Final Report

Researching the benefits of demonstration green roofs across Australia

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Delivery partner:

The University of Melbourne

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Researching the benefits of demonstration green roofs across Australia (GC16002)

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Public summary

The benefits and function of green roofs in urban environments are well understood but green roof construction in Australia is proceeding slowly compared to other countries. They are largely restricted to green roofs built for passive recreation on apartment buildings and offices in the CBD and inner suburbs of Australian cities. This indicates that substantial barriers to green roof implementation remain in Australia. The overarching objective of this project was therefore to better understand and overcome some of the fundamental cultural, community and horticultural barriers to greater green roof construction in Australia.

The project comprised four workstreams investigating 1) how the industry can overcome barriers to uptake, 2) the development of trait based, plant palettes for different green roof build-ups, 3) how maintenance can be better incorporated into green roof design and development and 4) what features make green roofs attractive and can also increase mental well-being for a wide range of people. Research consisted of extensive literature reviews and the development of new conceptual frameworks, innovative research to map a positive future for the Australian green roof industry using the appreciative enquiry method, traditional plant growth trials, investigations of the performance and maintenance history of existing green roofs and both qualitative and quantitative environmental psychology studies investigating the ability of green roofs to improve well-being using photos and videos.

It is envisaged that our project will have positive short, medium and long-term impacts on the Australian green roof industry. It brought the many different sectors of what is an inherently multidisciplinary industry together on several occasions, both in person and online, increasing understanding among the various actors, empowering them, and facilitating a shared understanding of what is needed to progress the industry. This led to an industry roadmap and the development of a "community of practice" which has formed independently but as a direct result of the project. We have increased industry understanding of the need for ongoing maintenance of green roofs and the importance of developing maintenance schedules for each green roof project. To upskill green roof contractors and reduce costs to building owners wanting to install green roofs, we have produced maintenance guidelines with example templates for different types of green roofs. The results of our green roof plant trials and experiments and environmental psychology research will be directly incorporated into green roof design guidelines. This will increase the diversity of green roof plant palettes by giving landscape architects and green roof designers the confidence to specify new species that have been robustly evaluated. It will also lead to the construction of green roofs that provide greater well-being benefits for the people living and working with them.

The project has developed a range of outputs including scientific papers detailing literature reviews and experimental studies that have been published in international journals, industry guidelines including the *Maintenance Guidelines for Australian Green Roofs* and South-east Australian specific green roof planting guidelines (available on the Hort Innovation and GIRG websites) and a *Roadmap for Green Roofs, Walls and Facades in Australia's Urban Landscapes 2020-2030* which is already generating positive change in the Australian green roof sector.

Keywords

Green roofs, barriers, green infrastructure, plant palettes, plant survival, maintenance, attention restoration, annual species, maintenance

Introduction

The benefits and function of green roofs in urban environments are well documented, with green roofs an established tool for creating cooler, more biodiverse and liveable cities. However, the number and area of Australian green roofs is increasing at an incremental pace compared to other regions worldwide. This may be because significant barriers to green roof adoption in Australia remain, including lack of information and uncertainty around construction, costs and maintenance, and a low level of knowledge around appropriate plant species and their horticultural requirements. Consequently, the overarching objective of the project was to better understand and overcome some of the fundamental cultural, community and horticultural barriers to greater green roof construction in Australia.

Green roofs consist of a series of layers, starting with a drainage or water retention layer, followed by a geotextile, a specifically engineered substrate, and on top the plants. Termed a "build-up" by the green roofs industry, the combination of layers with different characteristics strongly influences the types of plants that can be grown, the likelihood of its success and therefore the environmental, social and aesthetic benefits a green roof can provide. In countries with more developed green roof industries, plant combinations with characteristics that provide attractive, successful low maintenance green roofs can be readily specified for different green roof build-ups. Presently this is not possible in Australia due to a lack of plant performance and maintenance evaluation for different build-ups and different climatic conditions. Consequently, the palette of proven, attractive plants available to green roof designers in southern Australia remains small.

High quality maintenance is critical for green roofs to function and provide the benefits for which they were designed – for example cooling, stormwater control and places for people to socialise and interact with nature. Green roof maintenance differs from general landscape and horticultural maintenance. Maintenance needs to be considered in the design phase and be adequately resourced. Lack of adequate maintenance can lead to plant death and poorly functioning green roofs that are unattractive, which is a disincentive to those considering installing new green roofs as well as being costly to remediate.

Exposure to nature, including green roofs, can help maintain strong attention control and concentration, and increase a number of positive workplace behaviours. This makes green roofs potentially very attractive to employers and building owners as a way of supporting employee well-being and productivity, but the mechanisms underpinning how this works and the green roof design elements required are not well understood. Research has generally focused on a limited selection of green roofs with few design elements, cues of accessibility and use, and high maintenance or unsuitable plant choices. In this project we are building on these findings and investigating the types of green roof plants that are attractive to a wide range of people, and preferred green roof designs. This information will help us better understand the characteristics that increase the mental well-being of those viewing and using green roofs.

Methodology

The project had four workstreams each with multiple research components with their own methods and results. This final report provides a summary of the entire four-year research project rather than detailed explanations and results of the research components of each theme. For these details, please refer to the relevant milestone reports and outputs contained in the Appendices.

Workstream 1: *Assess the effectiveness of demonstration green roofs in overcoming barriers to green roof uptake*

<u>*Barriers to green roof construction – a systematic review*</u>

Given the benefits of green roofs have been known for over 50 years and been very well researched, why has green roof uptake has been slow in many parts of the world? There are potentially many barriers to adoption of new technologies. They include lack of knowledge, lack of local examples, as well as technical, policy and economic barriers. A systematic review of the barriers to green roof construction was undertaken to synthesise the scientific and grey literature. We then evaluated which barriers were most common and whether barriers differed regionally or with maturity of the green roof industry and identified which were most relevant to the Australian green roof sector.

<u>*Appreciative Enquiry Workshops*</u>

To further investigate barriers in a local context we ran two highly successful industry workshops in 2019 in Sydney (March) and Melbourne (April) to create a vision, and identify pathways, for greater greening in cities throughout Australia. The Green Roof, Walls and Facades Summits brought together researchers and over 60 practitioners from green infrastructure industries. Practitioners included architects and landscape architects, green roof installers, state government, water retailers, and substrate and nursery suppliers. We drew on organisational learning theory (March 1991) and understanding of roles for exploration and exploitation processes to explore better understand how to build collaborative capacity to drive sector process. Summits were designed to be generative and inclusive, encouraging contributors to share personal stories and diverse perspectives. Our design team worked with this in mind when collectively developing the general materials to stimulate discussion around our affirmative topics, selection of contributors and development of the summit agenda.

In these summits we used an Appreciative Inquiry (AI) approach, (Cooperrider & Srivastva, 1987) a form of action research with a theory of collective change for “organising and [a] method for changing social systems” (Bushe, 1999, p. 61). It explicitly affirms and develops positive images that people hold and harnesses them to provide a method for transforming an entire system (Bushe, 1999; Whitney & Cooperider, 2005) to build on ‘the best of’ current experience. It focuses on developing new knowledge, understanding and language creating “a new lens for seeing old issues…[so that] people have new ways to think about and discuss their organisation” (Bushe & Kassam, 2005, p. 164). AI harnesses the collective wisdom to achieve change (Whitney & Cooperider, 2005). This is likely to be particularly critical in diverse sectors such as GRWF where multi-actor and multi-organisational collaborations are required, and as such, also more likely to create change (e.g Hanleybrown, Kania, & Kramer, 2012). We asked participants to collectively create a vision of these future green cities and understand the role of collaborative networks in fostering adoption and sector growth.

Workstream 2: ***Develop proven, trait based, plant palettes fit for different green roof build-ups***

The major research component of this Workstream was significantly delayed and then reformulated due to ongoing difficulties our project partners - the City of Melbourne and Victorian Department to Environment, Land Water and Planning - had in constructing a demonstration green roof on 1 Treasury Place in Melbourne’s CBD. This demonstration site was designed to have 90 experimental research plots to investigate different green roof build ups, irrigation regimes and plant types. The resulting data, outputs and industry materials were intended to be the major elements of this Workstream. Unanticipated delays and barriers to retrofitting the 1 Treasury green roof - including expensive access and fire system upgrades - meant that this green roof could not be constructed during the duration of this grant program. Building investigations and a re-design are continuing at 1 Treasury Place but at the time of writing it was not yet confirmed if the green roof will be built.

In response to these project impacts our plant palette research was restricted to the Research Green Roof at Burnley. We investigated the effect of three substrate depths (10, 15 and 20 cm) on plant survival and condition for 75 green roof species over a 16-month period. Species were selected to reflect a range of native and exotic plant forms grown on Australian or Mediterranean green roofs, as well as untested species with suitable physiological or morphological traits. We were unable to investigate the effect of different irrigation regimes as we lacked the required experimental replication. We have taken a functional group and survival analysis approach, looking at the relationship between leaf traits and plant type on plant performance and survival, and matching this with substrate depth. Physical parameters, including substrate moisture and temperature, and air temperature and rainfall were also recorded. We undertook leaf and plant measurements in the laboratory for each species in order to identify functional groups. These groups will form the basis of our analysis and enable us to identify traits that confer enhanced performance for plants on green roofs under typical Australian conditions.

The Research Green Roof trial finished with a water deficit and heat experiment where supplementary irrigation was turned off over summer (2021-22) and plants were subject to extreme heat. Final survival data was collected in April 2022 and data collation and analysis are currently underway. Research outputs will be reported in a scientific paper and summarised in an industry-focused publication.

Green Roofs Design: Recommended Plant Palettes for Australian Green Roofs

A lack of information around suitable green roof plants for specific design objectives has been identified as a knowledge barrier limiting green roof uptake. Through this project we have developed recommended plant palettes for five common green roof typologies for southern Australian conditions:

- Lightweight, succulent-dominated green roof
- Lightweight green roof for habitat and biodiversity
- Green roof showcasing flowers and foliage
- Green roof for social, recreation and well-being outcomes
- Green roof for food production

Proven species have been identified through plant trials in this project, and from ten years of quantitative and qualitative data generated from the three Burnley green roofs (Demonstration Green Roof, Biodiversity Green Roof, Research Green Roof) and experimental research projects undertaken by academics and students in the Green Infrastructure Research Group. While the species lists are not exhaustive, we have curated groups of plants that can be used to achieve a range of green roof design objectives and functions, including stormwater control, biodiversity and human well-being benefits. We are working on final draft and formatting to the document that we hope will be widely used by designers, horticulturalists, planners, the construction sector and building owners.

Exploring the suitability of Australian Annuals for Green Roofs

As part of this projects aims to develop new plant palettes for different green roof build ups, PhD student Zahra Saraeian investigated the suitability of Australian annual species for green roof plant palettes. She explored the relationships between seed mass, germination attributes (germination percentage, lag, and rate) and the climate of species natural distribution of 58 Australian annual species from a wide range of habitats. Correlations and trade-offs between functional traits related to resource use and growth, phenology and germination strategies were also explored by growing 20 replicates of 18 Australian annual species under controlled non-limiting glasshouse conditions and measured plant functional traits, time to flowering and growth rate of each species.

She also evaluated how irrigation frequency affects plant cover, species abundance, richness and diversity, plant traits and functional diversity of a 16 species mixture of Australian annual species sown onto green roof modules. After a 2-month irrigated establishment phase, three irrigation treatments (2, 4 and 6 days between irrigation) were applied to the modules for three months.

Are succulence or trait combinations related to plant survival on hot and dry green roofs?

The many ecosystem services that green roofs can provide rely on good plant coverage and plant survival, which is challenging in hot and dry climates. While true succulents like *Sedum* spp. have been shown to survive well on green roofs, there are limited studies relating individual traits or trait combinations to survival in other life-forms. Succulence is a rarely studied trait that describes plant water storage in leaves, stems and roots, regardless of life-form. This means that succulence can occur in plants which are not considered to be true succulents like *Sedum* or *Crassula* species. Improving water availability through succulence may improve survival on unirrigated green roofs, but succulence, as a trait, has rarely been investigated in plants which are not true succulents.

PhD student Bihan Guo investigated whether succulence or trait combinations can relate well with survival and could be used to improve green roof plant selection for different substrate depths on hot and dry green roofs. She conducted two experiments with the same 11 Mediterranean species (five herbs, three sub-shrubs and three shrubs). The first experiment quantified plant traits under well-watered conditions including: succulence, leaf lethal temperature, water use, root:shoot ratio and leaf area and a green-roof module experiment to determine their survival in four substrate depths (10, 15, 20, and 25 cm).

Workstream 3: *Incorporating maintenance into green roof design and development*

Activities undertaken in this workstream included student research projects (Masters and PhD), an industry workshop and production of industry guidelines (*Maintenance Guidelines for Australian Green Roofs*).

Student research projects

Two Master of Urban Horticulture (MUH) student research projects were completed that formed part of this workstream. Damien Tang completed a systematic review of green roofs maintenance (2021) and James Steendam (2019) completed a project researching how the vegetation and substrates of four extensive green roofs in Melbourne changed since their construction in the early 2010’s.

PhD student Dean Schrieke is currently examining how water availability and *Sedum* cover influence the germination and establishment of weeds on green roofs, as part of his larger research project. To do this he created artificial gaps of increasing size in fifty-four green roof modules planted with *Sedum mexicanum*, with modules allocated to either a well-watered (WW) or water deficit (WD) treatment. Identical seed mixes composed of fourteen common green roof weeds species were scattered over modules and washed to substrate surface. Vegetation surveys were conducted twice monthly over an eight month period to assess the germination and community change of weeds species and a destructive harvest was conducted at the end of the experiment to quantify biomass and plant traits. The results should help to define the inputs and resource requirements in green roofs installation and maintenance, particularly around weed establishment and control.

Green roofs maintenance industry workshop

An online workshop on green roof maintenance, *Green Roof Maintenance Matters*, was hosted by the University of Melbourne on December 8, 2020, with four speakers with expertise in Australian green roofs (John Rayner, University of Melbourne; Michael Casey, Evergreen Infrastructure and MJC Horticulture; Sarah Hardgrove, Wildgrove Horticulture; and Scott Sherwood, Fytogreen Australia). 180 people registered for the event with the recording publicly available. Green Roof Maintenance Matters recording

Green roofs maintenance guidelines

In December 2019 the scope of this workstream was changed when construction of the Demonstration Green Roof at 1 Treasury Place Melbourne was further delayed. A guide to green roofs maintenance was proposed, creating a reference document that could be incorporated into the design and management of green roofs across Australia. To do this we reviewed existing green roof reports and guidelines, in Australia and internationally; and researched green roofs maintenance, synthesizing knowledge from academic and industry sources into development of the guidelines. An Industry Reference Group was also established in 2020 to guide and provide input to the project; this included Michael Casey (Australian Institute of Horticulture), Ben Foster (City of Melbourne), Kirsten Raynor (Horticultural Consultant), Scott Sherwood (Fytogreen Australia), Matthew Conroy (Junglefy) and Andrew Smith (University of Melbourne). We also engaged an international review of the document in 2021 before its completion, this was undertaken by Ed Snodgrass from Emory Knoll Farms, Inc./Green Roof Plants, USA.

Workstream 4: *Determine the types of green roofs aesthetically attractive to a wide range of people and better understand vegetation characteristics that increase the mental well-being of those viewing the green roof*

Psychological benefits of green roofs: Research Review

We developed a conceptual framework for analysing how green roofs can support psychological functioning in cities and apply this to review and reassess existing literature on the psychological and social dimensions of green roofs. The scope of our analysis included a diverse range of green roofs, including both extensive and intensive. Rather than treating these as separate types of green roofs, we considered how their physical and social attributes interact with the needs and actions of individuals in these environments and how these interactions could shape psychological experience. As the existing literature on psychological benefits of green roofs is very small, we drew on psychological and social-ecological research to present a consolidated framework for analysing human interactions with green roofs. We then used this framework to evaluate how psychological benefits of green roofs are influenced by the physical environment, social climate, activity and individual resources and adaptation.

Investigating what creates fascinating green roofs

Green roofs are a popular way of providing environmental benefits and places where people can experience and benefit from nature, but we know very little about the features and experiential characteristics that can support this. Fascination through interest and engagement is argued to be a key component of landscapes that restore wellbeing. We explored this proposition in two studies, investigating green roof landscapes. Study 1 used a photo-based survey, asking participants to rate 29 green roof images selected to represent a broad range of existing spaces internationally. Study 2 used interviews following virtual green roof visits, asking participants for their perceptions of the view and experience while visiting. We integrated findings across our two studies to identify features and characteristics of fascinating green roof experiences.

Psychology Student Research

A number of additional research projects associated with GC 16002 were conducted by psychology honours students supervised by project investigator Assoc. Prof. Katherine Johnson. They investigated how exposure to natural environments helps to restore attention which is important in the context of green roofs which can provide this in a highly urbanised environment.

