Snodgrass and Snodgrass 2006; Yok and Sia 2008). Low growing plant species that establish quickly to provide good coverage of the substrate are generally recommended. Snodgrass and Snodgrass (2006) prescribe an ideal rate of spread of between 15-25 cm in the first year for plants transplanted as plugs and caution against using plants with more aggressive growth rates.

Drought tolerance is another highly desirable trait. The shallow substrate of non-irrigated extensive green roofs can regularly dry out and drought tolerant species can better maintain adequate vegetation cover during these periods. In Singapore, it has been estimated that a green roof substrate can be depleted of moisture for 4 days or more in eight out of 12 months of the year, despite the region's high rainfall and humidity (Yok and Sia 2008). Drought tolerance takes various botanical forms, including succulent leaves, thick leaf cuticles, in-rolled leaf margins or curved leaf surfaces, grey or silver foliage; compact twiggy growth, and small evergreen leaves (Dunnett and Kingsbury 2008). Plants that rely on deep taproots for drought tolerance are, however, unsuitable for extensive green roofs (Snodgrass and Snodgrass 2006).

In order to provide consistent long term vegetation cover, the green roof planting should be comprised predominantly of hardy succulents or herbaceous perennials. Grasses can also be useful, but regular thatch removal is generally required to reduce fire risk. Plants that have the ability to self-propagate, such as geophytes or self-seeding annuals, can be used for seasonal interest - provided they do not become invasive (Dunnett and Kingsbury 2008; Snodgrass and Snodgrass 2006).

A root system that gives good anchorage for the plant and which binds the substrate together is desirable to prevent substrate scouring / erosion from strong winds or heavy rainfall. This is best achieved by using species with a shallow and dense rooting system, and with stems that root into the substrate as they grow (Dunnett and Kingsbury 2008).

As previously mentioned, Sedums are commonly used for extensive green roofs in the cool temperate regions of North America and Europe. Sedum species are succulents which exhibit crassulacean acid metabolism (CAM; Sayed 2001). As a result, they are highly drought tolerant. Dunnett and Kingsbury (2008) specify 20 Sedum species as being suitable for extensive green roofs in central Europe. More than 40 species are listed by Snodgrass and Snodgrass (2006) as being suited to various regions of North America.

Recent research in subtropical regions of the USA, such as Texas and Florida, shows that some of the 'tried and tested' Sedum species used in temperate regions are unable to cope with warm humid summer conditions (Aitkenhead-Peterson et al. 2011; Denison et al. 2009). By comparison, local native plant species exhibited superior performance in terms of plant survival and roof coverage. In Australia, *Sedum acre* grown in irrigated green roof microcosms (150 mm substrate depth) was shown to perform well in terms of plant survival (100%). However, this species could not sustain a high level of vegetation cover during the summer months under limited irrigation regimes of 10 or 20 days between watering. Within a 40 day period, coverage dropped dramatically from around 80% to 25% (Williams et al. 2010b).

Sedum is a highly diverse genus of comprising more than 400 species. Although the Sedum species commonly used in northern hemisphere temperate regions may not be suited to Australia’s hotter and drier climates, there are others within the genus that may be. In Singapore, six Sedum species have been shown to perform well in a 100 mm substrate depth and full sun conditions. These species were *S. mexicanum, S. nussbaumerianum, S. rubrotinctum* ‘Aurora’, *S. sarmentosum*, *S. sexangulare*, and *S. lineare* ‘Variegatum’ (Yok and Sia 2008). A prominent supplier (Emory Knoll Farms) of green roof plants in the USA specifies a mixed planting of succulents for the subtropical regions of the south coast which includes four *Sedum* varieties: *S. rupestre* ‘Angelina’, *S. clavatum*, *Sedum* ‘Lemon Coral’, and *S. lineare* ‘Variegatum’ (Ed Snodgrass, pers. comm., 2010).

Australia has a number of drought-adapted plants that are potentially suitable for EGRs. Research conducted in Melbourne found that the Australian native succulents *Carprobrotus rossii* and *Disphyma crassifolium* had better survival rates in an EGR situation than did native grasses and forbs (Williams 2010b). Under drought stress, *C. rossii* maintained the highest level of cover of all other species tested. Other Australian succulents considered worthy of investigation include species of Calandrinia and Portulaca (Williams 2010a).

1.2 Exterior green walls

Green walls comprise plants rooted in a vertical structure attached to a building as opposed to traditional façade greening, wherein plants are rooted in the ground and are trained to grow up a wall or trellis. The vertical structure in which the plants are grown usually takes the form of rigid modular panels filled with a specialised lightweight growing medium or a two-layer blanket of synthetic fabric in which ‘pockets’ are filled with plants and growing medium (Hopkins and Goodwin 2011).

Examples of contemporary green walls can be found throughout Europe and North America, but it is perhaps in Singapore that they have been most widely adopted. The vision of creating a ‘city in a garden’ has led to Singapore focusing much effort into the research and development of green wall systems that are suited to its tropical climate (Chiang and Tan 2009). In Australia, exterior green walls are a relatively new addition to the urban landscape. Hopkins and Goodwin (2011) presented five case studies of exterior living walls in Australia, most of which have been completed within the last 2 years. Among them are Brisbane’s King George Square and the entrance to the Adelaide Zoo, both of which are south facing green walls that use modular panel systems.

Many of the purported benefits of green walls are similar to those of green roofs; these being, lower heat loads on buildings, improved air quality, reduced noise pollution, enhanced biodiversity, greater aesthetic appeal, protection of underlying structure, and improved rainwater retention and quality. Recent studies are providing evidence to confirm these claims.

In Hong Kong, coverage of a concrete wall with modular vegetated panels reduced exterior wall temperatures by up to 16°C in summer (Cheng et al. 2010). In terms of internal wall temperatures, the authors found a difference of more than 2°C was maintained even late at night, indicating that green walls have significant ability to reduce power consumption for building cooling. At HortPark in Singapore, various green wall systems were assessed for their thermal performance by Wong et al. (2010a). Researchers reported differences in external wall temperatures of up to 10°C between vegetated and bare concrete walls.

The acoustic benefit derived from green walls varies according to their construction and level of vegetation cover. Wong et al. (2010b) showed that green wall substrate effectively reduces sound at low to middle frequencies. A relatively smaller reduction is achieved at higher frequencies due to the scattering effect of the foliage. As the level of vegetation cover increases, the sound absorption properties of a green wall also increase.

Plant selection has received less attention for green walls than it has for green roofs. Again, site specific considerations, such as aspect, prevailing winds and shading from other structures, make it difficult to prescribe a set palette of plants. Chiang and Tan (2009) have compiled a list of suggested plants for vertical greening in the tropics on the basis of trials conducted in Singapore over a six month period. In general, they recommend using plants that can withstand high temperatures and intense sunlight, as well as low soil moisture. Plants that provide thick, dense cover and which utilise crassulacean acid metabolism (CAM) were considered preferable. Although green walls are irrigated, drainage under gravity of narrow containers and a thin media profiles mean that the rooting substrate can dry out quite quickly. Drought resistant plants are more likely to survive such conditions. Substrate moisture content has been shown to vary from 15% to 45% (v/v) between the top and bottom of a modular green wall panel, respectively (Cheng et al. 2010).

Dunnett and Kingsbury (2008) caution against the use of monocultures in green walls, as these bear a high risk of failure through problems in cultivation or pathogen attack. Instead they recommend employing a range of species to help combat the microclimate differences that are likely to exist within the one wall. Plants that have a clumping rather than an upright growth habit are recommended. However, high vigour species should be avoided as they have a tendency to smother neighbouring plants and overload the support structure.

The Australian landscape architects Hopkins and Goodwin (2011) list the following criteria for green wall plants: a fibrous root system, strong stem to root connection, resistance to wind buffering, and good growth habit. Emphasis is placed on a plant’s ability to withstand high temperatures and wind velocities. The suggestion is made that plants found naturally on cliff tops or cliff faces are likely to succeed on a green wall given certain similarities between the two environments.

Development of a selection matrix for green wall plants should ideally encompass the substantial amount of plant selection information that exists for green roofs. Several of the traits mentioned in literature as being desirable for green roof plants also apply to plants in a green wall context. For example, ensuring that plants are not poisonous or don’t have thorns can be important for a green wall. Plants that pose a weed threat or which accumulate dry biomass should also be avoided.

Part 2: Plant selection matrix development

2.1 Approach

Plant species selection matrices for two living infrastructure situations of an extensive green roof and an external green wall were generated based on information presented in the literature review. The selection matrices were structured using a question and answer approach in which species are ultimately deemed ‘potentially suitable’, ‘potentially suitable under certain circumstances’, or ‘unsuitable’. The initial approach was to develop separate selection matrices for three different climatic regions in Australia. However, as most plant requirements recommended in literature relate more to the green roof or wall situation than to the climate, a single selection matrix was developed in which climate-specific traits were only highlighted if a plant was found to be unsuitable for a particular region.