Exposure to nature may improve attention performance through many means: modulation of alertness and one's connection to nature were investigated here, in two separate studies. In both studies participants performed the Sustained Attention to Response Task (SART) before and immediately after viewing a meadow, ocean, or urban image for 40 seconds, and then completed the Perceived Restorativeness Scale. In Study One (n = 68), an eye-tracker recorded the participants' tonic pupil diameter during the SARTs, providing a measure of alertness. In Study Two (n = 186), the effects of connectedness to nature on SART performance and perceived restoration were studied.

Results and discussion

Workstream 1: *Assess the effectiveness of demonstration green roofs in overcoming barriers to green roof uptake*

Barriers to green roof construction – a systematic review

The most common knowledge barriers were lack of local scientific research, lack of guidelines and standards, lack of knowledge of green roof benefits and lack of awareness around green roofs in general. In terms of lack of local scientific research, this focused on the need for more information on plants and substrates, costs and benefits. Knowledge barriers featured more frequently in the Australian and North American literature reviewed, compared to the more mature green roof market of Europe, and the developing markets of China and Nigeria.

Lack of policy and legislation was cited as a barrier in all regions reviewed. The most common barriers identified overall were the two barriers related to cost. The increased design and construction cost of green roofs was mentioned as a barrier in 22 of the papers reviewed, while maintenance costs were included in 18 papers. Lack of financial incentives was also a commonly cited barrier across the regions. Another common barrier overall was the immaturity of the green roof industry and the consequent lack of green roof expertise. Concerns re the structural load of green roofs was also cited in all regions reviewed whereas concerns around limited available roof area were only mentioned in all three Hong Kong papers.

The most common operational barrier identified was concerns re leaks and locating sources of leaks. Maintenance requirements and lack of knowledge around maintenance issues was also a frequently cited barrier.

Appreciative Enquiry Workshops

The results of the workshops highlight collaborative learning as key to development of a successful Australian green roof wall and façade industry. This revealed: (1) a government role in developing research partnerships, policy, and incentives, supporting discovery and exploring new opportunities (2) a national body role in advocating, and in supporting, engaging, and developing expertise, for implementation through capitalising on existing processes, and (3) cross-sector co-leading for multi-institutional alignment, and building sector capacity and knowledge, for sustaining collaborative learning cycles. It highlighted a pathway for sector evolution from adoption, to legitimation, and to diffusion and sector growth, providing evidence that the Australian GRWF sector has stalled in the legitimation phase and may be initiating change for continued progress

In line with our participatory and future-oriented approach, we have co-developed a 10-year roadmap for the sector, drawing in key themes and actions identified in the summits to set an agenda for progress (removed for review). This provides concrete guidance specific to the sector, nominating actors and actions to progress, while a scientific paper developed a model that can be applied to the field more broadly. Consistent with findings emerging from the summits, the roadmap highlighted key roles for collective discovery and early exploration of the sector as well as collective implementation through governance, planning and policy agendas required for achieving the vision for a GRWF sector in Australia.

Workstream 2: ***Develop proven, trait based, plant palettes fit for different green roof build-ups***

Green Roof Experiment - Greater substrate depth and leaf succulence increases plant survival on green roofs

We evaluated how substrate depth (10, 15 and 20 cm) affects survival of established plants on an unirrigated green roof in Melbourne over summer (16/12/21 to 28/02/22). We selected 75 taxa which are currently used or recommended for green roofs in Mediterranean-type climates, including Europe and Australia. These taxa varied in their life-form with 6 geophytes, 17herbs, 7 monocots (grasses and grass-like plants e.g. *Dianella admixta*), 26 shrubs and 19 succulents. Plants also differed in their leaf traits and we expected plants with greater leaf succulence (degree of leaf succulence; g H_2O cm^{-2} leaf area or leaf thickness) to have greater survival due their ability to access this stored water during dry periods.

We determined whether; 1) greater substrate depth increases survival under green roof conditions; and 2) survival is greater in life-forms associated with water storage (geophytes and succulents) or in plants with leaf traits associated with greater succulence.

The 75 plant species were planted in 4 replicate blocks in each of the three substrate depths (10, 15 and 20 cm deep scoria-based green roof substrate). Irrigation was supplied for 12 months to ensure good plant establishment before monitoring survival during summer without further irrigation and rainfall only. Figure 1 shows plant growth and coverage in each of the three substrate depths during establishment. Plant cover and growth was greater in 20 cm deep substrates despite water availability not being limiting during establishment. After establishment, plant survival was monitored weekly to determine when each individual plant died. Leaf traits were determined on well-watered plants.

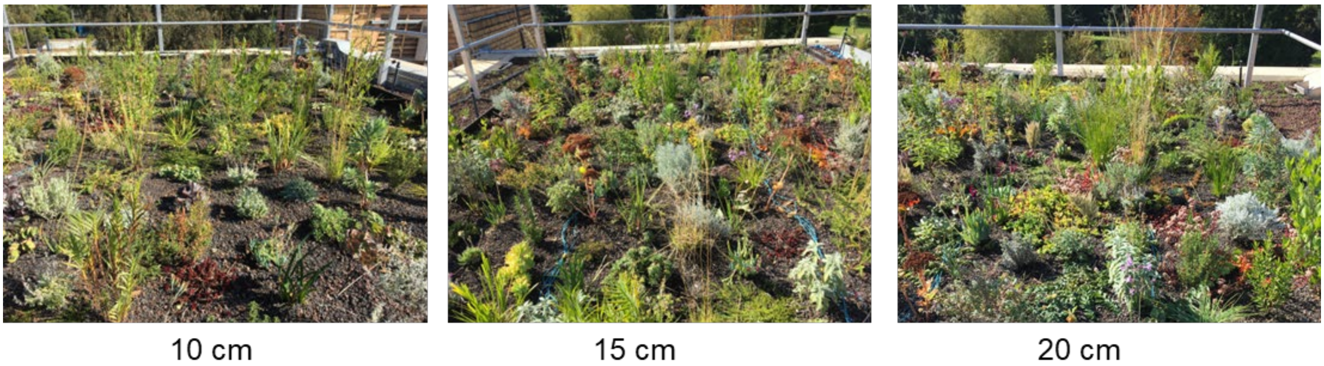

Fig. 1. Images of the experimental green roof showing plant coverage after six months establishment in each of the three substrate depths (10, 15 and 20 cm). Photos were taken on 5/05/2021. Plants were irrigated for 12 months before survival was monitored over summer without irrigation.

Over the summer period when plant survival was monitored, water was very limited on the green roof, with 70 days where the Climate Wetness Index (precipitation/mean air temperature) was less than 0.5, indicating that the climate was semi-arid (Figure 2). There were also 26 days where maximum air temperatures exceeded 30 ^{o}C.

Overall, plant survival was greater in deeper substrates and the best survivors were succulents, geophytes and monocots (Table 1). Shrubs survived better than herbs in 20 cm deep substrate. These results indicate that shrubs should be planted in at least 20 cm deep substrates, unless irrigation is supplied to keep plants alive over summer in Melbourne's climate.

Across all plants, survival was significantly greater (lower mortality score) in plants with greater leaf thickness (mm) and degree of leaf succulence (g H_2O cm^{-2} leaf area; Figure 3). This suggests that these two easily measured leaf traits can be used to select new plants for green roofs without the need to undergo extensive experimentation. However, care must be taken to ensure that they are selected from appropriate climates or from habitat templates with conditions that are similar to green roofs, e.g. rock outcrops, coastal cliffs and other shallow soil habitats where soil moisture is limiting during summer.

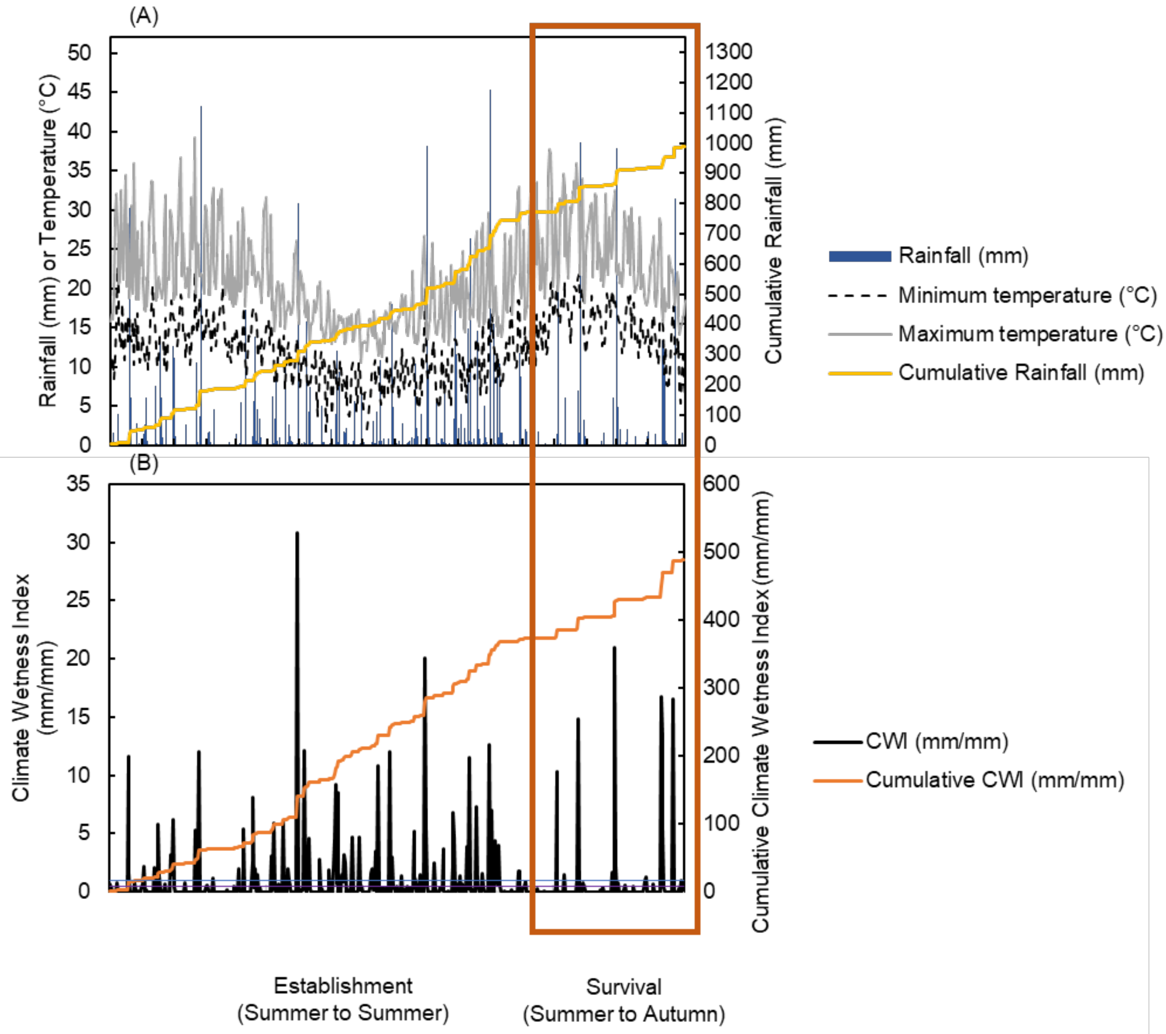

Fig. 2. (A) Maximum and minimum temperature, daily rainfall and cumulative rainfall from 5/11/2020 – 10/5/2022 (Bureau of Metrology, Melbourne Olympic station). (B) Climate Wetness Index (CWI) and cumulative CWI during 5/11/2020 – 10/5/2022, calculated as rainfall/evapotranspiration based on Fig. 2 (A). Above blue line, CWI > 1, means the evaporation is less than rainfall, while below the purple line (CWI < 0.5) represents when rainfall is less than half of the evaporation.

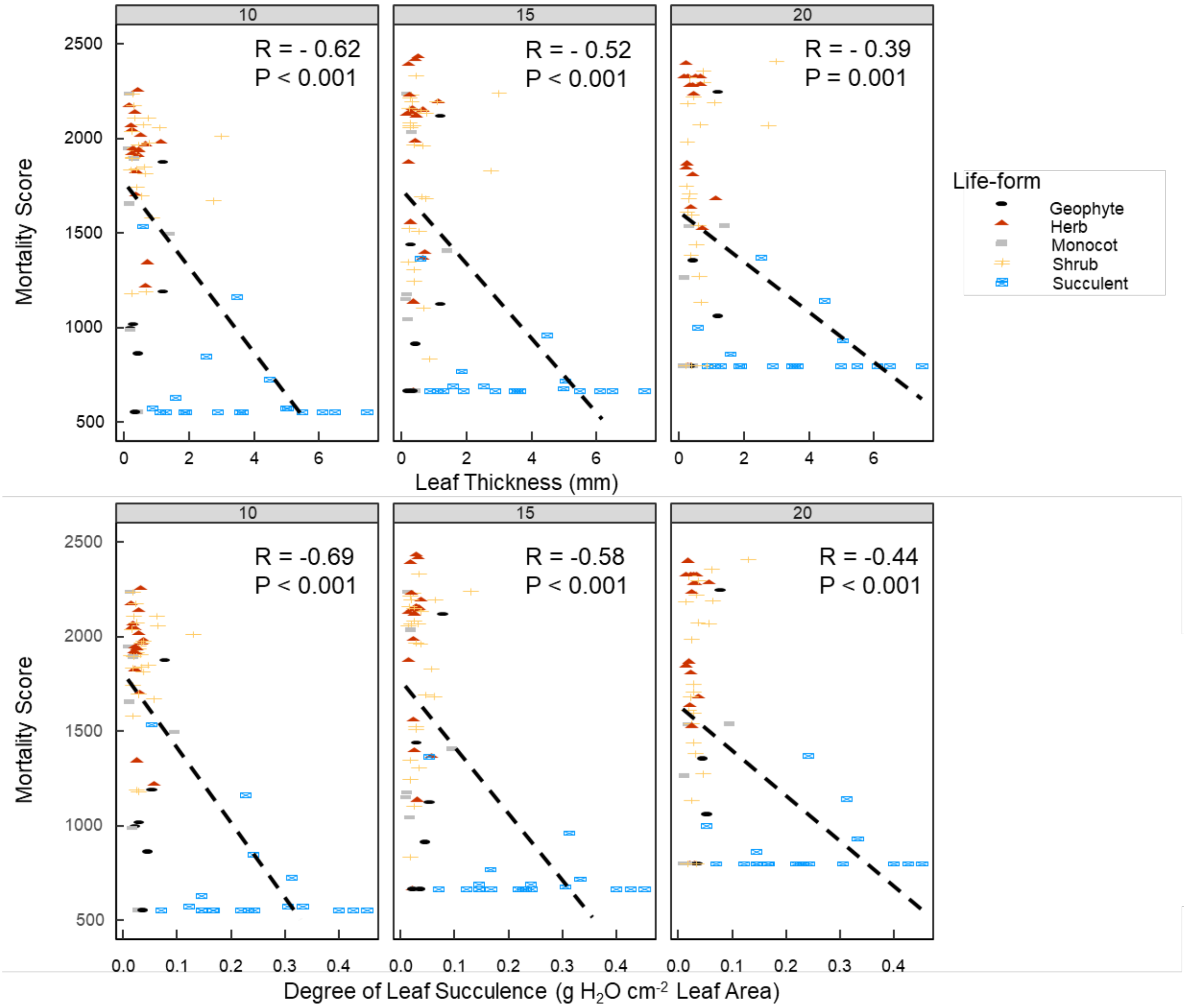

Fig. 3. Relationships between leaf thickness (mm) and degree of leaf succulence (g H_2O cm^{-2} leaf area) and mortality scores in 10, 15 and 20 cm substrate depths. Black dash trendlines show significant relationships among all species. R and P values for all species (Pearson correlation) are in black text. Pearson correlations showed there were no significant relationships within each life-form separately.

Information on plant performance of the 75 test species, plus information on over 150 species planted on Burnley demonstration green roofs and psychological studies into human preference and response to green roof species and designs will be incorporated into SE Australian specific green roof planting guidelines that are planned for release in early 2023.

<u>Exploring the suitability of Australian Annuals for Green Roofs</u>

PhD student Zahra Saraeian found that species from hotter and drier environments and from environments with higher annual temperature variation had greater seed mass. We found no relationship between seed mass, and germination percentage and speed. Lower germination was observed in species from hotter and drier environments as well as environments with more variable rainfall. Moreover, germination speed was greater in species from drier environments and environments with lower climate variability. Cluster analysis divided the species into two distinct groups based on plant functional traits. In group A, growth rate had a negative relationship with flowering time and therefore fast growing species were flowering faster. Germination speed positively affected flowering time in this group. In group B, growth rate and flowering time had negative relationships, and specific leaf area was the only functional trait related to growth and flowering time. The results of this experiment indicated that Australian annual species have different their life cycle strategies, information which can be used to design long flowering attractive green roofs.

In the direct seeded module study, plant cover was reduced at lower irrigation frequency (6 days), but ≥ 80% plant cover was achieved in all irrigation treatments. There was no effect of irrigation frequency on species abundance and richness; however, abundance, richness and diversity reduced over time, likely due to competition effects. Plant height and leaf area were also reduced by lower irrigation frequency. At the community level, functional diversity was unaffected by irrigation frequency. Our results indicate that green roofs sown with a mixture of Australian annual plants can achieve good plant coverage, as recommended by green roof guidelines, and maintain high diversity when minimally irrigated in their first growing

Are succulence or trait combinations related to plant survival on hot and dry green roofs?

PhD student Bihan Guo found that plant survival was not related to succulence and that increased internal water storage in non-succulent plants does not per se lead to greater survival in extreme conditions. Survival was also not related to individual traits relating to water use and leaf heat tolerance or trait combinations. Nevertheless, plants in the same functional groups had similar survival, which suggests plants with similar trait combinations can have similar survival on green roofs. This information can be useful when selecting new green roof species and may overcome the need for labour and time intensive green roof plant trials – instead identifying candidate species using a functional group approach.

Workstream 3: *Incorporating maintenance into green roof design and development*

Student research projects

MUH student Damien Tang analysed 56 research papers that made some reference to green roofs maintenance, finding that clear definitions and descriptions of maintenance were largely absent. He also found that the only maintenance issues outlined in any detail were irrigation and fertilization, maintenance challenges were poorly described and that and that there was a significant lack of meaningful data on maintenance tasks and costs. Damien's work has highlighted the need for more empirical research on green roofs maintenance, particularly data that can assist in quantifying the resource requirements and costs of maintenance.

MUH student James Steendam completed vegetation surveys and tested substrates for chemical and physical properties across four green roofs, comparing these to the original data where available. His results showed that there was a large decline in the original species planted across all four green roofs, with an average of 31.9% of persistence and an average gain of 72.2%. He also found significant changes in substrate properties, particularly through notable reductions in Water Holding Capacity (WHC) and Air-Filled Porosity (AFP) on three of the four green roofs, with one roof also showing significant acidification since installation. His research highlighted the need for clearer details on green roofs maintenance, including performance specifications, and the importance of record keeping when assessing the success and performance of green roof assets.

PhD student Dean Schrieke's research showed that weed species richness was highest in bare module treatments and decreased with increasing *Sedum mexicanum* cover. Well-watered modules generally had higher weed species richness and biomass than water deficit modules. Well-watered modules with high rates of *S. mexicanum* cover were dominated by one weed species (*T. repens*), which accounted for more than 90% of the weed biomass. However, *T. repens* biomass was significantly reduced in water deficit modules with high rates of *S. mexicanum* cover. We found that spontaneous communities in 'drill' modules were not significantly different to those in 100% cover modules, indicating that *S. mexicanum* is probably not physically preventing seed from reaching the substrate surface and instead is likely outcompeting weed species for resources. To limit weed species on green roofs it is desirable to maintain high *Sedum* coverage and limit water availability, focusing maintenance on removing potentially dominant weed plant species. However, to maximise species richness, limiting *Sedum* cover or creating and maintaining mosaics of bare substrate 'safe sites' within existing *Sedum* cover, alongside supplemental irrigation, is recommended.

Green roofs maintenance industry workshop

The 90-minute workshop attracted 180 registrations with 73 attending and a further 198 viewing the recording of the workshop online (up to April 9, 2022). The audience included participants from across Australia reflecting the diverse green infrastructure industry, including landscape architects and designers, facility managers, landscape and green roofs contractors, nursery growers, engineers and municipal officers. Feedback from participants has so far been very positive, with several noting that this workshop filled a significant knowledge gap in their organisation or industry.

Green roofs maintenance guidelines

Green roof maintenance is different from general landscape and horticultural maintenance; ensuring there is an understanding of the required maintenance to support the intended aesthetic and functional outcomes of a green roof is critical to their success. The guidelines have been written for those in planning, design, maintenance and management roles and include details on considerations during project design development, issues of access and safety, specific maintenance activities and tasks and monitoring, reporting and management. They also include examples of maintenance schedules for four different green roof types (roof garden, lightweight green roof, biodiversity green roof and productive green roof). The 44-page guidelines were released in January 2022 and will be formally launched at the NGIV *Greening Cities* Event on April 20, 2022.

Workstream 4: *Determine the types of green roofs aesthetically attractive to a wide range of people and better understand vegetation characteristics that increase the mental well-being of those viewing the green roof*

Psychological benefits of green roofs: Research Review

Green roofs are a relatively novel and inadequately understood form of urban greening. Our review was motivated by a concern that claims of psychological benefits associated with green roofs may therefore be overstated based on a small number of promising studies or overgeneralized from a larger body of research on psychological benefits of more traditional urban greenspace. We counter those risks by assessing how attributes of the physical environment, social climate, activity, individual resources and adaptation interact to shape experience of green roofs, and therefore potential psychological benefits. This analysis has revealed the complexity of experiences of green roofs, allowing us to better specify the circumstances under which green roofs may provide psychological benefits. While grassy and flowering vegetated roofs are most likely to support positive aesthetic and restorative outcomes, this is unlikely to occur without consideration of plant survival, impact of roof top heat and wind on human comfort, perceived access to the roof top, design fit with social norms for nature in cities, and provision for restorative activities and individual adaptation of the site.

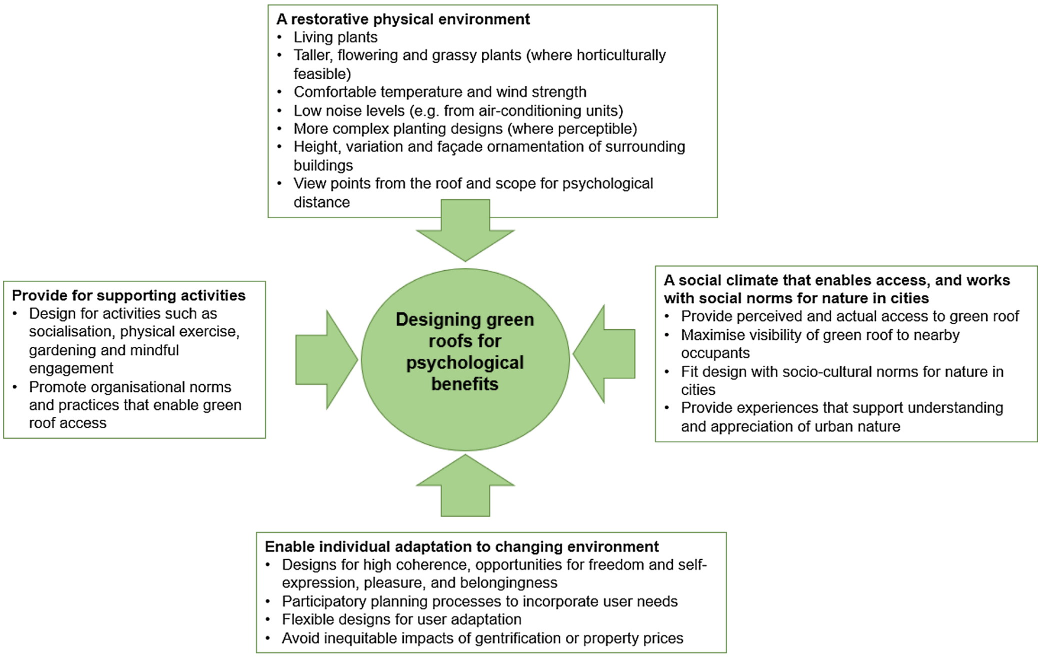

Figure 1. Consideration when designing green roofs for psychological benefits (From Williams et al 2019 Appraising the psychological benefits of green roofs for city residents and workers. Urban Forestry and Urban greening 44 126399

Investigating what creates fascinating green roofs

We identified complexity through space and time, movement into and of features in the landscape, multi-sensory engagement, and connecting with distance through vast vistas as key to fascinating green roof experiences. These characteristics were associated with features on and beyond the roof, both natural and built.

Visual features of green roof views associated with fascination we identified appeared to predominantly reflect features on the roof, often in the form of vegetation and complexity, and features that supported engaging with them. Complexity appeared to be distinguished through structural variation, colour, species, and in its absence, and linked with paths and traversable built or vegetated surfaces that potentially provided cues for access. Unexpectedly, the findings do not suggest features of the built environment or the view beyond the roof influence ratings of fascination significantly, although participants appeared to distinguish roofs with some enclosure. It is possible that features on the green roof primarily drive ratings of fascination, at least in the short-term.

Our findings and past research provide some practical suggestions for green roof design through features that support fascinating green roof experiences. First, carefully positioned 'tree-like structures' may be particularly relevant to designing green roofs where a range of climate and building constraints have rendered large trees unfeasible (Williams et al., 2021). The use of climbing plants often associated with these structures may help to capture the movement and sensory aspects of trees participants remarked upon. Use of these and similar structures may help to address concerns with challenging hot, dry, windy, and noisy green roof environments which detract from their capacity to provide restoration (Williams et al., 2019). Additionally, contrast through ground and built materials may be a possible way of providing fascinating colour on green roofs, especially across seasons, alongside varied topography that stimulates interest (cf. Mesimaki et al., 2019) and the potential for visible change and growth, alongside hardiness.

Other recommendations differ depending on access —either through onsite visits or through views from nearby or far buildings or streets. For example, green roof vegetation may be perceived differently from a distance where details associated with succulent green roofs may be difficult to appreciate and where meadows may be more appreciated (Loder, 2014). In such instances designers could consider emphasising interest and exploration from afar (Loder, 2014), whereas physically accessible green roofs should also incorporate possibilities for movement, appreciating complexity, and engaging the senses. However, our results also suggest caution as high visual access from surrounding buildings (as suggested by Williams et al., 2019) could constrain possibilities for fascination during green roof visits through concerns with overlooking.

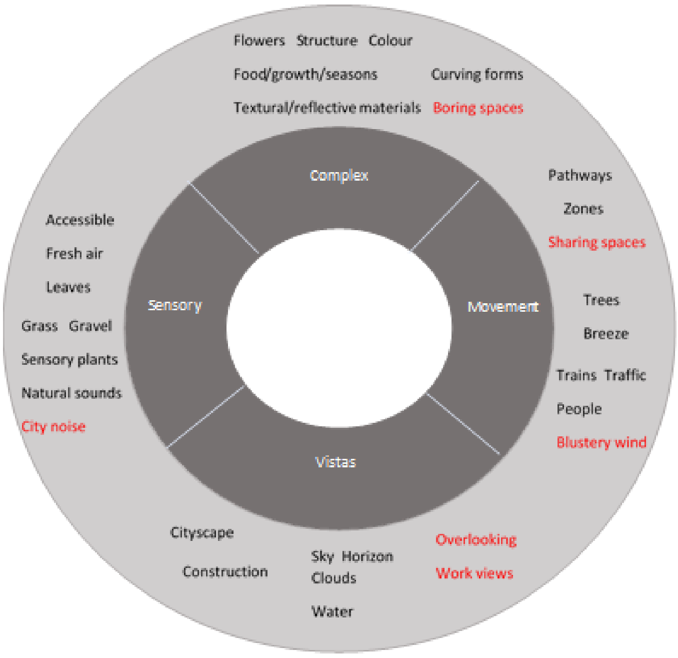

Figure 2. A model linking characteristics of fascinating green roof experiences (inner dark grey circle) with fascinating features on and beyond the roof (outer light grey circle), providing practical considerations for green roof design. Detracting features are shown in red text.

Psychology Student Research

In both studies, the image viewed was not associated with participants' sustained attention performance; both nature images were perceived as equally restorative, and more restorative than the urban image. The image viewed was not associated with changes in alertness. Connectedness to nature was not associated with sustained attention performance, but it did moderate the relation between viewing the natural images and perceived restorativeness; participants reporting a higher connection to nature also reported feeling more restored after viewing the nature, but not the urban, images. Dissociation was found between the physiological and behavioural measures and the perceived restorativeness of the images. The results suggest that restoration associated with nature exposure is not associated with modulation of alertness but is associated with connectedness with nature. This suggests that green roofs are more likely to benefit people with a higher connectedness to nature. This information could be used by organisations to benefit their employees and developers. The research has recently been accepted for publication in the international journal Frontiers in Psychology.

Outputs

Table 1. Output summary

Output	Description	Detail
Industry Outreach Event	*Planning and designing green roofs: advances in research* Industry Research Forum 13/12/2018	Horticultural scientists and ecologists from the Green Infrastructure Research Group presented major research findings from past and current green roof research projects, as well as highlighting future research directions. Particular focus was made on the HIA16002 and opportunities for future industry engagement. 90 attendees
Workshop	Green Roof Wall and Façade Industry Summits held in Melbourne and Sydney	Project staff ran two highly successful industry workshops in Sydney (March 2019) and Melbourne (April 2019) to create a vision, and identify pathways, for greater greening in cities throughout Australia. The summits brought together researchers and over 60 practitioners from green infrastructure industries. Practitioners included architects and landscape architects, green roof installers, state government, water retailers, and substrate and nursery suppliers. Intended Audience: Australian green roof industry
Workshop	Green Roofs Maintenance workshop (online)	An online 90-minute workshop on green roofs maintenance was held on December 8, 2020. Attracting 180 registrations with 73 attending and a further 198 viewing the recording of the workshop; the audience included landscape architects and designers, facility managers, landscape and green roofs contractors, nursery growers, engineers and municipal officers. Feedback from the diverse range of participants has been very positive, with several noting that this workshop filled a significant knowledge gap. Intended Audience: Entire Australian green roof industry
Scientific Paper	Review of research on psychological benefits of green roofs through a social-ecological lens on human-environment interactions	Williams, K. J. H., K. E. Lee, L. Sargent, K. A. Johnson, J. Rayner, C. Farrell, R. E. Miller, and N. S. G. Williams. 2019. Appraising the psychological benefits of green roofs for city residents and workers. Urban Forestry and Urban Greening 44. Intended Audience: researchers, green roof designers https://www.sciencedirect.com/science/article/abs/pii/S1618866719303279
Conference Presentation	International Conference on Environmental Psychology. Plymouth, UK. (September 4-6th, 2019).	Williams, K.J.H., Lee, K., Sergeant, L., Johnson, K., Rayner, J., Farrell, C., Miller, R., Williams, N.S.G. Appraising the psychological benefits of green roofs for city residents and workers. Intended Audience: Environmental psychology researchers
Conference Presentation	International Conference on Environmental Psychology. Plymouth, UK. (September 4-6th, 2019).	Katherine A. Johnson, Timothy Doman, Keitaro Machida, Jonathon H. Januar, Nicholas S.G. Williams, Leisa D. Sargent, Kate E. Lee, Kathryn J.H. Williams. The impact of a micro-nature experience on sustained attention performance and arousal. Intended Audience: Environmental psychology researchers
Conference Presentation	International Association for People-Environment Studies (IAPS), 21-26th June, Quebec City. (online format)	Lee, K.E., Sargent, L.D., Williams, N.S.G., & Williams, K.J.H. (2020). Flourishing green cities: Harnessing collective visions of green roofs, walls, and facades to develop a roadmap for change. Intended Audience: Environmental psychology and social science researchers

Conference Presentation	Greening Cities, April 20-21 2022. Event with NGIV, Burnley Campus, University of Melbourne	Final presentation and workshop on project outcomes (upcoming). A/Prof. J Rayner, MC Prof. N. Williams, Ten Years of Greening a Wide Brown Land; advances in green roof research, design and installation in Australian cities Dr C. Farrell, Green roof plants: a guide to selection and planting Spontaneous vegetation on green roofs – D. Shrieke (PhD student) Connectivity of green roofs for biodiversity – J. Schiller (PhD student) Performance of annual wildflowers on green roofs – Z. Saraeian (PhD student) Environmental stress and plant selection – B. Guo (PhD student)
Media	Article on The Conversation news website on the outcomes of the industry summits and resulting roadmap	Williams, N.S.G., Oke, C. and Sargent, L. 2020 Greening our grey cities: here's how green roofs and walls can flourish in Australia. The Conversation https://theconversation.com/greening-our-grey-cities-heres-how-green-roofs-and-walls-can-flourish-in-australia-139478 Intended Audience: General Public
Media	Article on project and outputs. Nursery Papers	Accelerating uptake and removing barriers to green roofs in Australia Nursery Papers, Nov 2021. Greenlife Industry Australia/Hort Innovation, Nursery Fund. Intended Audience: Greenlife Australia members – nursery sector.
Scientific Paper	Review of Australian green roof research that assesses the state of the industry and incorporates findings from our GRWF summits	Williams, N. S. G., R. S. Bathgate, C. Farrell, K. E. Lee, C. Szota, J. Bush, K. A. Johnson, R. E. Miller, A. Pianella, L. D. Sargent, J. Schiller, K. J. H. Williams, and J. P. Rayner. 2021. Ten years of greening a wide brown land: A synthesis of Australian green roof research and roadmap forward. Urban Forestry and Urban Greening 62. https://www.sciencedirect.com/science/article/abs/pii/S1618866721002041 Intended Audience: researchers, green roof designers, researchers
Report	Report compiling the industry recommended actions arising from the Green Roof Wall and Façade summits	Bathgate, R., N. S. G. Williams, L. D. Sargent, K. E. Lee, J. P. Rayner, M. Ritchie, J. Bush, K. J. H. Williams, K. A. Johnson, G. Hall, N. Pelleri, S. J. Wilkinson, and C. Martin. 2020. Roadmap for Green Roofs, Walls and Facades in Australia's Urban Landscapes 2020-2030. University of Melbourne, University of NSW and Hort Innovation. Melbourne. https://blogs.unimelb.edu.au/girg/files/2020/06/Roadmap-for-Green-Roofs-Walls-and-Facades-Report.pdf Intended Audience: Participants in the Australian green roof industry, Federal, state and local government policy makers
Technical Report	Maintenance Guidelines for Australian Green Roofs	Rayner, J., Lumsden, E. and Bathgate, R. (eds) 2022, Maintenance Guidelines for Australian Green Roofs, Report for Hort Innovation project GC16002, University of Melbourne (44 pages) Intended Audience: Green roof designers, construction and landscape maintenance contractors
Technical Report	Planting Guidelines for Australian Green Roofs	Rayner, J., Farrell, C., Williams, N.S.G., Lee, K.E. and Bathgate, R. (in prep). Planting Guidelines for Australian Green Roofs. Report for Hort Innovation project GC16002, University of Melbourne. Intended Audience: Green roof designers, landscape contractors, nursery suppliers