2.2 Extensive green roof plant selection matrix

1	To what height is this plant likely to grow?	**< 2.5 cm**	*Unsuitable*
		2.5 to 30 cm	*Go to Question 2*
		> 30 cm	*Unsuitable*
2	Does this plant have a shallow root system?	**Yes**	*Go to Question 3*
		No	*Unsuitable*
3	What is the life cycle of this plant?	**Annual**	*Go to Question 4*
		Biennial	*Unsuitable for long term coverage, otherwise go to Question 5*
		Perennial	*Go to Question 5*
4	Does this annual plant self-seed?	**Yes**	*Go to Question 5*
		No	*Unsuitable for long term coverage, otherwise go to Question 6*
5	Does this plant produce seeds that are dispersed by wind?	**Yes**	*Unsuitable (possible weed threat)*
		No	*Go to Question 6*
6	What is the likely spread of this plant within the first year?	**< 15 cm**	*Unsuitable*
		15 to 25 cm	*Go to Question 7*
		> 25 cm	*Unsuitable for roofs requiring minimal maintenance, otherwise go to Question 7*
7	Has this plant been identified as a weed in this region? (Check online at www.weeds.gov.au)	**Yes**	*Unsuitable*
		No	*Go to Question 8*

8	Is this plant prone to attack from pests or diseases?	**Yes**	*Unsuitable*
		No	*Go to Question 9*
9	Is this plant prone to nutrient deficiencies or toxicities?	**Yes**	*Unsuitable for mixed plantings on roofs requiring minimal maintenance, otherwise go to Question 10*
		No	*Go to Question 10*
10	Does this plant develop roots from lateral stems?	**Yes**	*Go to Question 12*
		No	*Go to Question 11*
11	Does this plant have stems that are easily broken?	**Yes**	*Unsuitable for roofs exposed to high wind velocities, heavy rain and/or hail, otherwise go to Question 12*
		No	*Go to Question 12*
12	Does this plant accumulate dry biomass (e.g. dead leaves)?	**Yes**	*Unsuitable for roofs requiring minimal maintenance (possible fire hazard), otherwise go to Question 13*
		No	*Go to Question 13*
13	Does this plant have drought tolerant characteristics (e.g. succulent leaves, grey or silver foliage, hairy leaves or thick leaf cuticle)?	**Yes**	*Go to Question 14*
		No	*Unsuitable for warm climates and/or climates with seasonal rainfall, otherwise go to Question 14*
14	Can this plant tolerate mild frost?	**Yes**	*Go to Question 15*
		No	*Unsuitable for temperate climates, otherwise go to Question 15*
15	Are any parts of this plant poisonous to humans?	**Yes**	*Unsuitable for rooftops with public access, otherwise go to Question 16*
		No	*Go to Question 16*
16	Do any parts of this plant have thorns?	**Yes**	*Unsuitable for rooftops with public access, otherwise this plant is potentially suitable for use on extensive green roofs in Australia*
		No	*This plant is potentially suitable for use on extensive green roofs in Australia*

2.3 Exterior green wall plant selection matrix

1	Does this plant have a clumping growth habit that is likely to provide thick, dense cover?	**Yes**	*Go to Question 2*
		No	*Unsuitable*
2	Does this plant have a shallow fibrous root system?	**Yes**	*Go to Question 3*
		No	*Unsuitable*
3	What is the life cycle of this plant?	**Annual**	*Unsuitable for long term coverage, otherwise go to Question 4*
		Biennial	*Unsuitable for long term coverage, otherwise go to Question 4*
		Perennial	*Go to Question 4*
4	Does this plant display a vigorous growth rate?	**Yes**	*Unsuitable for mixed plantings or walls requiring low maintenance, otherwise go to Question 5*
		No	*Go to Question 5*
5	Can this plant cope with full sun?	**Yes**	*Go to Question 6*
		No	*Unsuitable for unshaded walls with a northern, western or eastern aspect, otherwise go to Question 6*
6	Can this plant cope with full shade?	**Yes**	*Go to Question 7*
		No	*Unsuitable for walls with a southern aspect or sites overshadowed by surrounding buildings or plants, otherwise go to Question 7*
7	Has this plant been identified as a weed in this region? (Check online at www.weeds.gov.au)	**Yes**	*Unsuitable*
		No	*Go to Question 8*
8	Is this plant prone to attack from pests or diseases?	**Yes**	*Unsuitable*
		No	*Go to Question 9*
9	Is this plant prone to nutrient deficiencies or toxicities?	**Yes**	*Unsuitable for mixed plantings on walls requiring minimal maintenance, otherwise go to Question 10*
		No	*Go to Question 10*
10	Does this plant develop roots from lateral stems?	**Yes**	*Go to Question 12*
		No	*Go to Question 11*

11	Does this plant have stems that are easily broken?	**Yes**	*Unsuitable for walls exposed to high wind velocities, heavy rain and/or hail, otherwise go to Question 12*
		No	*Go to Question 12*
12	Does this plant accumulate dry biomass (e.g. dead leaves)?	**Yes**	*Unsuitable for walls requiring minimal maintenance (possible fire hazard), otherwise go to Question 13*
		No	*Go to Question 13*
13	Does this plant have drought tolerant characteristics (e.g. succulent leaves, grey or silver foliage, hairy leaves or thick leaf cuticle)?	**Yes**	*Go to Question 14*
		No	*Unsuitable for warm climates and/or climates with seasonal rainfall, otherwise go to Question 14*
14	Can this plant tolerate mild frost?	**Yes**	*Go to Question 15*
		No	*Unsuitable for temperate climates, otherwise go to Question 15*
15	Are any parts of this plant poisonous to humans?	**Yes**	*Unsuitable for walls with public access, otherwise go to Question 16*
		No	*Go to Question 16*
16	Do any parts of this plant have thorns?	**Yes**	*Unsuitable for walls with public access, otherwise this plant is potentially suitable for use on extensive green roofs in Australia*
		No	*This plant is potentially suitable for use on extensive green roofs in Australia*

Part 3: Green roof trial

3.1 Methodology

3.1.1 Trial site and green roof design

Four identical steel structures were custom-built for this project by R&F Steel Sheds. To allow ease of access, the dimensions of these low height demonstration sheds were 2370 mm length x 1530 mm width x 1015 mm height. The skillion roofs had a slope of 3° and were engineered to a load bearing capacity of 200 kg/m^2. Fielders TL5® steel panels in Colorbond® Pale Eucalypt® were used for roofing and wall cladding. The structures were situated on open and flat ground at The University of Queensland Gatton Campus (latitude 27°32’S, longitude152°19’E; Figure 1). They were oriented so that the roofs sloped towards the north so to maximise sun exposure during winter. Spacing between the structures was a minimum of 2.15 m to minimise any potential shading effects.

Extensive green roof components were installed on two of the structures in December 2010 (Figure 2). Firstly, two coats of a polyurethane waterproofing membrane (Enviro 700 PUR; Waterproofing Technologies, St Peters, NSW, Australia) were applied to the roof surface. Galvanised steel (1.5 mm thickness) was fixed to the roof perimeter to provide a 2270 mm length x 1350 mm width x 235 mm height containment area for the green roof components. Strips of expanded polystyrene (25 mm thickness) were laid between the raised ribs of the roofing steel to provide a relatively flat base for the subsequent layers. These further layers consisted of Elmich VersiCell® drainage module overlaid with Elmich VersiDrain® 25P water retention / drainage tray and geotextile (Brad Walker Agencies, Bardon, QLD, Australia) and 150 mm of Bioganic Earth green roof mix (Enviroganics, Brisbane, QLD, Australia). At this initial stage, a drip irrigation system comprising 2 L/h drippers (24 drippers per m^2; one per plant) was installed on each green roof. Planting of the roof was conducted on 29 December 2010. The substrate surface was then mulched with a 15 mm thick layer of Envirohydrate expanded clay (Enviroganics, Brisbane, QLD, Australia).

The climate during the trial period was atypical of the region, with substantially higher than normal rainfall during the summer and autumn months (Table 1). During winter, the minimum temperatures and rainfall were generally lower than normal. Irrigation was applied twice daily for 2 min. during the first month, once daily for the next week and twice per week thereafter until 15 May 2011, when it was reduced to once per week.

3.1.2 Trial plants

Five Australian native plant species identified by the selection matrix as being suitable for green roof culture in the subtropics were included in the evaluation trial: *Calandrinia balonensis* ‘Mystique’ (Broad Leaf Parakeelya), *Calandrinia eremea* (Twining Purslane), *Eremophila debilis* (Winter Apple), *Myoporum parvifolium* (pink-flowering form; Creeping Myoporum), and *Thelionema umbellatum* (Lemon Flax Lily). All species were sourced from commercial suppliers with the exception of *E. debilis.* This species was collected with permission from privately-owned bushland near Gatton, Queensland, and tentatively identified. A sixth species tentatively identified as *Sedum sexangulare* (Tasteless Stonecrop) was included in the trial as a non-native comparator. It was sourced from a private collection.

To achieve the required number of plants, all species were vegetatively propagated from cuttings at the Plant Nursery Unit of The University of Queensland, Gatton Campus. The plants were sun-hardened for at least one week and transplanted onto the green roofs as either plugs (*C. eremea*, *M.*

parvifolium, *S. sexangulare*) or tubestock (*C. balonensis, E. debilis, T. umbellatum*) at a density of 24 plants / m^2.

Figure 1. **Satellite image of green infrastructure trial site at the University of Queensland Gatton Campus**

(Google Earth image, 2010; downloaded 2011).

Table 1. **Climate data for The University of Queensland Gatton Campus**

The data represent a comparison of observations for the year 2011 with mean data from previous 20 years (1981-2010). From the Bureau of Metereology, www.bom.gov.au.

Month	Mean daily minimum temperature (°C)		Mean daily maximum temperature (°C)		Total monthly rainfall (mm)	
	2011	Mean	2011	Mean	2011	Mean
January	19.7	19.4	30.3	31.9	278.4	96.9
February	19.7	19.4	31.2	31.0	47.8	98.8
March	18.1	17.3	29.1	29.9	106.8	57.5
April	14.2	14.2	26.4	27.4	73.6	57.3
May	9.3	10.9	22.9	24.1	75.6	63.5
June	7.4	7.9	20.5	21.5	5.2	32.3
July	5.7	6.5	20.9	21.1	15.0	31.1
August	7.6	6.9	22.4	22.8	47.4	23.5
September	7.9	10.1	25.7	26.2	13.2	31.7

Figure 2. Stages involved in the extensive green roof installation

(a) the four custom-built steel structures at the trial site

(b) a partly-installed green roof showing the galvanised steel containment edge, expanded polystyrene strips and VersiCell□ drainage layer

(c) a close-up view of green roof components including the expanded polystyrene strips, VersiCell□ drainage layer, VersiDrain□ 25P water retention/drainage tray and geotextile layer

(d) the building up of the 150 mm thick layer of Bioganic Earth green roof substrate

(e) the installation of the drip irrigation system and planting of trial species; and

(f) a completed green roof showing the Envirohydrate mulch layer.