Scientific Paper	Research that investigates how connectedness to nature influences attention restoration benefits from exposure to nature – such as green roofs	Johnson, K.A., Pontvianne, A., Ly, V., Jin, R., Haris Januar, J. Machida, K., Sargent, L.D., Lee, K.E. Williams, N.S.G., Williams, K.J.H. (in press) Water and meadow views both afford perceived but not performance based attention restoration: Results from two experimental studies. Frontiers in Psychology. 809629 Intended Audience: Environmental psychology researchers
Scientific Paper	Research output from the Green Roofs and Walls summits detailing what participants think is required for a successful green roof industry	Lee, K. E., Sargent, L. D., Williams, K. J. H., Hall, G., Williams, N. S. G., 2022, A collaborative learning model for a flourishing green roofs, walls and facades sector: Exploring two major Australian cities, *Cities* 131. Intended Audience: green roof industry, government policy makes
Scientific Paper	Research that demonstrates Australian annual species are a good plant choice for green roofs	Saraeian, Z., Farrell, C., Williams, N. S. G., 2022, Green roofs sown with an annual plant mix attain high cover and functional diversity regardless of irrigation frequency, Urban Forestry and Urban Greening 73. 127594 Intended Audience: green roof researchers and designers

Photos/images/other audio-visual material

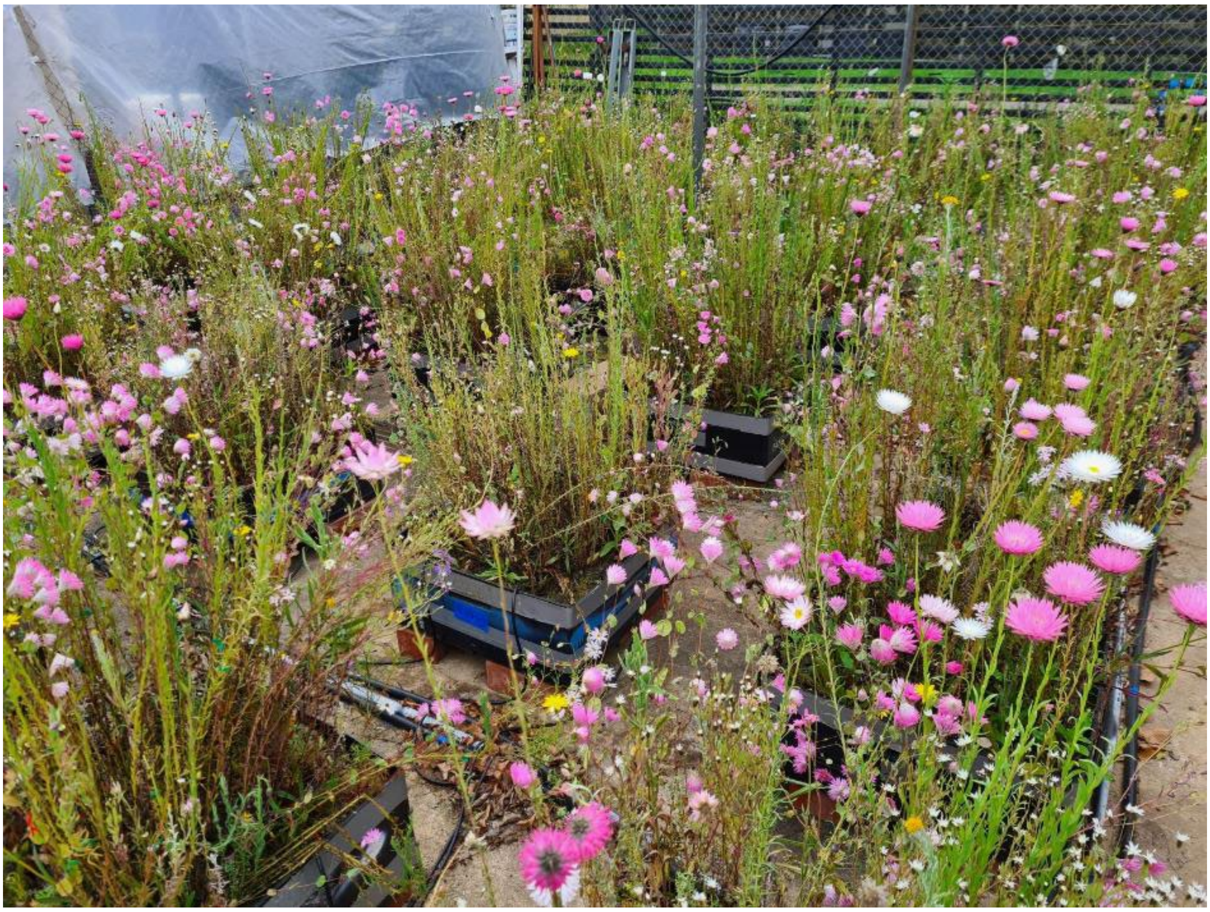

Figure 3. Green roof modules sown with a mixture of 16 Australian annual plant taxa (mainly from Asteraceae) achieved high cover and functional diversity in the 6 days irrigation frequency. Photo: Rebecca Miller Rebecca.Miller@rbg.vic.gov.au 8/9/20

a) Planting, 6 Nov 2020.

b) Planting, 6 Nov 2020, showing randomised plant placement with 4 replicate plants per species per plot.

c) 10 cm plot, May 2021, irrigated.

d) 15 cm plot, Feb 2021, irrigated.

e) View of all plots with 10 cm plot in foreground, March 2022, no irrigation.

f) 20 cm plot, March 2022, no irrigation. The number of species able to survive without irrigation was greatest in 20 cm and least in 10 cm plots.

Figure 4. Research Green Roof experiments showing 10, 15 and 20 cm substrate depth plant trials at planting (a, b), lush growth post establishement in irrgated plots (c, d) and after the water limiting/temperature trials with no supplementary irrigation to plots over summer (e, f).

Outcomes

Table 2. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
Intermediate outcomes			
Increased development industry awareness of the benefits of green roofs	Green Cities Fund: climatic and environmental; knowledge and information	Project research findings have been presented at events, including industry summits, conferences, workshops and seminars. Scientific and technical publications targeting industry professionals and practitioners have also been produced.	Registrations and participation in events. Green roof applications in some planning schemes (e.g. Green Factor Tool, City of Melbourne). Increased subscription to GIRG website and newsletter.
Improved green roof maintenance planning	Green Cities Fund: knowledge and information	An online, Australia-wide workshop on green roofs maintenance engaged industry practitioners on the need for maintenance planning Production of *Maintenance Guidelines for Australian Green Roofs*	Participation and survey responses to workshop participants. Incorporation of green roof maintenance plans as part of planning applications for green roofs (City of Melbourne). Engagement with participants when the guidelines are launched at the Greening Cities Event in April 2021.
A wider range of plants begin to be specified for green roofs	Green Cities Fund: knowledge and information	Production of the *Plants Guide for Australian Green Roofs*	To be launched in June, 2022
End of project outcomes			
An increase in the number of development proposals that incorporate green roofs	Green Cities Fund: knowledge and information	Increasing demand for green roofs increases the demand for plants and highlights their benefits in dense urban environments	Local government tracking of green roofs planning applications.
More local and state planning schemes and policies that include green	Green Cities Fund: knowledge and information	The project outputs (e.g. *Maintenance Guidelines, Plant Guide*)	Use of project outputs in planning approvals for green roofs.

roofs.		are made available to state govt and municipalities for planning green roofs.	
A larger, stronger. more integrated Australian Green Roof Industry	Green Cities Fund: knowledge and information	The Green Infrastructure summits and resulting report have catalysed the Industry	Formation of the Australasian Green Infrastructure Network – a new industry body

Monitoring and evaluation

Table 3. Key Evaluation Questions

Key Evaluation Question	**Project performance**	**Continuous improvement opportunities**
To what extent has the project increased industry awareness of green roofs in Australia and overcome barriers to uptake leading to increased demand for green roofs?	Despite not constructing a physical demonstration green roof, beyond that already present at Burnley, we have greatly increased industry awareness of key barriers and facilitated industry led discussions on how to overcome them. We have also provided resources for key participants to achieve this – see outputs	As evidenced by this project, barriers to retrofitting green roofs to existing building stock are still considerable and may have increased – i.e. stricter fire regulations. Greater acceptance of, and demand for, non-accessible green roofs designed for ecosystem services and not amenity is required.
Are the research findings relevant to green roof industry stakeholders? Are they readily transferable to further policy and implementation?	Excellent - Research findings have been incorporated into an industry roadmap, maintenance guidelines and green roof planting guide is in development	Strategic partnerships between researchers, Hort Innovation and professional industry groups such as AILA could considerable increase uptake and transferability.
How accessible were project events to the green roof industry?	Green Roof Wall and Façade summits were by invitation only as we needed to balance the audience as it was part of a research project. However, most invitees attended.	Maintenance workshop was livestreamed via zoom as it occurred during Melbourne's Covid lockdown. This provided opportunities to reach a larger audience and we had many attendees from interstate who would not normally have attended. Consequently, dual delivery events should be considered in future.
Did the project engage with industry effectively through project newsletters, workshops and conference presentations?	We had difficulties holding in-person workshops and attending conferences due to Covid 19 lockdown restrictions. Electronic project newsletters were produced and distributed widely. Workshops were run online.	Webinars and online workshops were very popular and increased project reach allowing interstate participants to attend. Consider dual delivery mode for future projects.
What additional opportunities, outputs and learnings has the project generated?	A number of additional student research projects were generated by the project. These increased understanding and broadened the projects scope and reach. We also took the opportunity to write a widely circulated article for The Conversation which generated additional media and publicity	Working with universities provides the opportunity to value add with related, additional student projects.

Recommendations

Recommendations for Hort Innovation

- Consider participating in and potentially funding a green infrastructure knowledge hub that provides independent information on green roofs, walls and facades. Its purpose will be to further reduce the barriers to green roof construction, facilitate industry growth and development and better appreciate the relative costs.
- Building industry capacity by improving knowledge and skills across key disciplines is needed for further growth of the green roof industry in Australia and to remove some remaining barriers.
- Engage with planning scheme amendments and building regulation reviews to advocate for green roofs, walls and facades.

Recommendations for Growers

- Be proactive in engaging with landscape architects and others designing green roofs to provide more interesting and diverse plant palettes suitable for use.
- Engage with landscape architects, project managers and others designing and managing green roofs to contract grow plants for specific projects, especially where new buildings have long lead times in construction.
- Consider developing a suite of 'green roof plants' suitable for different applications and uses and linked to the types of green roof designs and installations.

Recommendations for Green Roof Designers

- Retrofitting accessible green roofs to existing buildings is difficult and there are many unforeseen challenges and barriers.
- Design for function: GRWFs need to be designed to achieve their stated function(s) or objective(s), for example stormwater capture, biodiversity and human well being and aesthetics. Our research indicates different substrate depths and plant palettes should be used to achieve the different functions. Guidelines, standards and information shared through a 'Knowledge Hub' will assist in best practice to design that will optimise GRWF performance.
- Design for maintenance: Good maintenance is essential to the long-term performance of GRWFs. Maintenance requirements and costs should be considered in the design phase with input from those with expertise in GRWF maintenance and facilities management.
- Design for fascination: Fascinating green roofs are documented to provide greater well-being benefits for those using and viewing them. Fascinating green roof experiences involve vegetation complexity and ideally some height (trees, climbers), movement, sensory engagement, and potentially vast vistas from the roof.

Recommendations for Researchers

- Relying on other organisations to provide key research infrastructure is a risk. This project was severely affected by delays in constructing the demonstration green roof on 1 Treasury Place. This was ameliorated by redesigning the research program and greater utilisation of the green roofs at the University's Burnley Campus

Refereed scientific publications

Journal articles

Lee, K. E., Sargent, L. D., Williams, K. J. H., Hall, G., Williams, N. S. G., 2022, A collaborative learning model for a flourishing green roofs, walls and facades sector: Exploring two major Australian cities, *Cities* 131. https://doi.org/10.1016/j.cities.2022.103884

Johnson, K. A., Pontvianne, A., Ly, V., Jin, R., Januar, J. H., Machida, K., Sargent, L. D., Lee, K. E., Williams, N. S. G., Williams, K. J. H., 2022, Water and meadow views both afford perceived but not performance-based attention restoration: results from two experimental studies, Frontiers in Psychology 13. https://doi.org/10.3389/fpsyg.2022.809629

Saraeian, Z., Farrell, C., Williams, N. S. G., 2022, Green roofs sown with an annual plant mix attain high cover and functional diversity regardless of irrigation frequency, Urban Forestry and Urban Greening 73. 127594 https://doi.org/10.1016/j.ufug.2022.127594

Williams, K. J. H., K. E. Lee, L. Sargent, K. A. Johnson, J. Rayner, C. Farrell, R. E. Miller, and N. S. G. Williams. 2019. Appraising the psychological benefits of green roofs for city residents and workers. Urban Forestry and Urban Greening 44, 126399. https://doi.org/10.1016/j.ufug.2019.126399

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Williams, K. J. H., K. E. Lee, L. Sargent, K. A. Johnson, J. Rayner, C. Farrell, R. E. Miller, and N. S. G. Williams. 2019. Appraising the psychological benefits of green roofs for city residents and workers. Urban Forestry and Urban Greening 44, 126399.

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Intellectual property

No project IP or commercialisation to report

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Burnley Nursery Staff Nicholas Osbourne, Sascha Andrusiak, Rowan Berry and Brett Hough provided invaluable assistance supplying and maintaining plants for the research.

For the Green Roof, Wall and Facades Industry summits and resulting research we would like to acknowledge the inspiring and informative work of our summit design team industry partners Nick Alsop, Jock Gammon, Claire Martin, Mo Ritchie, lead facilitator Tanya James, and discussion facilitators Claire Farrell, Katherine Johnson, Bec Miller, and John Rayner. We would also like to thank Rachael Bathgate and Stephanie Ashby who helped organise our summits, and Sidonie Carpenter, Geoff Heard, Isabelle Mason, Lucy Sharman, and Kate Yates who provided insights into the sector context and development.

Appendices

Greenlife Industry Australia 2021, Accelerating uptake and removing barriers to green roofs in Australia, Nursery paper CIC_107030

Johnson, K.A., Pontvianne, A., Ly, V., Jin, R., Haris Januar, J. Machida, K., Sargent, L.D., Lee, K.E. Williams, N.S.G., Williams, K.J.H. (2022) Water and meadow views both afford perceived but not performance based attention restoration: Results from two experimental studies. Frontiers in Psychology. 809629

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Williams, K. J. H., K. E. Lee, L. Sargent, K. A. Johnson, J. Rayner, C. Farrell, R. E. Miller, and N. S. G. Williams. 2019. *Appraising the psychological benefits of green roofs for city residents and workers*. Urban Forestry and Urban Greening 44, 126399.

Williams, N. S. G., R. S. Bathgate, C. Farrell, K. E. Lee, C. Szota, J. Bush, K. A. Johnson, R. E. Miller, A. Pianella, L. D. Sargent, J. Schiller, K. J. H. Williams, and J. P. Rayner. 2021. *Ten years of greening a wide brown land: A synthesis of Australian green roof research and roadmap forward*. Urban Forestry and Urban Greening 62, 127179.

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Water and Meadow Views Both Afford Perceived but Not Performance-Based Attention Restoration: Results From Two Experimental Studies

Katherine A. Johnson[1], Annabelle Pontvianne[1], Vi Ly[1], Rui Jin[1], Jonathan Haris Januar[1], Keitaro Machida[1], Leisa D. Sargent[2], Kate E. Lee[3], Nicholas S. G. Williams[3] and Kathryn J. H. Williams[3]*

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Attention Restoration Theory proposes that exposure to natural environments helps to restore attention. For sustained attention—the ongoing application of focus to a task, the effect appears to be modest, and the underlying mechanisms of attention restoration remain unclear. Exposure to nature may improve attention performance through many means: modulation of alertness and one's connection to nature were investigated here, in two separate studies. In both studies, participants performed the Sustained Attention to Response Task (SART) before and immediately after viewing a meadow, ocean, or urban image for 40 s, and then completed the Perceived Restorativeness Scale. In Study 1 ($n = 68$), an eye-tracker recorded the participants' tonic pupil diameter during the SARTs, providing a measure of alertness. In Study 2 ($n = 186$), the effects of connectedness to nature on SART performance and perceived restoration were studied. In both studies, the image viewed was not associated with participants' sustained attention performance; both nature images were perceived as equally restorative, and more restorative than the urban image. The image viewed was not associated with changes in alertness. Connectedness to nature was not associated with sustained attention performance, but it did moderate the relation between viewing the natural images and perceived restorativeness; participants reporting a higher connection to nature also reported feeling more restored after viewing the nature, but not the urban, images. Dissociation was found between the physiological and behavioral measures and the perceived restorativeness of the images. The results suggest that restoration associated with nature exposure is not associated with modulation of alertness but is associated with connectedness with nature.

Keywords: sustained attention, attention restoration theory, pupillometry, connectedness to nature, SART, waterscape, meadow, alertness

INTRODUCTION

Sustained attention is the skill of maintaining concentration and inhibiting distractions (Robertson et al., 1997), which is difficult to maintain and fluctuate over time (Williams et al., 2018). This important form of attention underpins more complex cognitive functions (Anderson and Doyle, 2004), and everyday tasks like driving (Robertson, 2003) and learning (Shannon et al., 2021), making it a good candidate for nature interventions. Attention Restoration Theory (ART) proposes that exposure to particular environments, especially nature, helps to restore attention after depletion because natural environments gently capture externally-focused (exogenous) attention processes, thereby allowing internally-focused (endogenous) attention to rest and be replenished (Kaplan and Kaplan, 1989; Kaplan, 1995; Williams et al., 2018). Sustained attention has often (Hartig et al., 1991; Berto, 2005; Craig et al., 2015; Lee et al., 2015; Schutte et al., 2017; Amicone et al., 2019), but not always (Van den Berg et al., 2003; Nguyen et al., 2018; Cassarino et al., 2019; Hicks et al., 2020; Neilson et al., 2020), been associated with performance improvement after exposure to nature. Two recent meta-analyses revealed that the effect size of nature exposure on sustained attention performance was minimal (Ohly et al., 2016; Stevenson et al., 2018) and it was noted that the mechanisms underpinning the effects of nature exposure on sustained attention performance are not well understood (Stevenson et al., 2018). Here, two different mechanisms were examined in separately—alertness and connectedness to nature.

Alertness, being ready to respond, can be divided into three forms, phasic alertness—short-term readiness to make a response following a warning signal, tonic alertness—baseline readiness linked to circadian rhythm and wakefulness, and intrinsic alertness—voluntary readiness independent of external influences (Sturm and Willmes, 2001; Unsworth et al., 2018). Arousal, the non-specific activation of the brain during the wake state of the sleep–wake cycle, overlaps conceptually with alertness, with the term alertness used when participants are performing cognitive processes (Oken et al., 2006). Alertness can be measured physiologically through the diameter of the pupil (Unsworth and Robison, 2016; Van den Brink et al., 2016; Unsworth et al., 2018) and *via* questionnaires such as the Karolinska Sleepiness Scale (Åkerstedt and Gillberg, 1990). Pupil size is partly driven by the release of noradrenalin throughout the neocortex by the locus coeruleus in the brainstem (Joshi et al., 2016). Locus coeruleus activity closely corresponds with performance on vigilance tasks in monkeys (Aston-Jones et al., 1999) and humans (Alnæs et al., 2014), pupil diameter (Alnæs et al., 2014; Joshi et al., 2016), and participant-reported arousal (Alnæs et al., 2014; Morris et al., 2020).

Two forms of pupillary response, phasic and tonic, can be measured during a task. Phasic responses reflect momentary or task-induced changes in pupil size and are considered a measure of information processing load (Beatty, 1982). Tonic responses reflect a baseline pupillary response and are considered a measure of the internal state of alertness (Bradshaw, 1967; Beatty, 1982; Laeng et al., 2012). The relations between locus coeruleus tonic activity and task performance on sustained attention tasks vary along an upside-down U shape, where high and low levels of locus coeruleus tonic activity are associated with poor task performance, but intermediate levels are associated with strong task performance (Aston-Jones and Cohen, 2005; Oken et al., 2006). Accordingly, small and large tonic pupil diameter measures are associated with attentional lapses, as indicated by increased errors, slowing of responses, and increasing variability in responding (Kristjansson et al., 2009; Unsworth and Robison, 2016; Van den Brink et al., 2016; Unsworth et al., 2018). Sustained attention performance relies on a participant's intrinsic alertness (Oken et al., 2006) and is influenced by task-level factors including the pace (Parasuraman, 1979) and dullness of the task (Robertson et al., 1997). The task-level factors can be standardized by using one dull task, such as the Sustained Attention to Response Task (SART; Robertson et al., 1997). Performance on the SART activates the brain networks involved in sustaining attention (Manly et al., 2003) and correlates with the Cognitive Failures Questionnaire (CFQ; Broadbent et al., 1982) and the Attention-Related Cognitive Errors Scale (ARCES; Carriere et al., 2008; Smilek et al., 2010).

Three studies to date have examined the associations between nature images and pupil diameter; participants viewed photographs rated either high or low in restorative value (Nordh et al., 2010; Martínez-Soto et al., 2019; Marois et al., 2021). Nordh and colleagues noted that pupil size was smaller when participants viewed park photos they rated as more restorative. They interpreted these results to suggest that the more restorative park photos might have heightened relaxation resulting in a constriction of the pupil. The other two papers, in contrast, found that pupil diameter was larger when participants viewed high compared with low restorative photos. Martínez-Soto and colleagues interpreted these results within the context of the emotional valence of the photos, suggesting that a greater emotional response associated with higher restorative ratings of the photos was associated with a larger pupil size (Martínez-Soto et al., 2019). Marois and colleagues suggested that the nature images with higher restoration potential, the high-mystery images, may have prompter greater engagement of attention with the natural images (Marois et al., 2021). In the current study pupil diameter was used as a measure of alertness during a sustained attention task to investigate if exposure to nature was associated with sustained attention performance and modulation of alertness. Stevenson et al. (2018) determined that exposure to actual rather than virtual natural environments provided a stronger and more reliable effect on measures of working memory, attentional control, and cognitive flexibility. All the studies reviewed in the meta-analysis that measured sustained attention (vigilance) had presented participants with pictures (virtual) of environments (Stevenson et al., 2018). Here, pupil diameter was measured using a lab-based Tobii eye-tracker with a high (300 Hz) sampling rate to gain an accurate measurement of pupil size. Because of the lab-based eye-tracker, a choice was made to use pictures of nature rather than exposure to actual natural environments.

Responses to natural and urban environments may be influenced by personal characteristics including identifying with, and connecting to, nature. For example, Wilkie and Stavridou (2013) showed that identifying with the country-side was associated with higher perceived restoration for natural images and lower perceived restoration for urban images, whereas preferring the city was associated with similar restoration ratings for natural and urban images (Wilkie and Stavridou, 2013). The effects on restoration outcomes appear less clear, with a follow-up study reporting similar differences for positive mood, but not for negative mood or attention (Wilkie and Clouston, 2015). Connectedness to nature is defined as an individual's cognitive and emotional bond to the natural world (Mayer and Frantz, 2004). Recent studies have suggested a positive association between connectedness to nature, perceived restoration (Berto et al., 2018; van den Bogerd et al., 2018) and preference for higher, possibly more naturalistic vegetation in urban settings (Lee et al., 2014). It is unclear, however, whether individuals with low connectedness to nature find non-natural settings (e.g., urban environments) restorative, as proposed by Berto et al. (2018). It may be that an individual perceives an environment to be restorative when that environment has a biophilic quality that is compatible with that person's level of connectedness to nature (Berto et al., 2018). As the restorative potential of a setting varies from person to person (Hartig et al., 1997), perhaps for people with a weak connectedness to nature being presented with a less natural environment may allow them to experience higher perceived restoration (Berto et al., 2018). Therefore, it would be interesting to examine whether an urban environment has the potential to be perceived as restorative among those with low connectedness to nature. Exploring the relation between connectedness to nature and perceived restorativeness would provide insight into whether the perceived restoration of natural and urban environments differ for individuals with varying degrees of connectedness to nature.

Although water is present in studies investigating sustained attention and exposure to nature, little consideration has been given to the differential effect that water in landscapes or waterscapes may have had on sustained attention performance or perceived attention restoration. Behavioral evidence from studies using natural stimuli containing both vegetation and water showed restorative effects on sustained attention, attentional capacity, and the attention networks (Hartig et al., 1991; Berto, 2005; Berman et al., 2008; Mayer et al., 2009; Craig et al., 2015). In contrast, Van den Berg et al. (2003) found that videos of water in natural and urban settings had no restorative benefit on sustained attention (Van den Berg et al., 2003). Only two studies have examined specifically the effects of water views on attention performance, with neither study finding water images to be more restorative than urban or greenery images (Emfield and Neider, 2014; Nguyen et al., 2018). These studies provide equivocal evidence of the restorative effects of water views on attention performance. In terms of perceived attention restoration, several researchers have found that both natural and urban scenes with water were associated with greater perceived restorative potential than those without water (Völker and Kistemann, 1982; Purcell et al., 2001; Felsten, 2009; White et al., 2010; Grassini et al., 2019). White et al. (2010) found a dose–response effect of water on perceived restorativeness, but water-only images were perceived as less restorative than mixed and greenery-only images (White et al., 2010). These findings conflict with work by Nielson and colleagues (2017), which showed no consistent pattern in the effect or proportion of water on perceived restorativeness and no evidence of difference in perceived restorativeness between water-only and greenery-only images (Nielson et al., 2018). Views of water alone may be equivalent or possibly less restorative than views containing greenery.

This paper describes two studies that attempt to understand better the roles played by alertness and connection to nature in the interplay between sustained attention performance and exposure to nature. In Study 1, the differential effects of viewing images of meadow, water, and urban environments on sustained attention performance, alertness, and perceived restorativeness were measured. Study 2 was a modified and extended replication of Study 1 with a focus on the role of connectedness to nature on sustained attention performance and perceived restorativeness.

Study 1

Sustained attention performance is dependent upon an appropriate level of alertness (Alnæs et al., 2014). Exposure to nature may lead to an improvement in alertness from either low (Lee et al., 2015) or a high level (Ulrich et al., 1991). Lee et al. (2015) postulated that the maintenance of sustained attention control after viewing a flowery meadow roof image, compared with a degradation in performance following the viewing a concrete roof image, was due to nature gently stimulating one's level of alertness after becoming fatigued. Study 1 aimed to examine differential effects of viewing images of a meadow, an ocean, and an urban view on sustained attention performance, alertness, and perceived restoration. The procedure of Lee et al. (2015) was used, where participants completed the SART, then viewed an image for 40s that simulated a micro-break away from concentrating on the task, and then completed the SART again. Consistent with the literature showing the attentional benefits of exposure to green spaces, including Lee et al. (2015) and Schutte et al. (2017). Hypothesis 1 was that sustained attention performance would decline least for participants allocated the meadow image, moderately for those allocated the ocean image, and most for those allocated the urban image, as measured by SART performance. Hypothesis 2 predicted that alertness, as indexed by tonic pupil diameter, would decline least for the participants viewing the meadow image, moderately for those viewing the ocean image, and most for those viewing the urban image during the SART. In line with previous research on waterscapes (Nielson et al., 2018), Hypothesis 3 was that perceived restorativeness, as measured by scores on the Perceived Restorativeness Scale (Hartig et al., 1997), would be similar for the participants viewing the meadow and ocean images, and higher for those viewing the nature images than the urban image.

TABLE 1 | Descriptive statistics for participants' demographic, KSS, ARCES, and PRS scores by Group, for Study 1.

Variable	Meadow group	Ocean group	Urban group	All	Statistical test for group difference
Number of participants	23	24	21	68	
Mean age in years (SD)	21.4 (6.9)	19.3 (1.3)	21.2 (7.0)	20.6 (5.6)	$F(2,65) = 1.03$, $p = 0.364$
Sex, count male/female	9/14	8/16	5/16	22/46	$\chi^2(2, N = 68) = 1.19$, $p = 0.551$
Handedness, count left/right	0/23	1/23	0/21	1/67	$\chi^2(2, N = 68) = 1.86$, $p = 0.394$
Mean baseline KSS (SD)	4.8 (1.3)	4.6 (1.4)	4.4 (1.6)	4.6 (1.4)	Group: $F(2,65) = 0.24$, $p = 0.79$
Mean post-intervention KSS (SD)	6.0 (1.8)	5.8 (1.8)	5.8 (1.7)	5.9 (1.8)	Time: $F(1,65) = 49.43$, $p < 0.001$*** Group × Time: $F(2,65) = 0.04$, $p = 0.97$
Mean ARCES (SD)	2.8 (0.5)	2.9 (0.7)	2.6 (0.4)	2.8 (0.5)	$F(2, 65) = 2.10$, $p = 0.131$
Mean PRS (SD)	3.9 (0.8)	3.8 (0.9)	2.9 (1.1)^	3.5 (1.0)	$F(2,65) = 8.21$, $p < 0.001$, $\eta_p^2 = 0.20$***
Mean Being Away PRS Subscale (SD)	3.4 (1.4)	3.4 (1.4)	2.1 (1.4)^	3.0 (1.5)	$F(2,65) = 6.23$, $p < 0.003$, $\eta_p^2 = 0.16$**
Mean Fascination PRS Subscale (SD)	4.0 (1.0)	3.8 (1.2)	3.3 (1.4)	3.7 (1.2)	$F(2,65) = 1.92$, $p = 0.156$, $\eta_p^2 = 0.06$
Median Coherence PRS Subscale (IQR)	5.5 (1.0)	5.5 (1.1)	4.0 (2.3)^	5.3 (1.8)	$H(2) = 15.51$, $p < 0.001$, $\eta_p = 0.21$***
Mean Compatibility PRS Subscale (SD)	3.0 (1.0)	2.8 (1.3)	2.3 (1.3)	2.7 (1.2)	$(2,65) = 2.28$, $p = 0.110$, $\eta_p^2 = 0.07$

*SD, standard deviation; KSS, Karolinska Sleepiness Scale; ARCES, Attention-Related Cognitive Errors Scale; PRS, Perceived Restorativeness Scale; IQR, Interquartile Range.^Urban Group score is significantly different from the Meadow and Ocean Groups. *p<0.05, **p<0.01, ***p<0.001.*

Study 1 Method

Participants

Seventy-nine participants were 1st year psychology students who received course credit for their participation. Participants were randomly assigned to one of three groups (meadow, ocean, or urban), using a Latin square. Toward the end of recruitment, a small number of participants were directly allocated to the groups to achieve gender balance. Six participants were excluded because they reported taking medications that might impact their thinking skills, including medications for psychosis, depression, or anxiety. A further five participants were excluded for making 30 or more omission errors on the SART as per the procedure of Lee et al. (2015), suggesting they were not attempting the task appropriately. The final sample was 68 participants (see **Table 1**). Ethics approval for this study was received from the University of Melbourne Psychological Sciences Human Ethics Advisory Group (ethics approval ID 1954077.1).

FIGURE 1 | The meadow image shown for 40 s between the baseline and post-intervention SARTs in Studies 1 and 2.

FIGURE 2 | The ocean image shown for 40 s between the baseline and post-intervention SARTs in Studies 1 and 2.

Materials and Apparatus

Stimuli Selection

Three images were taken from a realistic human observer perspective in similar weather conditions (see **Figures 1–3**). Two-thirds of each image was filled with the experimental environment (meadow, ocean, or urban) and one third with blue sky and white clouds. The three images presented similar complexity and were perceived by the authors as high in restorative characteristics (Kaplan, 1995). No people or animals were present in any of the images. Vegetation, water, and urban elements were each present in one image only and excluded from other images.

Scales

The Attention-Related Cognitive Errors Scale

The Attention-Related Cognitive Errors Scale (ARCES) is a 12-item self-report scale measuring the behavioral consequences of attention lapses in everyday situations (Carriere et al., 2008). Participants rated how frequently such attention lapses occurred to them on a 5-point Likert scale ranging from 1 (never) to 5 (very often). Scores on the revised ARCES correlate positively with errors on

FIGURE 3 | The urban image shown for 40 s between the baseline and post-intervention SARTs in Study 1.

the SART (Cheyne et al., 2006; Smilek et al., 2010). In this dataset, the ARCES had high internal consistency, Cronbach's $\alpha = 0.85$.