3.1.3 Experimental design

A randomised complete block design was adopted in this study. The six plant species (treatments; n=6) were blocked according to roof elevation (viz., upper, middle or lower position on the roof slope) on each of two green roof structures. Each block consisted of two rows of 12 plants. The first two plants in each row represented one experimental unit—experimental units comprised four plants of the one species, spaced approximately 20 cm apart in a quadrant formation. The next two plants in each row represented a second experimental unit, and so forth. Hence, each roof contained 72 plants configured in 6 rows of 12 plants.

3.1.4 Data collection

Monthly plant evaluations were conducted from 11 February to 24 August 2011. Plant health was rated for all plants (n=24) using a 3-point scale of: 1 = thriving; 2 = alive, but with signs of pest, disease or other stresses; and 3 = dead. Plant height and width were measured along with visual assessments of plant development stages (flowering and seed set) and pest/disease incidence.

Overhead photographs were taken of each experimental unit using a 14 megapixel Olympus digital camera (model μ-5010). The proportional (%) vegetation cover for the 20 x 20 cm quadrant bound by the four plants was then calculated using image analysis software (Image-Pro Plus version 5.1; Media Cybernetics, Inc.).

Canopy temperature for each species (n=6), substrate surface temperature and ambient air temperature (20 cm above canopy level) were measured at midday on a clear day using an Agri-Therm III™ 6110L handheld differential infra-red thermometer (Everest Interscience Inc., Tucson, AZ, USA) with emissivity set at the recommended value of 98% (Monteith & Unsworth 2008).

Throughout the trial period, the internal surface temperature of the steel roofing was recorded at 30 min. intervals for all four structures (i.e. two with a green roof and two without) using a Tinytag Plus 2 datalogger (model TGP420; Gemini Data Loggers, UK) fitted with a fast-response thermistor probe (model PB-5002) placed centrally within each structure. Daily minimum and maximum temperatures were calculated for each roof and compared with ambient air temperature data collected by The University of Queensland Gatton weather station, located < 1 km from the trial site.

3.1.5 Data analysis

Vegetation coverage and midday canopy temperature data were subjected to a three-factor (viz. species, elevation, roof) analysis of variance using a general linear model (SAS statistical analysis software, version 9.2). Separate analyses were conducted for each evaluation time. Where significant differences ($P<0.05$) were found to exist between species, a Tukey's studentised range multiple comparison test was performed.

3.2 Results

3.2.1 Plant species for green roofs

Plant survival differed greatly among species (Figure 3). Two of the Australian native species, *Myoporum parvifolium* and *Eremophila debilis,* and the non-native comparator species *Sedum sexanagulare* exhibited 100% survival over the 8 months following transplanting onto the green roof. Plant health for these species was consistently high, with only minor caterpillar and / or aphid infestations observed during late summer and early autumn. *Thelionema umbellatum* survival was also high, but a decline in plant health resulted in a 4% loss of plants by early winter (June). Over half of the remaining plants were exhibiting reduced vigour and leaf necrosis by the end of the trial. The two *Calandrinia* species rapidly succumbed to crown and root rot as a result of the unusually high rainfall during summer. By winter, all *C. balonensis* plants had died. *C. eremea* showed a similar trend, but was able to partially regenerate from seed set after a late summer flush of flowering.

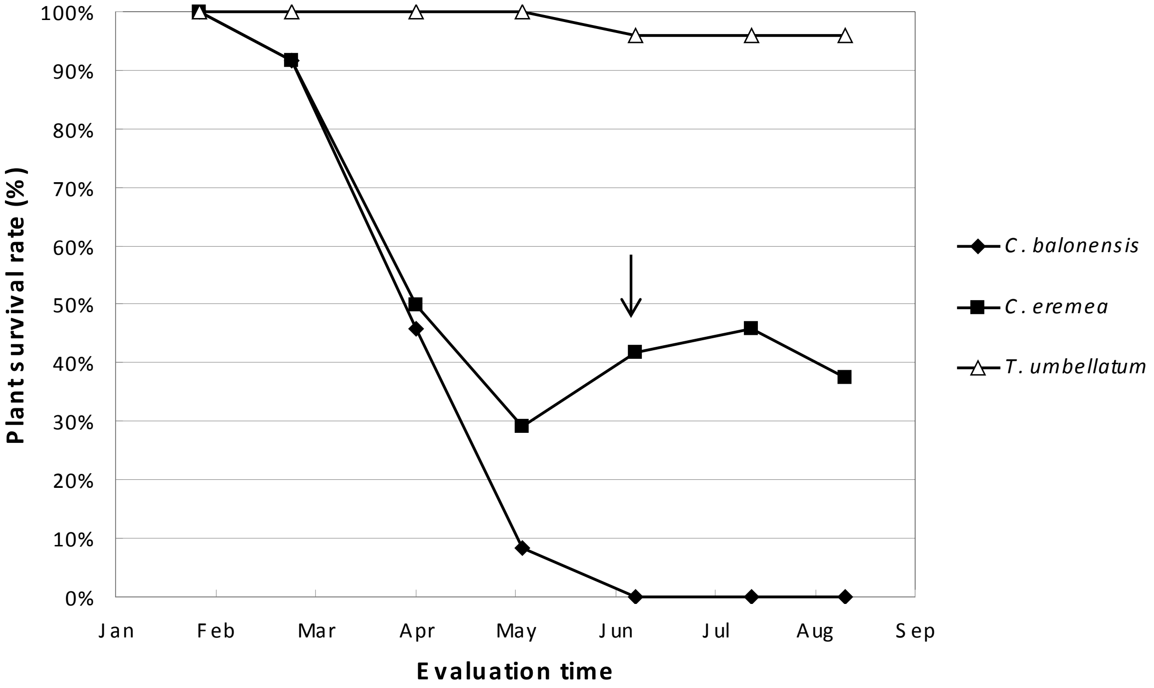

Figure 3. Survival of three plant species grown on an extensive green roof in south east Queensland

Arrow indicates regeneration of *Calandrinia eremea* from self-seeding. Data are not shown for the species exhibiting 100% survival throughout evaluation period—*Myoporum parvifolium*, *Eremophila debilis* and *Sedum sexangulare*.

At no point in the trial did the plants exhibit signs of water deficit stress, such as wilting or leaf abscission. This indicates that a 150 mm extensive green roof in south east Queensland may be adequately maintained with an irrigation regime that delivers 3.2 L/m^2/week from late summer to autumn and 1.6 L/m^2/week during winter.

Plant growth rates varied greatly between species. *E. debilis* showed vigorous growth both in terms of plant height (Figure 4) and width (Figure 5). Five months after transplanting, it was necessary to prune all plants of this species to prevent it from smothering the other trial species. This aggressive growth may make *E. debilis* unsuitable for extensive green roofs, unless it is the only species desired on the roof or there is a scheduled maintenance plan in place to ensure that it is contained (Snodgrass and Snodgrass 2006, p. 63). Most of the other trial species reached heights of between 10 and 15 cm. This is an ideal height range for an extensive green roof situation, as short plants tend to be less prone to wind damage and easier to maintain (Snodgrass and Snodgrass 2006, p. 83). *C. eremea* exhibited mean plant heights of less than 7 cm throughout the trial period. Initially, this was caused by the poor health of the plants and, afterwards, by the fact that the self-sown seedlings had not reached full maturity by the trial's end.

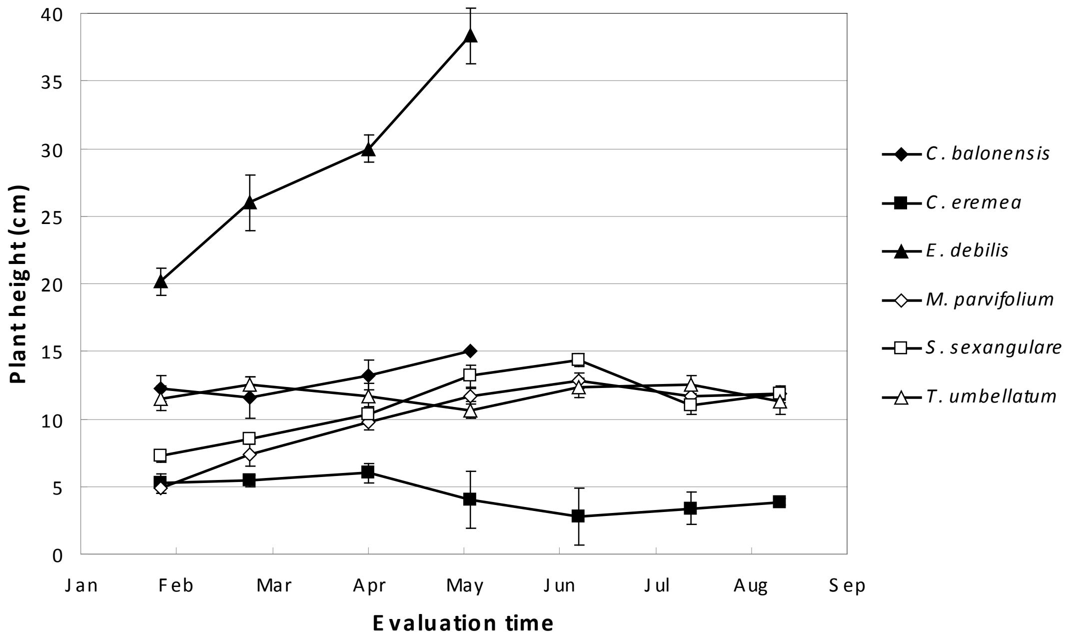

Figure 4. **Mean plant height of six species grown on an extensive green roof in south east Queensland**

Data from June to August are not available for two species due to loss of all *C. balonensis* plants and pruning of all *E. debilis* plants. Error bars indicate ± standard error of the mean.