The Karolinska Sleepiness Scale

The Karolinska Sleepiness Scale (KSS) is a single-item self-report scale used to assess an individual's level of sleepiness (Åkerstedt and Gillberg, 1990). Participants rated their current level of sleepiness on a 9-point Likert scale ranging from 1 (extremely alert) to 9 (extremely sleepy).

The Perceived Restorativeness Scale

The Perceived Restorativeness Scale (PRS) is a 26-item measure of the perceived restorativeness of a particular environment (Hartig et al., 1997). The PRS is divided into four subscales: Being Away, Fascination, Coherence, and Compatibility. Participants used a 7-point Likert scale to rate the degree to which each of the 26 statements applied to their experience of viewing the image (0 = Not at all; 6 = Completely). In this dataset, the internal consistency of the PRS was high, Cronbach's $\alpha = 0.94$.

Sustained Attention to Response Task

The random version of the SART (Robertson et al., 1997) was administered using E-Prime 2.0 on a desktop computer with a Tobii TX300 eye-tracking monitor. Single digits from 1 to 9 appeared in the middle of the computer screen in a pseudo-random sequential order, such that the no-go "3" never appeared twice in a row. Twenty-two SART cycles of nine digits were presented, totaling 198 trials. Each trial consisted of the presentation of a fixation cross for 500 ms, followed by the digit for 150 ms, then by another fixation cross for 2,000 ms and then a variable period—a jitter, ranging between 1,170 and 1859 ms, while the fixation cross was shown. Accounting for the jitter, the inter-stimulus interval (ISI) ranged from 3,820 to 4,509 ms. The jitter was introduced to allow the pupil diameter to return to its tonic level after the visual presentation of the SART stimuli. The digits and cross were displayed in black Arial typeface on a white background. Participants completed a 9-trial practice SART, which contained one No-Go digit ("3"). The first (baseline SART) and second (post-intervention SART) SARTs each consisted of 22 No-Go trials and 176 Go trials. Each SART took approximately 14 min to complete.

Eye-Tracking

Pupil diameter was used as a measure of alertness. Pupil diameter was recorded using Tobii TX300, an eye-tracking device built into a 23-inch monitor. The monitor resolution was fixed at $1{,}920 \times 1{,}080$ pixels and the sampling rate was 300 Hz, generating 300 binocular data samples per second. A fixed chinrest, positioned 65 cm from the monitor, was used to restrict head movement and ensure optimal eye-tracking accuracy. A nine-point calibration procedure preceded each SART and image viewing.

Procedure

Participants were tested individually in a laboratory lit with indirect fluorescent lighting. After being informed about the study and signing a consent form, participants completed a demographic questionnaire, the KSS, and the ARCES on Qualtrics. Participants were then invited to sit in front of the computer monitor and adjust their position to fit the chinrest most comfortably. Participants received instructions to left-click on the computer mouse whenever any digit other than "3" appeared (Go trials), not to click when the digit "3" was presented (No-Go trial), and to respond as quickly and accurately as possible. Participants completed the practice SART before completing the baseline SART. After completing the baseline SART, a digital image representing a meadow, an ocean, or an urban city, was presented in full screen for 40 s, using Tobii Studio software. Participants were told that they could look freely at the image and to do nothing else during this time. After viewing the image, participants completed the post-intervention SART and then returned to Qualtrics to complete the KSS and the PRS.

Data Preparation

The behavioral and eye-tracking data collected *via* E-Prime and the Tobii TX300 eye-tracker were imported to MATLAB for cleaning and analysis.

SART Data

The SART data were prepared and analyzed according to a published method (Johnson et al., 2020), with the scripts available at DOI: 10.17605/OSF.IO/NTWY7. Data from the SARTs were divided into two (trials 0–99 and 100–198), to measure for any differences in performance across the course of the task. Time-on-task effects are an effective measure of change and potential decline in performance (Johnson et al., 2007). *Omission errors*, a failure to respond to the Go stimuli, and *commission errors*, responding to the No-Go stimulus "3," were counted for each half of the baseline and post-intervention SARTs. After response times (RTs) less than 100 ms were removed (Luce, 1986), RTs were fitted to an ex-Gaussian distribution using maximum-likelihood-based distribution-fitting routines (Lacouture and Cousineau, 2008), and *mu*, *sigma*, and *tau* were fitted to each participant's data set using MATLAB. Mu, sigma, and tau were calculated for each SART half. Mu and sigma represent the mean and variability of the Gaussian distribution, respectively, where tau measures the centrality of the exponential component of the RT data and represents the skewed tail of the distribution. Tau reflects very long RTs and is thought to indicate attention lapses (Leth-Steensen et al., 2000).

Pupil Data

Right and left pupil diameter data were analyzed separately, per participant. The data were segmented into 198 trials and analyzed on a trial-by-trial basis. Pupil data from trials with either a commission or an omission error were excluded. The data from 500 ms before stimulus onset to 2.1 s after onset were analyzed. Outliers and blinks were identified and excluded. Trials with 50% or more of the pupil data missing were noted, and individuals were excluded if more than 50% of their trials were missing. The *mean tonic pupil diameter* per trial was calculated from the 150 pupil diameter data points recorded between −500 ms (trial onset) and 0 ms (stimulus onset). These data were then averaged across the left and right eyes. The grand mean tonic pupil diameter per participant per half of each SART was then calculated. These data were then used to calculate the *linear change in mean tonic pupil diameter* by taking the coefficient of the linear regression, treating mean tonic pupil size as the outcome variable and trial order as an independent variable. The linear change in tonic pupil diameter per participant per half of each SART was then calculated.

Missing Data

Pupil data from the post-intervention SART were missing for one participant. After missing data was replaced with the mean values of the whole sample (calculated for each trial), analyses were run with and without this participant's dataset. The overall pattern of results did not differ therefore this dataset was included in all analyses.

Statistical Analyses

The dependent variables were the errors of omission and commission, mu, sigma, tau, linear change in tonic pupil diameter, and mean tonic pupil diameter for each half of the baseline and post-intervention SARTs, the KSS at baseline and post-intervention, and the PRS scores. Each dependent variable was calculated per participant and averages were calculated for each of the three groups. Statistical analyses were conducted using R version 3.5.2, RStudio version 1.2.1320, and the lme4 and stats packages (R Core Team, 2012; Bates et al., 2020). All hypotheses were tested with an alpha set at $p < 0.05$.

Prior to hypothesis testing, any demographic and characteristic differences between the three groups were investigated using a one-way between groups analysis of variance (ANOVA) for parametric data, independent-samples Kruskal-Wallis test for non-parametric data, and Pearson's Chi-Square test for categorical data. To examine whether participants were fatigued before the image intervention, within-group differences between the two halves of the baseline SART were investigated using a repeated measures *t*-test for parametric and related-samples Wilcoxon Signed Ranked test for non-parametric data. To test if participants were feeling sleepier after completing the two SARTs, any differences between the baseline and post-intervention KSS were tested using a repeated measures two-way ANOVA with Group and Time (baseline, post-intervention) as the factors.

Linear mixed-effects models were used to test the first and second hypotheses. Each of the SART variables (commission errors, mu, sigma, tau) and pupil variables (linear change in tonic pupil diameter, mean tonic pupil diameter), were modeled separately. The fixed effects: Baseline SART variable, Age, Sex, Group, SART Half, and the interaction between Group and SART Half, were included to explain variance in participants' post-intervention SART and pupil measures. Each individual participant was added as a random effect. To test hypothesis 3, group differences (meadow, ocean, urban) on the PRS main and subscale scores were analyzed using a one-way ANOVA. An independent-samples Kruskal-Wallis test was used to examine group differences when violations of normality occurred. When the overall test was significant, a post-hoc Tukey HSD test was used alongside the one-way ANOVA, and Dunn's test alongside the Kruskal-Wallis test, to perform multiple pairwise comparisons between the three groups to examine where the significant differences lay.

Study 1 Results

Demographic Data and Participant Characteristics

The three groups did not differ in terms of age, sex, handedness, or ARCES (see **Table 1**).

Baseline SART Performance and Pupil Data

Descriptive statistics for each SART outcome measure are presented in **Table 2**. There were no baseline group differences in either SART half for any of the SART or pupil measures. Very few omission errors were made therefore no further analyses of this measure were undertaken. Taking each group separately and examining if there were differences between the two halves of the first SART, the linear change in tonic pupil diameter decreased in the first half and then increased in the second half of the baseline SART for the meadow group, $T = 23.0$, $z = -3.79$, $p < 0.001$, $r = -0.56$. Likewise, it decreased in the first half but then plateaued in the second half for the ocean, $T = 3.0$, $z = -4.99$, $p < 0.001$, $r = -0.72$, and urban groups, $T = 4.0$, $z = -4.50$, $p < 0.001$, $r = -0.69$. The mean tonic pupil diameter significantly decreased from the first to second half of the baseline SART for all three groups, meadow, $t(22) = 2.85$, $p = 0.009$, ocean, $t(23) = 4.91$, $p < 0.001$, urban, $t(20) = 3.83$, $p = 0.001$. For the SART variables, there were no significant half effects during the baseline SART for any group (see **Supplementary Table S1**).

KSS at Baseline and Post-intervention

There was no significant difference in the Karolinska Sleepiness Scale (KSS) score between the three groups (see **Table 1**).

TABLE 2 | Descriptive statistics for each group for the SART and pupillometry variables for Study 1.

Variable	SART	Half	Meadow	Ocean	Urban	All	Group difference statistics
Omission Errors, median (IQR)	Baseline	First	0.0 (1.0)	0.0 (1.0)	0.0 (0.0)	0.0 (1.0)	H(2) = 3.34, p = 0.188
		Second	1.0 (1.0)	0.0 (1.0)	0.0 (1.0)	0.0 (1.0)	H(2) = 1.79, p = 0.410
	Post-intervention	First	0.0 (1.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.3)	
		Second	1.0 (2.0)	0.5 (1.0)	0.0 (1.0)	0.0 (1.0)	
Commission Errors, median (IQR)	Baseline	First	3.0 (4.5)	3.0 (3.3)	3.0 (3.0)	3.0 (3.5)	H(2) = 0.07, p = 0.966
		Second	3.0 (4.5)	4.0 (3.3)	3.0 (4.0)	3.0 (3.3)	H(2) = 0.78, p = 0.678
	Post-intervention	First	4.0 (4.5)	3.0 (3.3)	2.0 (4.0)	3.0 (5.0)	
		Second	4.0 (4.0)	4.5 (4.0)	3.0 (4.0)	4.0 (4.0)	
Mu (ms), median (IQR)	Baseline	First	313 (87)	304 (47)	322 (110)	308 (70)	H(2) = 1.42, p = 0.496
		Second	310 (74)	296 (59)	311 (69)	305 (71)	H(2) = 1.96, p = 0.375
	Post-intervention	First	284 (61)	282 (54)	277 (66)	283 (64)	
		Second	293 (76)	276 (48)	270 (71)	279 (71)	
Sigma (ms), median (IQR)	Baseline	First	32 (23)	28 (21)	39 (20)	36 (21)	H(2) = 2.75, p = 0.252
		Second	44 (29)	34 (17)	37 (29)	36 (25)	H(2) = 2.32, p = 0.313
	Post-intervention	First	30 (14)	30 (33)	29 (24)	29 (21)	
		Second	30 (28)	36 (24)	24 (16)	31 (26)	
Tau (ms), median (IQR)	Baseline	First	75 (64)	70 (46)	65 (59)	72 (50)	H(2) = 1.37, p = 0.505
		Second	89 (45)	67 (43)	79 (40)	76 (49)	H(2) = 2.66, p = 0.265
	Post-intervention	First	70 (47)	55 (48)	72 (49)	68 (54)	
		Second	73 (78)	67 (40)	76 (46)	74 (48)	
Linear Change in Tonic Pupil Diameter (mm), median (IQR)	Baseline	First	−0.002 (0.002)	−0.002 (0.002)	−0.002 (0.003)	−0.002 (0.002)	H(2) = 1.63, p = 0.443
		Second	0.001 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	H(2) = 3.14, p = 0.208
	Post-intervention	First	−0.001 (0.002)	−0.001 (0.002)	−0.001 (0.002)	−0.001 (0.002)	
		Second	0.000 (0.002)	0.000 (0.002)	0.000 (0.001)	0.000 (0.001)	
Mean Tonic Pupil Diameter (mm), mean (SD)	Baseline	First	2.68 (0.33)	2.83 (0.30)	2.76 (0.29)	2.76 (0.31)	F(2,65) = 1.35, p = 0.267
		Second	2.63 (0.31)	2.73 (0.29)	2.68 (0.28)	2.68 (0.29)	F(2,65) = 0.72, p = 0.493
	Post-intervention	First	2.67 (0.30)	2.75 (0.26)	2.70 (0.25)	2.71 (0.27)	
		Second	2.64 (0.30)	2.73 (0.28)	2.65 (0.28)	2.67 (0.29)	

The post-intervention group differences were tested using the linear mixed models, reported in text. SART, Sustained Attention to Response Task; IQR, interquartile range; SD, standard deviation; ms, milliseconds; and mm, millimetres.

There was a significant time main effect, with all three groups indicating an increase in sleepiness after the post-intervention SART. There was no interaction between time and group.

Hypothesis 1: Sustained Attention Performance

There was no difference in sustained attention performance outcomes across the three groups. For the commission errors, mu, and tau, baseline SART performance was a significant predictor of performance in the post-intervention SART (see **Table 3**). For tau, more extremely slow responses in the second compared with the first half of the post-intervention SART were made by all groups (see **Table 2**). There were no other significant effects of Group, Age, Sex, SART Half, or Group by SART Half interaction for these measures. For sigma, none of the predictor variables explained a significant amount of variance in the post-intervention SART performance.

Hypothesis 2: Tonic Pupil Diameter

There was no difference in the tonic pupil diameter measures across the three groups. For both the pupil diameter measures, the baseline SART measurement was a significant predictor of the post-intervention SART measurement (see **Table 3**). All participants, irrespective of group, showed a decrease in linear change in tonic pupil diameter in the first half and a plateau in the second half of the post-intervention SART, while the mean pupil diameter decreased from the first to second half of the post-intervention SART (see **Tables 2**, **3**). Group, Age, Sex, and the Group by SART Half interaction were not significant for either pupil diameter measure (see **Table 3**).

Hypothesis 3: Perceived Restorativeness

Complete Scale

There was a significant group difference for the mean PRS score (see **Table 1**). Post-hoc tests indicated that viewing the image of the meadow or the ocean was perceived as being more restorative than viewing the urban image, $p = 0.001$ and $p = 0.005$, respectively. There was no significant difference in perceived restorativeness between viewing the meadow and ocean images, $p = 0.849$.

Subscales

For both the Being Away and Coherence subscales, there were significant Group differences (see **Table 1**), in which participants rated the meadow, Being Away $p = 0.008$, Coherence $p = 0.002$, and ocean, Being Away $p = 0.009$, Coherence $p = 0.002$, images as more restorative than the urban image. No difference was found between the meadow and ocean images, Being Away $p = 0.996$, Coherence $p = 0.999$. For the Fascination and Compatibility subscales, there were no significant Group differences.

TABLE 3 | Results from the Linear Mixed-Effects Models for Hypotheses 1 and 2 for Study 1.

Variable	*F*(df)	*F* value	*p*
Errors of Commission			
Baseline SART Commission Error Performance	*F* (1, 102)	52.75***	<0.001
Age	*F* (1, 49)	2.98	0.091
Sex	*F* (1, 49)	0.25	0.616
Group	*F* (2, 48)	0.98	0.381
SART Half	*F* (1, 51)	0.0001	0.993
Group x SART Half	*F* (2, 51)	1.24	0.297
Mu			
Baseline SART Mu Performance	*F* (1, 80)	108.11***	<0.001
Age	*F* (1, 46)	3.59	0.064
Sex	*F* (1, 46)	0.40	0.531
Group	*F* (2, 47)	0.45	0.638
SART Half	*F* (1, 49)	0.14	0.711
Group x SART Half	*F* (2, 49)	0.18	0.835
Sigma			
Baseline SART Sigma Performance	*F* (1, 127)	1.33	0.251
Age	*F* (1, 55)	0.61	0.439
Sex	*F* (1, 54)	0.04	0.840
Group	*F* (2, 55)	0.94	0.396
SART Half	*F* (1, 56)	0.0009	0.976
Group x SART Half	*F* (2, 58)	0.22	0.802
Tau			
Baseline SART Tau Performance	*F* (1, 96)	41.00***	<0.001
Age	*F* (1, 58)	0.002	0.963
Sex	*F* (1, 59)	0.47	0.498
Group	*F* (2, 59)	0.86	0.430
SART Half	*F* (1, 62)	4.56*	0.037
Group x SART Half	*F* (2, 60)	0.53	0.589
Linear Change in Tonic Pupil Diameter			
Baseline SART Linear Change in Pupil Diameter	*F* (1, 127)	18.32***	<0.001
Age	*F* (1, 127)	1.08	0.301
Sex	*F* (1, 127)	0.07	0.797
Group	*F* (2, 127)	0.84	0.433
SART Half	*F* (1, 127)	4.79*	0.030
Group x SART Half	*F* (2, 127)	0.67	0.514
Mean Tonic Pupil Diameter			
Baseline SART Mean Pupil Diameter	*F* (1, 70)	326.63***	<0.001
Age	*F* (1, 59)	1.24	0.270
Sex	*F* (1, 59)	1.36	0.248
Group	*F* (2, 59)	0.24	0.785
SART Half	*F* (1, 68)	4.44*	0.039
Group x SART Half	*F* (2, 62)	0.65	0.527

*df, degrees of freedom and SART Half, difference between the first and second half of the post-intervention SART. *p<0.05; **p<0.01; ***p<0.001.*

Study 1 Discussion

Contrary to expectations, there were no group differences in performance on the SART or in pupillometry measures post the image intervention. During the baseline SART all three groups performed well and were able to maintain their performance across the two halves. The decline in mean tonic pupil diameter over the course of the baseline SART, however, suggested that all three groups were becoming less alert. During the post-intervention SART participants in all groups made more extremely long responses, as indicated by the tau measure, in the second half of the task. Tau is thought to index attentional lapses (Leth-Steensen et al., 2000). The measured increase in tau in the second half of the task is interpreted as evidence of an increase in attentional lapses, which may be a consequence of cognitive fatigue. This finding was supported by evidence of physiological lowering of alertness, with the tonic pupil size diminishing across the course of the task, in all three groups. A time-on-task effect indicated by a diminishment of pupil size over the course of the task is consistent with the literature (Unsworth and Robison, 2016; Van den Brink et al., 2016). All three groups indicated an increase in sleepiness on the KSS from before the baseline SART and immediately after the post-intervention SART, and there was no effect of the image viewed on the KSS. Nevertheless, participants reported feeling more restored after viewing either nature image, particularly in terms of Being Away and Coherence, with no differences noted between the meadow and ocean groups. Previous research most often uses nature images with a combination of water and vegetation, and this combination is perceived as most restorative (White et al., 2010). Here, with the meadow and ocean clearly differentiated, both were perceived as equally restorative. There were no differences between the three images

TABLE 4 | Descriptive statistics for participants' demographics, KSS scores, ARCES scores, PRS scores, and CNS scores for each group, for Study 2.

Variable	Meadow group	Ocean group	Urban group	All	Group difference statistics
Number of participants	66	60	60	186	
Mean age in years (SD)	20.2 (5.9)	20.3 (4.6)	19.9 (3.7)	20.1 (4.8)	$F(2, 183) = 0.11$, $p = 0.893$
Sex, count male/female	24/42	14/46	16/44	54/132	$\chi^2(2, N = 186) = 2.83$, $p = 0.243$
Handedness, count left/right/either	5/59/2	4/56/0	4/54/2	13/169/4	$\chi^2(4, N = 186) = 2.03$, $p = 0.730$
Mean baseline KSS score (SD)	4.7 (1.7)	5.1 (1.5)	4.6 (1.6)	4.8 (1.6)	Group: $F(2, 183) = 1.270$, $p = 0.283$ Time: $F(1,183) = 21.979$, $p < 0.001$***
Mean post-intervention KSS score (SD)	5.2 (1.8)	5.5 (1.4)	5.3 (1.7)	5.3 (1.7)	Group × Time: $F(2,183) = 0.611$, $p = 0.544$
Mean ARCES score (SD)	2.9 (0.7)	2.9 (0.6)	2.8 (0.5)	2.9 (0.6)	$F(2, 183) = 0.59$, $p = 0.556$
Mean PRS score (SD)	3.8 (1.1)	4.1 (1.0)	2.8 (0.8)^	3.6 (1.1)	$F(2,183) = 29.93$, $p < 0.001$, $\eta_p^2 = 0.25$***
Median Being Away Subscale score (IQR)	3.7 (1.8)	3.8 (2.6)	1.9 (2.7)^	3.4 (2.8)	$H(2) = 30.18$, $p < 0.001$, $\eta_p^2 = 0.15$***
Mean Fascination Subscale score (SD)	3.5 (1.5)	3.8 (1.4)	2.3 (1.3)^	3.2 (1.6)	$F(2,183) = 18.05$, $p < 0.001$, $\eta_p^2 = 0.16$***
Median Coherence Subscale score (IQR)	5.3 (1.5)	5.5 (1.3)	4.5 (1.6)^	5.3 (1.8)	$H(2) = 18.23$, $p < 0.001$, $\eta_p^2 = 0.09$***
Mean Compatibility Subscale score (SD)	3.1 (1.4)	3.4 (1.3)	2.1 (1.0)^	2.9 (1.4)	$F(2,183) = 17.09$, $p < 0.001$, $\eta_p^2 = 0.16$***
Mean CNS score (SD)	3.5 (0.6)	3.5 (0.7)	3.3 (0.6)	3.4 (0.6)	$F(2, 183) = 1.68$, $p = 0.190$

*SD, standard deviation; IQR, interquartile range; KSS, Karolinska Sleepiness Scale; ARCES, Attention-Related Cognitive Errors Scale; PRS, Perceived Restorativeness Scale; Subscale, Subscales of the PRS; CNS, Connectedness to Nature Scale. ^Urban Group score is significantly different from the Meadow and Ocean Groups. *p<0.05, **p<0.01, ***p<0.001.*

in terms of the fascination and compatibility sub-scales of the PRS. The urban image was a scene from a rooftop, which might afford a more expansive and evocative outlook. This image was modified in Study 2 to test this interpretation. These findings suggest performing two SARTs results in a fatiguing effect, and that while viewing the nature images did not provide physiological or behavioral benefits, providing no support for Hypotheses 1 and 2, participants noted a sense of restoration from the meadow and ocean images, supporting Hypothesis 3.

Study 2

Study 2 was a modified and extended replication of Study 1. First, eye-tracking was not performed because the study was conducted online due to the COVID-19 pandemic. Second, a ground-level version of the urban stimulus was used to address limitations associated with inconsistent visual perspectives across the three images. In Study 1, the meadow and ocean images were taken at ground-level, whereas the urban image was taken from a rooftop. A high-level perspective, such as the urban view used in Study 1, affords greater perceptual and conceptual coherence (Slepian et al., 2015), and therefore greater extent. This may have increased perceived restorativeness and influenced the results relating to the urban view in Study 1. Third, the Connectedness to Nature Scale (CNS) was included to investigate if one's connectedness to nature was associated both with sustained attention performance and perceived restoration after viewing one of the three images. Beneficial effects of nature on sustained attention performance may depend on how much the participant felt connected to nature (Mayer and Frantz, 2004).

Keeping the hypotheses similar between the two studies based on the previous literature, Hypothesis 1 was that sustained attention performance would decline least for the meadow group, moderately for the ocean group, and most for the urban group, as measured by SART performance. Hypothesis 2 was that perceived restorativeness would be similar for the meadow and ocean groups, and higher in the nature groups than in the urban group. Hypothesis 3 predicted that connectedness to nature would moderate the relation between the type of image viewed and both sustained attention performance and perceived restoration. Higher CNS scores in the meadow and ocean groups but lower CNS scores in the urban group were expected to predict better SART performance and higher PRS scores.

Study 2 Method

Participants

Two hundred and fifteen participants were from the 1st-year psychology participant pool ($n = 182$) and the broader population ($n = 33$). They had not participated in Study 1. Participants were randomly assigned to one of three groups (meadow, ocean, or urban). Toward the end of recruitment, a small number of participants were directly allocated to the ocean group to achieve approximately equal group sizes. Fifteen participants were excluded because they reported a diagnosis of a condition that might impact their thinking skills, such as depression, anxiety, or Attention Deficit Hyperactivity Disorder. One participant was excluded because they had taken medication that may have affected their cognitive performance, and 13 were excluded for making 30 or more omission errors on the SART. The final sample included 186 participants (see **Table 4**). Ethics approval for this study was received from the University of Melbourne Psychological Sciences Human Ethics Advisory Group (ethics approval ID 1954077.3).

Materials and Apparatus

Stimuli Selection

The meadow and ocean images were taken from Study 1 and the urban image was taken from a personal collection (see **Figure 4**).

Scales

The ARCES, KSS, and PRS from Study 1 and the Connectedness to Nature Scale (CNS) were used. The CNS is a 14-item self-report scale that measures an individual's affective connection to the natural world (Mayer and Frantz, 2004).

FIGURE 4 | The urban image shown for 40 s between the baseline and post-intervention SARTs in Study 2.

Participants rated, on a 5-point Likert scale, the degree to which each of the 14 statements applied to them (1 = Strongly Disagree; 5 = Strongly Agree). In this dataset, the CNS had high internal consistency, Cronbach's $\alpha = 0.83$.

Sustained Attention to Response Task

The random version of the SART was administered online through Inquisit software by Millisecond. Twenty-five SART cycles of the nine digits were presented, totaling 225 trials, presented in a pseudo-randomized order. A trial sequence consisted of the digit appearing for 250 ms, followed by a mask (cross within a circle) for 900 ms. The inter-trial interval was 1,150 ms. The digits and mask were displayed in white Arial typeface on a black background. Participants completed an 18-trial practice SART, which contained two No-Go digits ("3"). The baseline and post-intervention SARTs consisted of 25 No-Go trials and 200 Go trials each. Each SART took approximately 4 min to complete.

Procedure

The study was administered online *via* Qualtrics and Inquisit, and participants were tested in their own time, on their own computer. All instructions were provided visually. After receiving information about the study, participants provided informed consent. Participants completed a demographic questionnaire, the KSS, and the ARCES on Qualtrics. They then installed Inquisit Player software to complete the SART. Upon starting the SART on Inquisit, participants were instructed to press the spacebar with their dominant hand's index finger as quickly and accurately as possible every time they saw a digit other than "3" appear on the screen (Go trials) and withhold their response when the digit "3" appeared (No-Go trial). Participants completed the practice SART before completing the baseline SART. After the baseline SART, a digital image representing a meadow, an ocean, or an urban view was presented on full screen for 40 s using Inquisit. Participants were instructed to look freely at the image and to do nothing else during this time. After viewing the image, participants completed the post-intervention SART, and then returned to Qualtrics to complete the KSS, PRS, and CNS.

Data Preparation

The SART data were imported into MATLAB for cleaning and analysis using the same method as Study 1.

Statistical Analyses

The dependent variables were the errors of omission and commission, mu, sigma, and tau for each half of the baseline and post-intervention SARTs, the KSS before and after the SARTs, and the PRS scores. The moderating variable for Hypothesis 3 was the CNS score. Each dependent and moderating variable was calculated per participant and averages were calculated for each of the three groups. Statistical analyses were conducted using the same software as Study 1. All hypotheses were tested with an alpha set at $p < 0.05$.

Prior to hypothesis testing, differences between the three groups and within-group differences between the two halves of the baseline SART were investigated using the same method as Study 1. To test if participants were feeling sleepier after completing the two SARTs, any differences between the baseline and post-intervention KSS were tested using a repeated measures two-way ANOVA with group and time (baseline, post-intervention) as the factors. The same analysis techniques from Study 1 were used to test the first two hypotheses. To test Hypothesis 3, moderation analyses using multiple linear regression with an interaction term between Group and CNS scores, in predicting SART performance and PRS scores, were conducted.

Study 2 Results

Demographic Data and Participant Characteristics

The three groups did not differ in terms of age, sex, handedness, mean ARCES, or mean CNS scores (see **Table 4**).

Baseline SART Performance

Descriptive statistics for each SART outcome measure are presented in **Table 5**. There were no baseline group differences in either SART half for any of the SART measures. Very few omission errors were made in either SART, therefore no further analyses of this measure were undertaken. Taking each group separately and examining if there were differences between the two halves of the task, sigma significantly increased for the urban group, $T = 429$, $z = -3.58$, $p < 0.001$, $r = -0.33$, and tau significantly increased for the ocean group, $T = 625$, $z = -2.13$, $p = 0.033$, $r = -0.19$. There were no other significant differences between the baseline SART halves for the other SART variables for any of the three groups (see **Supplementary Table S2**).

KSS at Baseline and Post-intervention

There was no significant difference in the Karolinska Sleepiness Scale (KSS) between the three groups. There was a significant time main effect, with all three groups indicating an increase in sleepiness after the post-intervention SART. There was no interaction between time and group.

Hypothesis 1: Sustained Attention Performance

There was no difference in sustained attention performance outcomes across the three groups. For all the SART measures,

TABLE 5 | Descriptive statistics of each group for the SART variables for Study 2.

Variable	SART	Half	Meadow Median (IQR)	Ocean Median (IQR)	Urban Median (IQR)	All Median (IQR)	Group difference statistics
Omission Errors (count)	Baseline	First	0.0(2.0)	0.0(2.0)	0.0(2.0)	0.0(2.0)	$H(2) = 0.83$, $p = 0.659$
		Second	1.0(3.0)	1.0(2.3)	0.0(2.0)	1.0(3.0)	$H(2) = 3.12$, $p = 0.210$
	Post-intervention	First	0.5(2.0)	0.5(2.0)	0.5(2.0)	0.5(2.0)	
		Second	1.0(4.0)	1.0(3.0)	1.0(3.0)	1.0(3.8)	
Commission Errors (count)	Baseline	First	6.0(4.8)	6.0(4.0)	7.0(4.0)	6.0(4.0)	$H(2) = 0.50$, $p = 0.780$
		Second	6.0(5.0)	6.0(5.0)	6.0(4.0)	6.0(5.0)	$H(2) = 0.26$, $p = 0.878$
	Post-intervention	First	7.0(5.0)	7.0(4.3)	7.0(5.0)	7.0(5.0)	
		Second	7.0(5.0)	7.0(5.0)	7.0(6.3)	7.0(5.0)	
Mu (ms)	Baseline	First	264(77)	270(67)	264(57)	265(62)	$H(2) = 1.39$, $p = 0.498$
		Second	255(100)	267(74)	269(64)	265(82)	$H(2) = 0.14$, $p = 0.933$
	Post-intervention	First	264(116)	258(92)	256(78)	258(93)	
		Second	274(128)	258(82)	259(105)	264(100)	
Sigma (ms)	Baseline	First	45(28)	41(29)	36(20)	41(27)	$H(2) = 4.54$, $p = 0.103$
		Second	49(33)	46(29)	46(22)	47(26)	$H(2) = 1.21$, $p = 0.546$
	Post-intervention	First	54(39)	47(28)	47(24)	47(33)	
		Second	57(47)	52(26)	56(30)	54(34)	
Tau (ms)	Baseline	First	53(48)	49(41)	56(43)	53(45)	$H(2) = 2.25$, $p = 0.325$
		Second	61(57)	56(51)	52(49)	56(51)	$H(2) = 3.88$, $p = 0.144$
	Post-intervention	First	55(58)	55(70)	52(59)	53(62)	
		Second	67(73)	71(68)	60(61)	65(68)	

The post-intervention group differences were tested using the linear mixed models, reported in text. SART, Sustained Attention to Response Task; IQR, interquartile range; and ms, milliseconds.

baseline SART performance explained variance in post-intervention SART performance (see **Table 6**). Younger participants made more commission errors than older participants in the post-intervention SART. Irrespective of group, participants showed a significant increase in sigma from the first to second half of the post-intervention SART. There were no other significant effects of Age or SART Half, and there were no significant effects of Group, Sex, or Group by SART Half interaction for any of the measures.

Hypothesis 2: Perceived Restorativeness

Complete Scale

The mean PRS score differed significantly between the three groups (see **Table 4**). Post-hoc tests indicated that viewing the image of the meadow or the ocean were perceived as more restorative than viewing the urban image, both $p < 0.001$. There was no significant difference in perceived restorativeness between viewing the meadow and ocean images, $p = 0.353$.

Subscales

For the Being Away, Coherence, Fascination, and Compatibility subscales, there were significant Group differences, in which participants rated the meadow, Being Away $p < 0.001$, Coherence $p = 0.005$, Fascination $p < 0.001$, Compatibility $p < 0.001$, and ocean, all subscales $p < 0.001$, images as being more restorative than the urban image. No significant difference was found between the meadow and ocean images, Being Away $p = 0.999$, Coherence $p = 0.900$, Fascination $p = 0.393$, Compatibility $p = 0.356$.

Hypothesis 3: Connectedness to Nature, Group, and SART Performance

The CNS scores had no moderating effect on any of the SART measures. There were no significant main effects of CNS score or Group and no interactions between Group and CNS for any of the SART measures (see **Table 6**).

Hypothesis 3: Connectedness to Nature, Group, and Perceived Restorativeness

For the PRS complete scale, a main effect of Group and an interaction between Group and CNS scores were found, but there was no main effect of CNS score. For the main effect of Group, the meadow and ocean images were rated more highly on the PRS than the urban image, and the meadow and ocean images were rated similarly (see **Table 7**). For the interaction, participants who reported lower CNS scores were less likely to report a high PRS score after viewing their image, irrespective of their group. Those with higher reported CNS scores who viewed the meadow and ocean images rated those images with a higher PRS compared with those who viewed the urban image (see **Figure 5**).