The rate of spread as measured by plant width was surprisingly high for most of the trial species (Figure 5). In North America, an acceptable rate of spread for green roof plants is between 15 and 25 cm within the first year (Snodgrass and Snodgrass 2006, p. 62). For all species in the current trial this degree of spread was achieved within 6 weeks from transplanting. By May, 21 weeks after transplanting, *M. parvifolium* and *S. sexangulare* also required pruning to prevent them from overgrowing the other species. However unlike *E. debilis*, the plants received pruning to their perimeter only as opposed to the entire canopy. Such high rates of spread may be attributable to the region's subtropical climate and the high organic component of the green roof substrate. Nagase and Dunnett (2011) showed that a substrate comprising 10% organic matter was best for maintaining a stable rate of growth in a well watered extensive green roof, whereas substrate containing 50% organic matter encouraged excessive soft growth.

Rapid growth rates translate to high levels of vegetation cover (Table 2; Figure 6; Figure 7). Complete coverage of the substrate surface was achieved within 5 months for *E. debilis, M. parvifolium* and *S. sexangulare*. *C. balonensis* showed a steady increase in coverage initially, but this declined with subsequent plant losses. Plant losses were also responsible for the low level of coverage exhibited by *C. eremea*. Slow growth rate meant that *T. umbellatum* did not achieve 100% coverage within the trial period. The slight decrease in coverage observed for this species during late winter (August) resulted from two things, a lack of new growth and necrosis of older leaves in all plants.

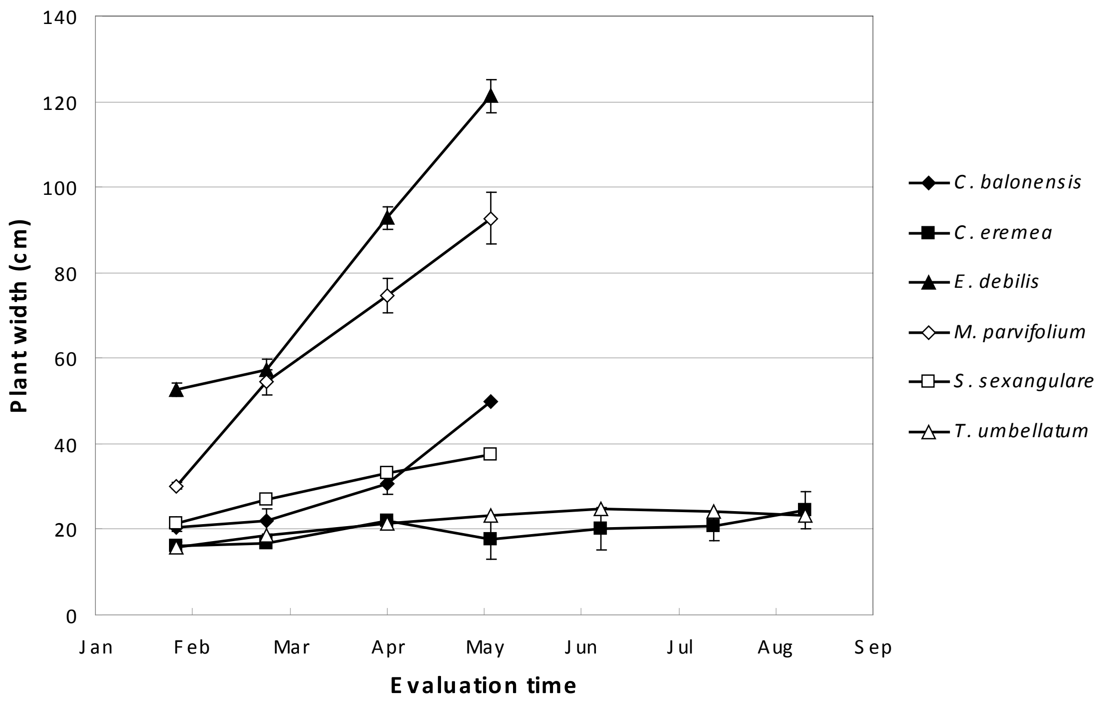

Figure 5. **Mean plant width of six species grown on an extensive green roof in south east Queensland**

Data from June to August are not available for four species due to loss of all *C. balonensis* plants and pruning of all *E. debilis*, *M. parvifolium* and *S. sexangulare* plants. Error bars indicate ± standard error of the mean.

Table 2. **Mean proportion of vegetation cover (%) of six species grown on an extensive green roof in south east Queensland.**

Different letters within the same column denote significant difference (P<0.05).

Species	Evaluation time						
	February	March	April	May	June	July	August
E. debilis	83 a	90 a	97 a	100 a	100 a	100 a	100 a
M. parvifolium	43 b	87 a	96 a	100 a	100 a	100 a	100 a
S. sexangulare	47 b	80 a	95 a	100 a	100 a	100 a	100 a
C. balonensis	42 b	54 b	39 b	32 b	n.d.	n.d.	n.d.
T. umbellatum	13 c	17 c	26 b	40 b	42 b	44 b	39 b
C. eremea	15 c	22 c	18 b	11 b	9 c	11 c	11 c

n.d. = no data available

C.balonensis plants did not survive to Week 34

Figure 6. Overhead photographs depicting the level of vegetation cover provided by three succulent species

Grown on an extensive green roof in south east Queensland at 6, 21 and 34 weeks after transplanting.

Significant differences in midday canopy temperature of up to 12 °C were observed between the species (Table 3). *E. debilis* consistently displayed the lowest canopy temperatures and these tended to be either similar to or slightly above the ambient air temperature at the time. It is likely that the plant's open structure promotes turbulent air flow in and around the plant, thereby allowing heat to readily dissipate from the foliage. *M. parvifolium* also displayed low canopy temperature for most of the trial period, with mean temperatures the same or lower than ambient air temperature on four occasions.

The highest canopy temperatures were observed in the Australian native succulent *C. eremea*. In summer (February), the mean midday canopy temperature for this species was almost 50°C. It is possible that these plants were operating under crassulacean acid metabolism (CAM). Under CAM, stomata are closed during the day to conserve water and so dissipation of heat by transpiration cooling is prevented. Australian *Calandrinia* are known to facultatively utilise CAM. In *C. polyandra*, Winter and Holtum (2011) have shown that CAM is triggered by drought stress and reversed by adequate water and nutrient supply.

It would be interesting to determine the effect that these differences in canopy temperature have on the surface temperature of the substrate beneath the plants. In a study by Sendo et al. (2010), differences of up to 11°C were observed in the maximum substrate temperatures under four different plant species. The authors concluded that the higher temperatures resulted from a closely packed canopy which limited air movement.

Figure 7. Overhead photographs depicting the level of vegetation cover provided by three non-succulent species

Grown on an extensive green roof in south east Queensland at 6, 21 and 34 weeks after transplanting.

Table 3. Mean midday canopy temperatures of six species

Grown on an extensive green roof in south east Queensland.
Different letters within the same column denote significant difference (P<0.05).

Species	Evaluation time						
	February	March	April	May	June	July	August
E. debilis	38.8 a	33.0 a	26.3 a	24.2 a	19.9 a	25.7 a	26.6 a
M. parvifolium	44.2 ab	34.8 ab	28.3 ab	24.5 ab	18.5 a	26.8 ab	29.3 ab
S. sexangulare	47.7 b	35.5 abc	32.8 bc	27.3 ab	19.8 ab	30.7 cd	29.4 abc
T. umbellatum	47.7 b	36.8 bc	33.0 bc	27.3 ab	21.6 b	29.3 bc	31.1 bc
C. balonensis	41.4 a	38.5 cd	36.8 c	27.8 ab	23.8 c	29.9 c	29.8 bc
C. eremea	49.4 b	41.5 d	38.4 c	29.0 b	25.7 c	33.3 d	32.9 c
Ambient air	36.8	34.8	30.2	23.5	19.4	23.6	29.3
Substrate surface	61.5	39.6	40.1	34.2	26.6	35.9	29.4

3.2.2 Green roof thermal performance

The maximum temperatures recorded on the interior surface of the steel roof sheeting were consistently lower for the green roofs compared with the control (i.e. uninsulated steel) roofs (Figure 8). Differences between the two, based on mean daily maximum temperatures calculated for each month, ranged from 10.2°C in winter to 20.5°C in summer.

The greatest difference in daily maximum temperature between the control and green roofs was 24.0°C observed on 16 March 2011 and may be attributed to high ambient temperatures (31.0°C maximum), clear conditions and low wind speeds. On this day, the mean maximum temperature of the control roofs was 61.5°C compared with 37.5°C for the green roofs.

Irrespective of time of year, the additional thermal mass supplied by the green roofs resulted in their daily minimum temperatures being 3 to 5°C higher that those of the control roofs (Figure 9). Although consistent, these small differences show that the greatest thermal benefit of green roofs in south east Queensland will be in the reduction of summer cooling costs rather than winter heating costs. Unexpectedly, the ambient temperatures presented in Figure 9 are higher than those of the control roofs. Differences in microclimate between the trial site and The University of Queensland Gatton weather station are a possible reason for this discrepancy.

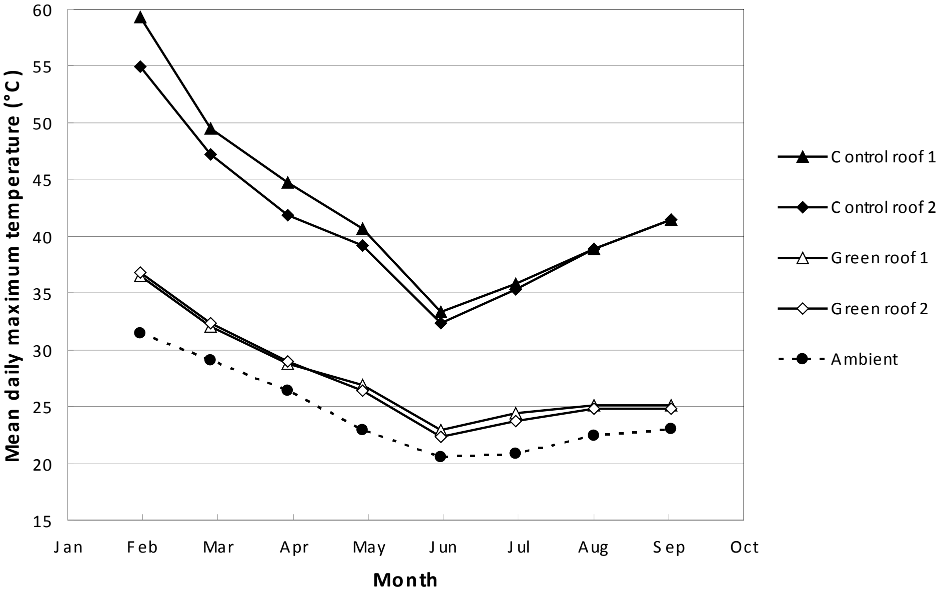

Figure 8. Comparison of daily maximum internal surface temperatures for steel roofs fitted with (green roof) or without (control roof) extensive green roof infrastructure

Ambient temperatures are from the nearby (<1 km) University of Queensland Gatton weather station, the records of which are published by the Bureau of Meteorology (www.bom.gov.au).

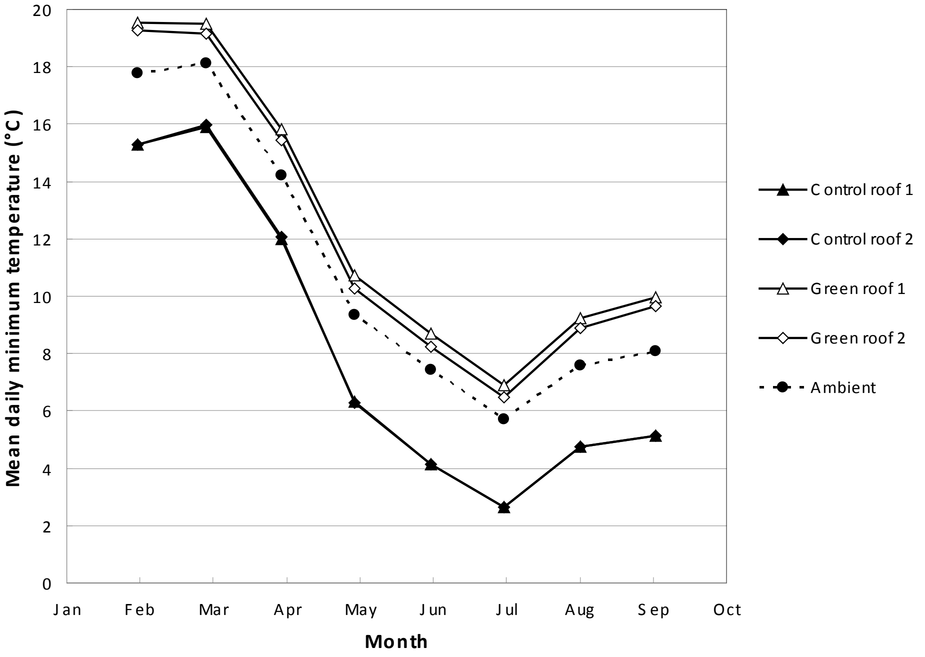

Figure 9. Comparison of daily minimum internal surface temperatures for steel roofs fitted with (green roof) or without (control roof) extensive green roof infrastructure

Ambient temperatures are from the nearby (<1 km) University of Queensland Gatton weather station, the records of which are published by the Bureau of Meteorology (**www.bom.gov.au**).

Part 4: Green wall trial

4.1 Methodology

4.1.1 Trial site and green wall design

Shading of eastern and western walls is recommended in south east Queensland to minimise heat gain in buildings, particularly during summer (Luxmoore et al. 2005). For this reason, a west facing orientation was chosen for the green walls in this trial. Two Elmich Vertical Green Modules (VGMs) that had been pre-planted with the trial species were secured to the west facing wall of each of the two green roof demonstration sheds on 2 June 2011 (Figure 10). The VGMs consisted of a rigid recycled plastic frame 560 mm (height) x 500 mm (width) x 250 mm (depth) and a geotextile liner filled with Bioganic Earth green wall mix (Enviroganics, Brisbane, QLD, Australia). Each module accommodated 16 plants in a 4 x 4 configuration.

The VGMs were hand-watered as required to maintain plant health, with 8-10 L of water slowly applied to the top of each module every 1 to 2 weeks. Climate for the trial period appear in Table 1.

4.1.2 Trial plants

Seven Australian native plant species identified by the selection matrix as being suitable for green wall culture in the subtropics were included in the evaluation trial: *Bulbine vagans* (Bulbine Lily), *Calandrinia remota* (Round Leaf Parakeelya), *Dianella tasmanica* (Little Devil – Tasman Flax Lily), *Hardenbergia violacea* (Bushy Blue - Native Sarsaparilla), *Plectranthus argentatus* (Silver Plectranthus), *Plectranthus parviflorus* (Blue Spires; Cockspur Flower), and *Ricinocarpos pinifolius* (compact form; Wedding Bush). *R. pinifolius* and the two *Plectranthus* species were sourced from private collections. All other species were sourced from commercial suppliers.

To achieve the required number of plants, all species were vegetatively propagated from cuttings or division at the Plant Nursery Unit of The University of Queensland's Gatton Campus. Tubestock of each species was transplanted into the VGMs on 5 May 2011 and maintained in a greenhouse with regular hand watering. The VGMs were gradually moved from a horizontal to vertical position over the first week. After a one month establishment period, the VGMs were transferred to the trial site.

4.1.3 Experimental design

A randomised complete block design was used in this study. The seven plant species (treatments) were blocked according to VGM. Each VGM held 2 or 3 plants (replicates) of each species. The capacity of a VGM is 16 plants and therefore equal replication of the seven species was not possible.

4.1.4 Data collection

Monthly plant evaluations were conducted from 3 June to 17 September 2011. Plant health was rated using a 3-point scale of: 1 = thriving; 2 = alive but with signs of pest, disease or other stresses; and 3 = dead. Measurements of plant height (including overhanging foliage), width and depth (horizontal distance that plant extends perpendicular to VGM surface), plant development stages (flowering and seed set), and pest / disease incidence were also recorded.

Photographs were taken of each VGM using a 14 megapixel Olympus digital camera (model μ-5010). Beyond the first month, photographs of individual plants could not be obtained due to encroachment of foliage from neighbouring plants. Hence, the proportion of vegetation cover for each species could not be determined.

Figure 10. Stages involved in the green wall installation

(a) a Vertical Green Module (VGM) being filled with Bioganic green wall substrate

(b) the planted VGMs in the greenhouse during the establishment period

(c & d) an installation of VGMs on the western wall of the demonstration sheds.

Canopy temperature for each species was measured as per the green roof trial (refer to Section 3.1.4), except that measurements were taken at 1.30 pm when the plants were in full sun. Canopy temperatures were not recorded for plants that were completely shaded by surrounding foliage.

Throughout the trial period the internal surface temperature of the western wall was recorded at 30 min. intervals for all four structures (i.e. two with a green wall and two without) using the data loggers described in Section 3.1.4. One logger was placed centrally on the wall of each structure. Daily minimum and maximum temperatures were calculated for each wall and compared with ambient air temperature data collected by The University of Queensland Gatton weather station, located <1 km from the trial site.

4.1.5 Data analysis

Canopy temperature data were subjected to a three-factor analysis of variance (species, VGM, wall) using a general linear model. Separate analyses were conducted for each evaluation time. Where significant differences ($P<0.05$) were found to exist between species, a Tukey's studentised range multiple comparison test was performed.

4.2 Results

4.2.1 Plant species for green walls

Plant survival rate over the trial period was 100% for all species, with the exception of *H. violacea* and *R. pinifolius*, which showed a decline from 100% in July to 56% and 63% in September, respectively. Both species displayed relatively slow growth rates and were unable to compete against surrounding plants for space and sunlight. *D. tasmanica* also had difficulty competing against more vigorous species. It managed to survive by sacrificing its mature leaves in favour of new basal shoots that were able to better cope with the lower light conditions. This explains the initial decreases in plant height (Figure 11) and width (Figure 12), and the overall decrease in plant depth (Figure 13), observed for this species.

B. vagans showed the most rapid growth in terms of plant height (Figure 11). This was due more to the elongation of overhanging leaves than it was to upright growth. Although the cascading foliage created a spectacular visual effect, plants growing below *B. vagans* tended to become completely smothered. Plants of *B. vagans* and *P. parviflorus* showed the highest rates of spread (Figure 12) and outward growth from the VGM surface (Figure 13), and eventually became the dominant green wall cover (Figure 14). The dense canopy of variegated foliage and abundant pale purple flowers make *P. parviflorus* an attractive choice for green walls (Figure 14; Wall 1 Week 10). However in high visibility sites, spent flowers might be removed as they detract from the appearance of the wall (Figure 14; Wall 1, Week 17). Also, adequate light should be provided, since shaded stems and leaves had a tendency to wither and die.

The slower growing *P. argentatus* was able to maintain a steady rate of upward and outward growth despite the overcrowded conditions. It was beginning to successfully compete for space and light by the end of the trial. The large silver leaves created a striking contrast to the darker green foliage of *B. vagans*. Despite being a tropical species with a reputation for being frost-sensitive, *P. argentatus* displayed no signs of damage when exposed to ambient temperatures as low as -2°C.

The succulent species *C. remota* produced weak stems that tended to grow down and across the vertical green module (). The weakness of the stems limited outward growth and hence the ability of the species to successfully compete against neighbouring plants. Both the stems and the leaves were brittle and prone to breakage. This is a problem in situations where green wall vegetation is exposed to mechanical disturbance; e.g. high wind velocities, human handling.

Canopy temperature was shown to vary by as much as 10°C between the different trial species (Table **4**). The two *Plectranthus* species consistently displayed the highest canopy temperatures. It is possible that the fine hairs covering the leaf surface restricted boundary layer air movement, thus reducing transpiration and preventing the dissipation of excess heat to the atmosphere. *Calandrinia remota* consistently displayed the lowest canopy temperature.

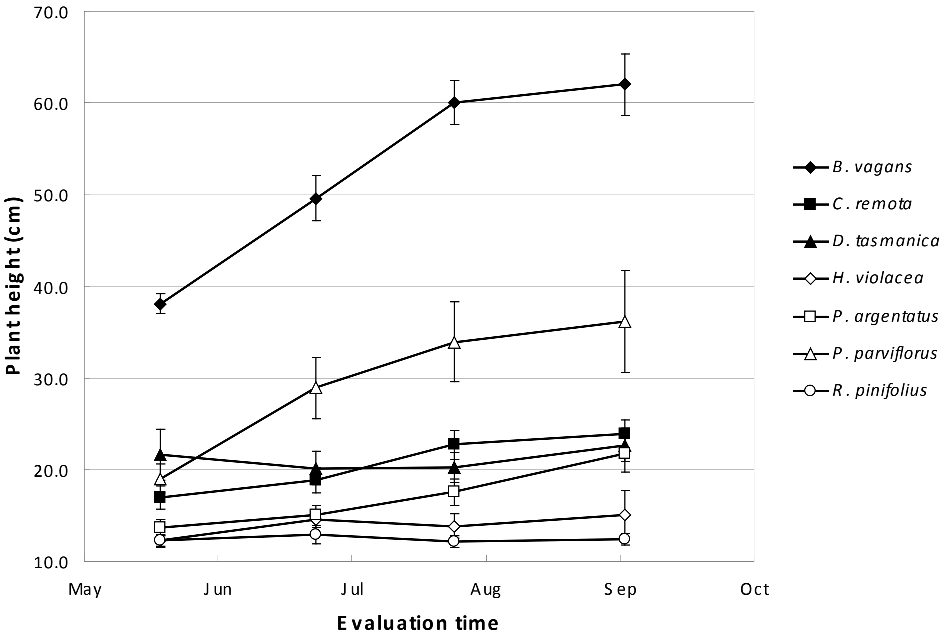

Figure 11. Mean plant height of seven Australian native species

Grown on a west facing green wall in south east Queensland. Error bars indicate ± standard error of the mean.

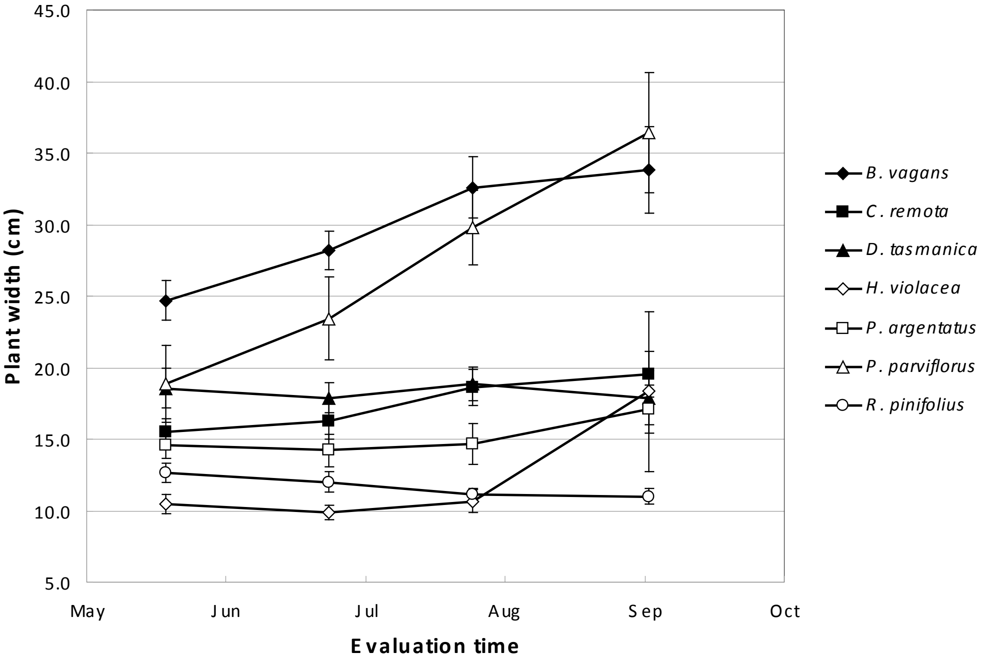

Figure 12. Mean plant width of seven Australian native species.

Grown on a west facing green wall in south east Queensland. Error bars indicate ± standard error of the mean.

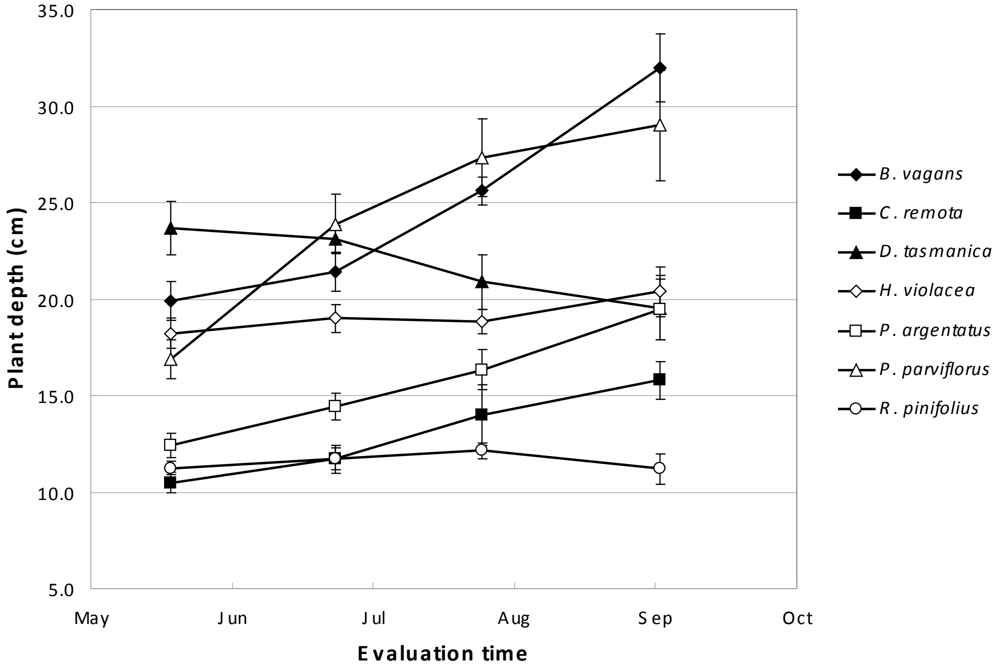

Figure 13. Mean plant depth of seven Australian native species

Grown on a west facing green wall in south east Queensland. Error bars indicate ± standard error of the mean.

Table 4. Mean canopy temperatures of seven Australian native species

Grown on a west facing green wall in south east Queensland. Measurements were taken at 1:30 pm when plants were in full sun.
Different letters within the same column denote significant difference (P<0.05).

Species	Evaluation time			
	June	July	August	September
C. remota	26.5 a	23.8 a	26.3 a	32.4 a
D. tasmanica	27.0 ab	22.9 a	29.1 abc	n.d.
R. pinifolius	27.9 abc	25.2 ab	27.7 ab	n.d.
H. violacea	28.6 abc	24.9 ab	30.3 bc	36.0 a
B. vagans	30.5 abc	26.0 ab	27.8 ab	36.0 a
P. parviflorus	32.0 c	27.9 ab	30.7 bc	36.6 a
P. argentatus	36.7 d	28.6 b	32.2 c	42.0 b
Daily maximum temperature*	22.0	21.4	24.1	26.5

n.d. = no data available; * Daily maximum temperatures are from University of Queensland Gatton weather station records published by the Bureau of Metereology (www.bom.gov.au).

Figure 14. Growth of seven Australian native species

Grown on a west facing green wall in south east Queensland

4.2.2 Green wall thermal performance

The VGMs were shown to substantially reduce the mean daily maximum temperature of the western wall, with greater differences observed as ambient temperature increased (Figure 15). The greatest difference in daily maximum temperature between the bare steel (control) walls and green walls was 17.7°C observed on 6 September 2011. On this day, the mean maximum temperature of the control walls was 45.2°C compared with 27.5°C for the green walls. Greater differences than these would likely be observed if the trial was extended to include the summer months. Throughout the trial period the mean daily maximum temperature of the green walls were within 2°C of that of the ambient air. Conversely, the mean daily maximum temperature of the control walls exceeded 37°C in early Spring (September), more than 14°C above the ambient air temperature.

Mean daily minimum temperatures showed little variation between the green walls and the control walls (Figure 16). Although the green wall temperatures were always higher, differences between the two rarely exceeded 2°C. The control walls displayed minimum temperatures that were below that of the ambient air. As suggested in Section 3.2.2, this is likely due to microclimate differences between the trial site and the weather station from which the ambient air temperatures were sourced.

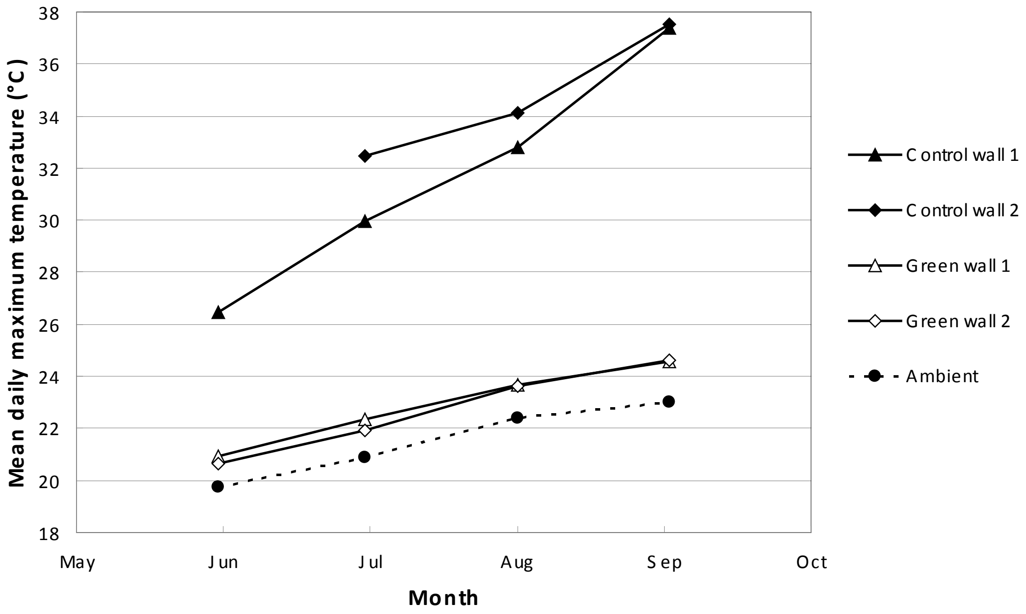

Figure 15. Comparison of daily maximum internal surface temperatures for west facing steel walls fitted with (green) or without (control) vertical green modules

Ambient temperatures are from University of Queensland Gatton weather station records published by the Bureau of Metereology (**www.bom.gov.au**).

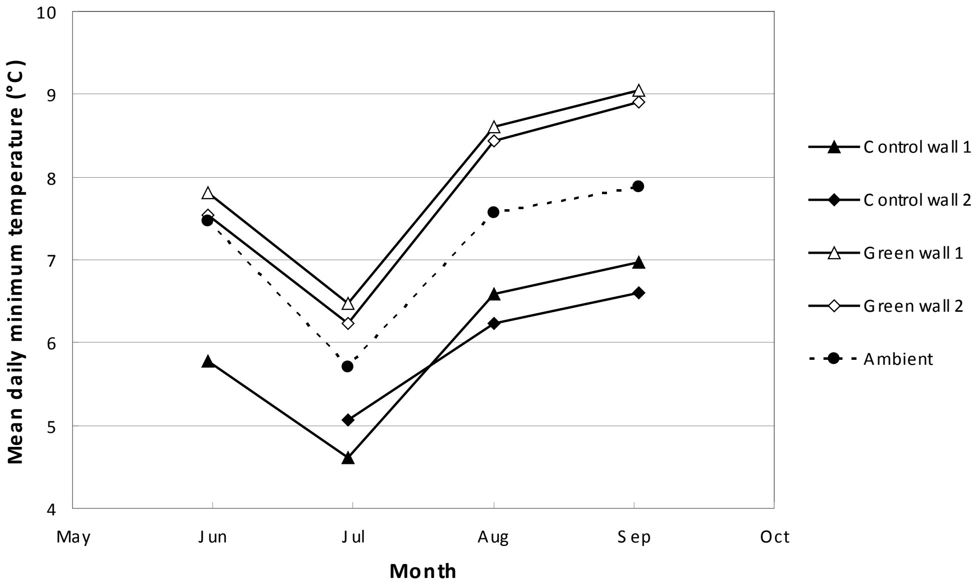

Figure 16. Comparison of daily minimum internal surface temperatures for west facing steel walls fitted with (green) or without (control) vertical green modules

Ambient temperatures are from University of Queensland Gatton weather station records published by the Bureau of Metereology (**www.bom.gov.au**)

Part 5: Workshop

5.1 Approach

A ‘Living Wall and Green Roof Plants for Australia’ Workshop was conducted on 19 July 2011 at The University of Queensland’s Gatton Campus. Invitations were sent to people involved in the areas of green infrastructure, landscape architecture and amenity horticulture, as well as relevant state government departments and local councils in the south east Queensland region. The event provided an opportunity to showcase the results of the current research project and develop further linkages between research, industry and government sectors. The program included presentations by Dr Melinda Perkins (UQ), Mr Brad Walker (Elmich), Mr Cameron Turner (Aussie Colours), Mr John Daly (Enviroganics), and Mr Mark Thomson (Shiavello Group; Australian Green Development Forum). These were followed by a tour of the green infrastructure trial site and a forum titled ‘Growing the Industry’ wherein workshop delegates were asked to identify key areas in which research could help to progress Australia’s green infrastructure industry into the future.

5.2 Outcomes

The ‘Living Wall and Green Roof Plants for Australia’ Workshop attracted 26 attendees from industry, government and research (Figure 17; Figure 18). The ‘Growing the Industry’ forum generated over an hour of vigorous discussion. The forum generated the following key areas for future research, in descending order of priority:

- The cooling effect of the plants and the green roof/wall system (i.e. substrate and other structural components) needs to be quantified for our local climate. Determination of R values was suggested as a way to achieve this. How do the R values compare with those of other structural materials (e.g. insulated roofing)?

- Cost-benefit analyses that use real, local data are needed to demonstrate the feasibility of green roofs / walls to potential clients. A suggestion was made to set up trials in Brisbane CBD to showcase the technologies at work.

- Researchers need to link in with those agencies involved in setting environmental / sustainability indicators, such as Green Building Council and the Australian Institute of Landscape Architects.

- Sustainability of green roof/wall plants and media in a subtropical context needs to be determined, both with and without supplementary irrigation. Long term studies are needed. For example, can a green roof last for 20 years in terms of plantings, substrate and structural integrity?

- Modelling of the effect of green infrastructure on a broader scale (i.e. beyond the immediate site) is needed. What effect would widespread implementation of green infrastructure have on the urban heat island effect? A suggestion was made that this research is already happening in Australia but there is need / scope to extend this research to subtropical climates, including to Brisbane specifically.

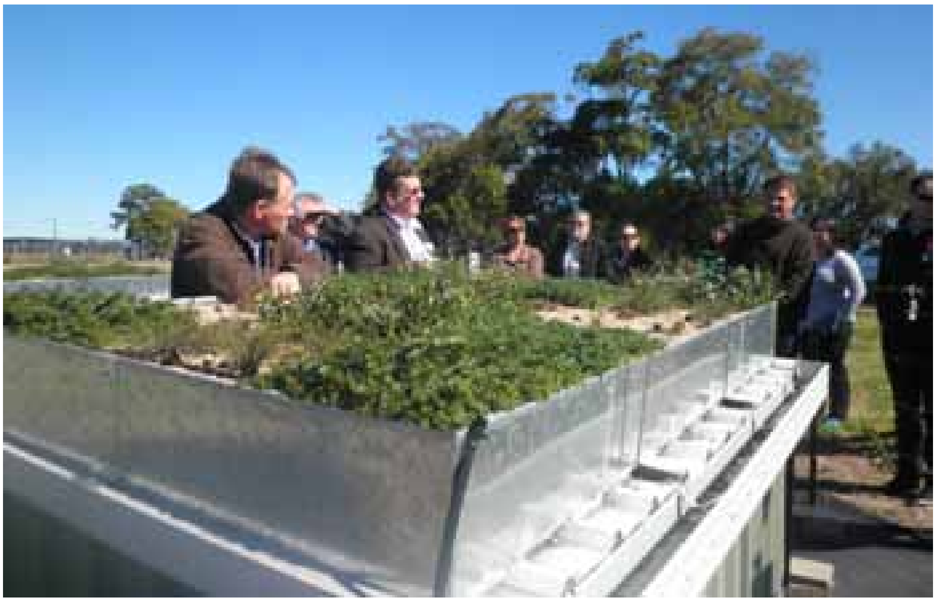

Figure 17. **Tour of the green roof and living wall trial site at UQ Gatton provided to workshop attendees**

Figure 18. **Workshop contributors inspecting one of the demonstration green roofs**

From left Jose Florenciano (Aussie Colours), Brad Walker (Elmich), Melinda Perkins (UQ), Mark Thomson (Shiavello Group), John Daly (Enviroganics) and Daryl Joyce(UQ)

Implications

Until now there has been limited information available on the suitability of Australian native plant species for extensive green roofs and external green walls in Australia’s northern regions. This general limitation plus a specific lack of ‘local’ data to quantify the claimed benefits of green infrastructure have hindered its uptake in these regions. The research presented in this project report is an initial step forward. It has identified select Australian native plant species that can be successfully used for extensive green roofs and external living walls in a subtropical climate (Sections 3.2.1 and 4.2.1). It has also demonstrated that both applications can provide substantial thermal benefits, particularly during warmer months (Sections 3.2.2 and 4.2.2). An important issue is that industry specifications of green infrastructure in the subtropics should account for the consideration that a warmer climate is conducive to rapid plant growth, which may add to maintenance costs. This phenomenon may be countered by limiting the organic fraction of the growing medium and / or minimising the use of fertilisers and supplementary irrigation. Greater uptake of green infrastructure is likely to occur as the tangible benefits of green roofs and walls become increasingly well understood in Australian applications, including subtropical and tropical climate contexts.

Recommendations

From the project, it is clear that long-term evaluation of a wider range of plant species, substrate formulations and irrigation regimes is required to support increasing confidence in green infrastructure for Australia. This is particularly so for the warmer northern regions where little information is publicly available at present. Attendant climate-specific modelling of environmental benefits such as thermal buffering and mitigation of stormwater flows is vitally important to ensure their accurate representation in building sustainability indicators such as the Green Building Council’s ‘Green Star’ rating. This would offer greater incentive for implementation of green infrastructure.

While there are currently few investors in this new and emerging industry, its growth in the subtropics will likely continue to generate greater interest and needs in the medium to long term. In this regard, the industry should seek to invest in its future through regional R, D and E providers and RIRDC.

References

Aitkenhead-Peterson, J, Dvorak, B, Volder, A & Stanley N 2011, ‘Chemistry of growth medium and leachate from green roof systems in south-central Texas’, *Urban Ecosystems*, vol. 14, pp. 17-33.

Chiang, K & Tan, A 2009, *Vertical Greenery for the Tropics*, jointly published by National Parks Board, National University of Singapore, and Building and Construction Authority, Singapore.

Cheng, C, Cheung, K & Chu, L 2010, ‘Thermal performance of a vegetated cladding system on facade walls’ *Building and Environment*, vol. 45, pp. 1779-1787.

Coffman, R & Davis, G 2005, ‘Insect and avian fauna presence on the Ford Assembly Plant ecoroof’, in *Proceedings of the Third Annual International Green Roofs Conference: Greening Rooftops for Sustainable Communities*, The Cardinal Group, Toronto.

Denison, T, Fikoski, K, Livingston, E, Lohr, M & Miller, C 2009, ‘Green Roof Evaluation at Shadow Wood Preserve’, Paper prepared for the Environmental Institute for Golf, Lawrence, KS.

Dunnett, N & Kingsbury, N 2008, *Planting Green Roofs and Living Walls*, Timber Press, Portland, OR.

Durhman, A, Rowe, B & Rugh, C 2007, ‘Effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof plant taxa’, *HortScience*, vol. 42, pp. 588-595.

Durhman, A, Rowe, B & Rugh, C 2006, ‘Effect of watering regimen on chlorophyll fluorescence and growth of selected green roof plant taxa’, *HortScience*, vol. 41, pp. 1623-1628.

Feng, C, Meng, Q & Zhang, Y 2010, ‘Theoretical and experimental analysis of the energy balance of extensive green roofs’, *Energy and Buildings*, vol. 42, pp. 959-965.

Getter, K & Rowe, D 2009, ‘Substrate depth influences *Sedum* plant community on a green roof’, *HortScience*, vol. 44, pp. 401-407.

Getter, K, Rowe, B, Robertson, P, Cregg, B & Andresen J 2009, ‘Carbon sequestration potential of extensive green roofs’, *Environmental Science and Technology*, vol. 43, pp. 7564-7570.

Gregoire, B & Clausen, J 2011, ‘Effect of a modular extensive green roof on stormwater runoff and water quality’, *Ecological Engineering*, vol. 37, pp. 963-969.

Hopkins, G & Goodwin, C 2011, *Living Architecture: green roofs and walls*, CSIRO Publishing, Collingwood, VIC.

Köhler M 2006, ‘Long-term vegetation research on two extensive green roofs in Berlin’, *Urban Habitats*, vol. 4, pp. 3-26.

Köhler, M & Poll, P 2010, ‘Long-term performance of selected old Berlin greenroofs in comparison to younger extensive greenroofs in Berlin’, *Ecological Engineering*, vol. 36, pp. 722-729.

Kosareo, L & Ries, R 2007, ‘Comparative environmental life cycle assessment of green roofs’, *Building and Environment*, vol. 42, pp. 2606–2613.

Li, J, Wai, O, Li, Y, Zhan, J, Ho, Y, Li, J & Lam, E 2010, ‘Effect of green roof on ambient CO2 concentration’, *Building and Environment*, vol. 45, pp. 2644-2651.

Luxmoore, D, Jayasinghe, M & Mahendran M 2005, ‘Mitigating temperature increases in high lot density sub-tropical residential developments’, *Energy and Buildings*, vol. 37, pp. 1212-1224.

Maas, J, Verheij, R, Groenewegen, P, de Vries, S & Spreeuwenberg, P 2006, ‘Green space, urbanity, and health: how strong is the relation?’, *Journal of Epidemiology and Community Health*, vol. 60, pp. 587-592.

Monteith, J & Unsworth M 2008, *Principles of Environmental Physics*, Elsevier Academic Press, Oxford, UK.

Monterusso, M, Rowe, B & Rugh, C 2005, ‘Establishment and persistence of *Sedum* spp. and native taxa for green roof applications’, *HortScience*, vol. 40, pp. 391-396.

Nagase, A & Dunnett N 2011, ‘The relationship between percentage of organic matter in substrate and plant growth in extensive green roofs’, *Landscape and Urban Planning*, vol. 103, pp. 230-236.

Sayed, O 2001, ‘Crassulacean acid metabolism 1975-2000, a check list’, *Photosynthetica*, vol. 39, pp. 339-352.

Sendo, T, Kanechi, M, Uno, Y & Inagaki, N 2010, ‘Evaluation of growth and green coverage of ten ornamental species for planting as urban rooftop greening’, *Journal of the Japanese Society of Horicultural. Science*, vol. 79, pp. 69-76.

Sendo, T & Uno, Y 2007, ‘What kind of plant species are the best for urban rooftop gardening?’, *Acta Horticulturae*, vol. 762, pp. 333-339.

Snodgrass, E & McIntyre L 2010, *The Green Roof Manual*, Timber Press, Portland, OR.

Snodgrass, E. and Snodgrass, L 2006, *Green Roof Plants: a resource and planting guide*, Timber Press, Portland, OR.

Susca, T, Gaffin, S & Dell’Osso, G 2011, ‘Positive effects of vegetation: urban heat island and green roofs’, *Environmental Pollution*, vol. 159, pp. 2119-2126.

Van Renterghem, T & Botteldooren, D 2008 ‘Numerical evaluation of sound propagating over green roofs’, *Journal of Sound and Vibration,* vol. 317, pp. 781–799.

Van Woert, N, Rowe, D, Andresen, J, Rugh, C & Xiao, L 2005, ‘Watering regime and green roof substrate design affect *Sedum* plant growth’, *HortScience*, vol. 40, pp. 659-664.

Williams, N, Rayner, J & Raynor, K 2010a, ‘Green roofs for a wide brown land: opportunities and barriers for rooftop greening in Australia’, *Urban Forestry and Urban Greening*, vol. 9, pp. 245-251.

Williams, N, Hughes, R, Jones, N, Bradbury, D & Rayner, J 2010b, ‘The performance of native and exotic species for extensive green roofs in Melbourne, Australia’, *Acta Horticulturae*, vol. 881, pp. 689-696.

Winter, K and Holtum, J 2011, ‘Induction and reversal of crassulacean acid metabolism in *Calandrinia polyandra*: effects of soil moisture and nutrients’, *Functional Plant Biology*, vol. 38, pp. 576-582.

Wolf, D & Lundholm, J 2008, ‘Water uptake in green roof microcosms: effects of plant species and water availability’, *Ecological Engineering*, vol. 33, pp. 179-186.

Wong, N, Tan P, Chen Y 2007, ‘Study of thermal performance of extensive rooftop greenery systems in the tropical climate’, *Building and Environment*, vol. 42, pp. 25–54.

Wong, N, Tan, A, Chen, Y, Sekar, K, Tan, P, Chan, D, Chiang, K & Wong, N 2010a, ‘Thermal evaluation of vertical greenery systems for building walls’, *Building and Environment*, vol. 45, pp.663-672 .

Wong, N, Tan, A, Tan, P, Chian, K and Wong, N 2010b, ‘Acoustics evaluation of vertical greenery systems for building walls’, *Building and Environment*, vol. 45, pp. 411-420.

Yang, J, Yu, Q & Gong, P 2008, ‘Quantifying air pollution removal by green roofs in Chicago’, *Atmospheric Environment*, vol. 42, pp. 7266-7273.

Yok, T & Sia, A 2008, *A Selection of Plants for Green Roofs in Singapore*, National Parks Board, Singapore.

Living Wall and Green Roof Plants for Australia

by Melinda Perkins and Daryl Joyce

Publication No. 11/175

The green infrastructure industry is concentrated in urban centres around Australia, particularly in the southern capital cities of Melbourne, Adelaide and Sydney. A gradual progression of the industry further north is now occurring.

This report provides the industry with greater knowledge of plant selection for extensive green roofs and living walls in Australia's challenging subtropical climate. The many environmental, economic and social benefits of green infrastructure have resulted in its increasing adoption overseas. However, a lack of proven plant species suited to Australian conditions has deterred growth of the industry in this country.

This report is targeted at horticulturalists, landscape architects and commercial suppliers of green infrastructure components.

RIRDC is a partnership between government and industry to invest in R&D for more productive and sustainable rural industries. We invest in new and emerging rural industries, a suite of established rural industries and national rural issues.

Most of the information we produce can be downloaded for free or purchased from our website <www.rirdc.gov.au>.

RIRDC books can also be purchased by phoning 1300 634 313 for a local call fee.

Most RIRDC publications can be viewed and purchased at our website:

www.rirdc.gov.au

Contact RIRDC:
Level 2
15 National Circuit
Barton ACT 2600

PO Box 4776
Kingston ACT 2604

Ph: 02 6271 4100
Fax: 02 6271 4199
Email: rirdc@rirdc.gov.au
web: www.rirdc.gov.au
Bookshop: 1300 634 313

RIRDC Innovation for rural Australia