Study 2 Discussion

Contrary to predictions, there were no group differences in performance on either half of the post-intervention SART. During the baseline SART there was an increase in sigma for the urban group and in tau for the ocean group, but random allocation to the three groups was used and these slight group differences occurred before presentation of the image. Like Study 1, there was no effect of the image on SART performance, providing no support for Hypothesis 1. In this faster version, with each digit appearing every 1.15 s compared with 3.8 to 4.5 s in the eye-tracking SART, all participants performed the second half of the post-intervention SART with increased sigma rather than tau, as found in Study 1. Sigma is a measure of RT variability that indexes lapses in sustained attention

TABLE 6 | Results from the Linear Mixed-Effects Models for Hypotheses 1 and 3 for Study 2.

Variable	*F*(df)	*F* value	*p*
Errors of Commission			
Baseline SART Commission Error Performance	*F* (1, 317)	112.88***	<0.001
Age	*F* (1, 142)	5.82*	0.017
Sex	*F* (1, 140)	0.86	0.355
Group	*F* (2, 140)	0.06	0.946
SART Half	*F* (1, 143)	0.81	0.370
Group x SART Half	*F* (2, 143)	0.72	0.489
CNS (Hypothesis 3)	*F* (1, 137)	0.03	0.853
Group x CNS (Hypothesis 3)	*F* (2, 142)	0.32	0.727
Mu			
Baseline SART Mu Performance	*F* (1, 335)	36.92***	<0.001
Age	*F* (1, 140)	3.13	0.079
Sex	*F* (1, 139)	0.18	0.668
Group	*F* (2, 139)	0.30	0.744
SART Half	*F* (1, 141)	0.34	0.562
Group x SART Half	*F* (2, 141)	0.75	0.474
CNS (Hypothesis 3)	*F* (1, 136)	1.45	0.231
Group x CNS (Hypothesis 3)	*F* (2, 136)	0.15	0.863
Sigma			
Baseline SART Sigma Performance	*F* (1, 360)	21.32***	<0.001
Age	*F* (1, 174)	0.005	0.943
Sex	*F* (1, 175)	0.06	0.809
Group	*F* (2, 175)	1.29	0.277
SART Half	*F* (1, 182)	3.93*	0.049
Group x SART Half	*F* (2, 176)	0.89	0.414
CNS (Hypothesis 3)	*F* (1, 171)	2.71	0.101
Group x CNS (Hypothesis 3)	*F* (2, 171)	0.862	0.444
Tau			
Baseline SART Tau Performance	*F* (1, 361)	38.78***	<0.001
Age	*F* (1, 172)	0.007	0.933
Sex	*F* (1, 172)	0.21	0.651
Group	*F* (2, 173)	0.13	0.880
SART Half	*F* (1, 176)	3.81	0.052
Group x SART Half	*F* (2, 175)	0.27	0.761
CNS (Hypothesis 3)	*F* (1, 169)	2.86	0.093
Group x CNS (Hypothesis 3)	*F* (2, 169)	0.03	0.970

df, degrees of freedom and SART Half, difference between the first and second half of the post-intervention SART. $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$.

TABLE 7 | The moderation analysis examining the interaction between group and Connectedness to Nature Scale (CNS) scores, in predicting the Perceived Restorativeness Scale (PRS) Score in Study 2.

Predictors	Perceived Restorativeness Scale Scores					
	b	SE	95% CI		*t*(180)	*p*
			LL	UL		
Meadow—Urban	0.98	0.16	0.60	1.35	6.18***	<0.001
Ocean—Urban	1.27	0.16	0.89	1.65	7.87***	<0.001
Meadow—Ocean	−0.29	0.16	−0.66	0.08	−1.86	0.154
CNS Scores	−0.003	0.19	−0.38	0.38	−0.02	0.988
Meadow × CNS—Urban × CNS	1.02	0.27	0.49	1.56	3.77***	<0.001
Ocean × CNS—Urban × CNS	0.78	0.26	0.27	1.29	3.03**	0.003
Meadow × CNS—Ocean × CNS	0.24	0.26	−0.27	0.75	0.94	0.348

b, beta coefficient; SE, standard error; CI, confidence intervals; LL, lower limit; UL, upper limit. Model $R^2=0.41$, $F(5, 180)=24.87$, $p<0.001$; $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$.

(Johnson et al., 2015). This change is interpreted as a sign of attentional fatigue and was noted in all three groups. As in Study 1, the baseline SART may have caused small levels of attentional fatigue that only became manifest when completing the second, post-intervention SART. Indeed, all three groups reported an increase in sleepiness from before the baseline

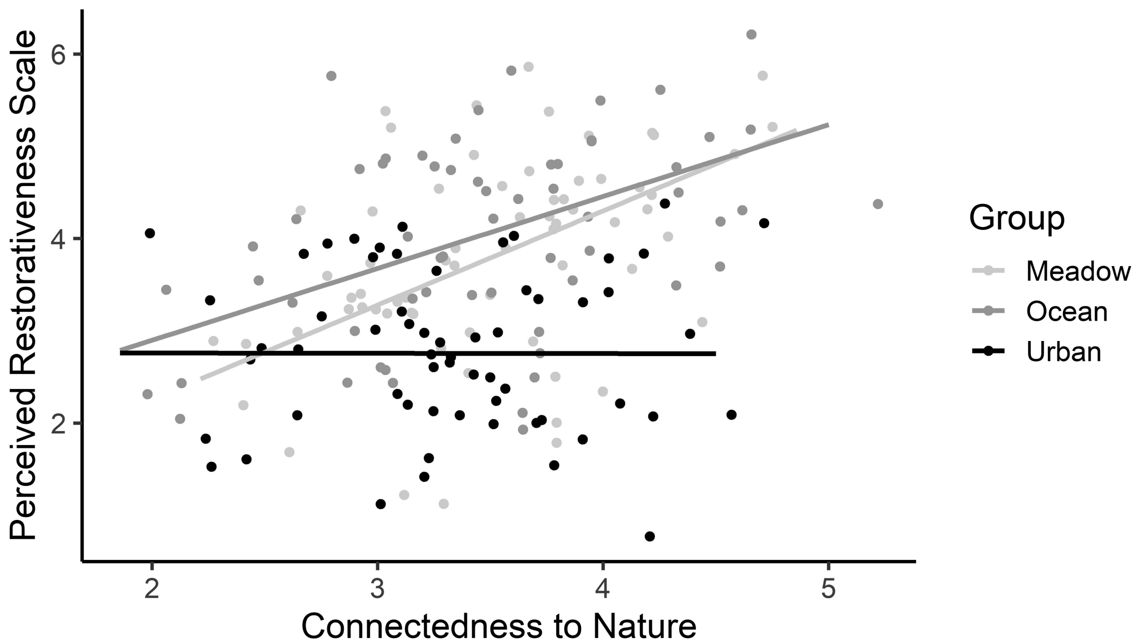

FIGURE 5 | The interaction between Connectedness to Nature Scale scores and group on the Perceived Restorativeness Scale scores, from Study 2. The grey shading represents the 95% confidence intervals.

SART to after completing the second SART, and there was no effect of the image on the KSS measure. Younger participants made more commission errors than older participants during the post-intervention SART. This observation may reflect better impulse control with age (Vallesi et al., 2021) and is consistent with research by Carriere et al. (2010) in which SART errors tended to decrease linearly with age (Carriere et al., 2010). No age effect was observed on the other SART variables.

As predicted and consistent with Study 1, the natural images were perceived as more restorative than the urban image, and the meadow and ocean images were rated as equally restorative, supporting Hypothesis 2. In contrast with Study 1, these results held true for all four subscales. This finding provides support for the speculation that the rooftop view offered by the urban image in Study 1 explained the lack of difference in fascination and compatibility between the three groups.

How connected one felt to nature was not associated with SART performance, irrespective of which image was viewed. Nevertheless, connectedness to nature did moderate the relation between viewing images of natural environments and how restorative the image was perceived. While high CNS scores predicted high PRS scores for the meadow and ocean groups, low CNS scores did not predict higher PRS scores for the urban group. The third hypothesis was partially supported. This finding is consistent with van den Bogerd et al. (2018), who found that individuals with a strong connectedness to nature rated green spaces as more restorative than individuals with low connectedness to nature (van den Bogerd et al., 2018). The finding runs against the idea that those with low connectedness to nature might have experienced higher restoration when presented with low biophilic environments, as proposed by Berto et al. (2018). Here, for participants with a weaker connectedness to nature, how restorative the image was perceived was not associated with the content of the image.

GENERAL DISCUSSION

Two recent meta-analyses suggested that the effects of nature exposure on sustained attention performance are small and the mechanisms underpinning this effect remain unclear (Ohly et al., 2016; Stevenson et al., 2018). The present research aimed to examine if viewing images of vegetation, water, or an urban setting led to a change in alertness (Study 1) and behavioral performance on the Sustained Attention to Response Task (SART; Studies 1 and 2), the perceived restorative value of that image (Studies 1 and 2), and the extent to which one's connection to nature played a role in both sustained attention performance and the perceived restoration of the viewed image (Study 2). There were three key findings. First, there was no difference in the pupillometry measures of alertness, sustained attention performance, or how sleepy participants felt after exposure to the meadow, ocean, or urban environment image. Second, both natural environments were perceived as being places with more restorative potential than the urban environment, with no difference found between the meadow and ocean views. Third, stronger connectedness to nature amplified the perceived restorativeness of the nature images, but not of the urban image; this effect was not noted in the behavioral performance on the SART. This differentiation between the physiological and behavioral findings compared with the perception of the restorative value of the images is novel. The findings provide new avenues for research on the mechanisms underpinning how nature exposure may operate to restore attention.

Lee et al. (2015) speculated that the beneficial effects of viewing a flowering meadow image on sustained attention performance may have been due to gentle stimulation of alertness leading to enhanced attention control. Using an eye-tracker, the present research found that viewing nature images did not beneficially influence tonic pupil diameter, a measure of alertness. All three groups showed a decrease in linear change in tonic pupil diameter in the first half and a plateau in the second half of the post-intervention SART, and a decrease in the mean pupil diameter from the first to second half of the post-intervention SART, both of which are suggestive of a decrease in alertness. Likewise, all three groups performed the SART with increased response time variability in the second half of the post-intervention SART (tau in Study 1, sigma in Study 2), suggestive of declining sustained attention. The reason why different forms of response time variability increased over the post-intervention task between the two studies is unclear but may be due to the timing differences of the two studies. In Study 1, the inter-trial interval varied between 3.8 and 4.5 s to enable enough time between trials for the pupil size to return to the tonic, baseline, level. In contrast, Study 2 excluded pupillometry and hence, used the standard Fixed SART with an inter-trial interval of 1.15 s. The longer inter-trial interval in Study 1 may have induced more attention lapses, as indexed by more very slow responses measured using tau. The shorter inter-trial interval in Study 2 may have induced more moment-to-moment variability in responding, as indexed by sigma. Using a psychomotor vigilance task, Unsworth and colleagues reported that with a long inter-stimulus interval of 8 compared with 2 s, or with a variable interval, participants performed the task with slower responses and with smaller tonic pupil diameter, suggesting that lapses of attention are associated with lower alertness levels (Unsworth et al., 2018). In both studies all three groups reported an increase in sleepiness, measured using the KSS, following completion of the two SARTs. The pupillometry data, together with the behavioral data from the SART, and the KSS measure, suggest that participants were becoming less attentive and alert over the course of the two SARTs. The SART is a deliberately fatiguing task; a cumulative effect of performing the SART twice may have occurred. To date this is the first study to use pupillometry during a sustained attention task to test the immediate effects of viewing a nature image. The three other studies using pupillometry measured pupil diameter as participants viewed photos of different forms of nature, finding opposite effects (Nordh et al., 2010; Martínez-Soto et al., 2019; Marois et al., 2021). Here, the participants showed physiological and behavioral evidence of fatigue during both the baseline and post-intervention SARTs, and reported feeling sleepier after completing both SARTs, but with no relief proffered by viewing the nature images for the 40 s period tested here.

Regarding performance on the SART, the results from both Studies One and Two suggested that exposure to the images of nature did not influence sustained attention performance. This finding conflicts with similar research that found exposure to natural images compared with urban images led to faster response times (Berto, 2005), less response time variability and fewer omission errors (Lee et al., 2015; Cassarino et al., 2019). This finding is consistent, however, with Berto's research in study 3 (Berto, 2005), which found no significant difference between viewing natural or urban images on any SART outcome measures, and Lee et al. (2015) who reported no difference between groups on mean response time and commission errors. It is also congruent with work by Nguyen et al. (2018), who failed to observe any restorative effect of nature images containing varying proportions of water and greenery (Nguyen et al., 2018), and Cassarino, Maisto, and colleagues (2019), who observed no differences when comparing SART performance after a simulated drive in a computerized rural or urban road environment (Cassarino et al., 2019). Together the pupil diameter and SART performance findings suggest that the mechanisms underpinning attention restoration associated with exposure to nature, using a 40 s view of a static image, are not related to alertness or cognitive functioning.

The findings from both studies strongly suggest that although the participants did not show physical or cognitive evidence of benefit after viewing the meadow or ocean images, they perceived the meadow and ocean images as places where they could feel restored. Indeed, the data from Study 2 indicated that one's perception of restoration was tightly linked to how connected one felt to nature, as proposed by Mayer and Frantz (Mayer and Frantz, 2004). Connectedness to nature was found to moderate the relation between viewing images of natural environments and perceived restorativeness of the places in Study 2. Participants with high connectedness to nature were more likely to rate the nature images as more restorative than those with low connectedness to nature, while how connected to nature one felt was irrelevant to the restorative value of the urban image. The rooftop urban image provided some minor restorative benefits compared with the ground level urban image, with no group differences noted between the perceived restoration of the meadow, ocean, and rooftop urban images in terms of Fascination and Compatibility. The ground urban image, in contrast, did not afford such perceived benefits, with the meadow and ocean images rated as more restorative on all four subscales of the Perceived Restoration Scale. Connectedness to nature is an important moderator of perceived restorativeness of nature images. This finding highlights the important role that positive feelings and emotion play in nature-based restoration, echoing the argument put forth by colleagues that affective responses to the natural scene may explain some of the restorative value of nature (Craig et al., 2015; Martínez-Soto et al., 2019). This is an important future line of research for understanding the mechanisms associated with the Attention Restoration Theory.

In these two studies, the images presented to the participants were static photos. The Stevenson et al. (2018) meta-analysis encouraged the use of actual exposure to natural environments over the use of virtual exposure (Stevenson et al., 2018), especially in studies measuring sustained attention and vigilance. Here, a choice was made to use static images because of the use of the lab-based eye-tracker. An improvement in design in future research would include the use of mobile eye-tracking and actual exposure to different environments. Future research might also consider extending the length of duration of exposure to the different environments, as Stevenson et al. (2018) argued that longer exposure may be moderating the restorative effect of natural environments compared with control conditions. Another limitation of the two studies is that confounds associated with color, shape, shade, familiarity with the image, associations with leisure and work, heat, relaxation, and stress were not addressed. These factors could be systematically address in future research. One limitation specific to Study 2 was that the experimenters did not have control over where the participants looked when they were instructed to view the image for 40s, as the study was conducted online due to restrictions associated with COVID-19. Future research might consider broadening the concept of connection to nature to measure feelings, thoughts, and experiences people might have with nature separately, possibly through the use of the Nature Relatedness Questionnaire (Nisbet et al., 2008). These limitations and confounds may help explain why there were no physiological or behavioral differences measured between the three groups.

Here, with the use of a well-established neuropsychological test of sustained attention, alertness measured using an eye-tracker with a high sampling rate, the current best measurement of response time with the use of the Ex-Gaussian model, and a replication of the behavioral results from Study 1 in Study 2, no benefits of viewing the nature images over the urban image were measured physiologically or behaviorally. How connected one felt to nature had a strong effect on how restorative the meadow and ocean images, but not the urban image, were rated. This finding highlighted the importance of emotional response to nature, familiarity with nature, and the perspective of self within the world.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found here: https://osf.io/56xqv.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Melbourne Psychological Sciences Human Ethics Advisory Group. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KJ designed and directed the project. KJ, AP, and VL were involved in the planning and main conceptual ideas of the manuscript and wrote the manuscript. AP and VL collected and analyzed the data. RJ, JJ, and KM were involved in the data analysis and coding. KJ, LS, KL, NW, and KW obtained funding for the project. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.809629/full#supplementary-material

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A collaborative learning model for a flourishing green roofs, walls and facades sector: Exploring two major Australian cities

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ABSTRACT

The combined challenges of climate change, urban densification, and pandemic-related isolation and stress have strengthened the case for increased greening in cities where their social and environmental benefits have captured the interest of policy-makers. Green roofs, walls, and facades (GRWF) are an established solution in many space-constrained northern hemisphere cities. This is not the case in Australia where GRWF sector growth is slower. To understand how to accelerate the uptake of GRWF, we ran appreciative inquiry summits in Sydney and Melbourne. We examined (1) actions for flourishing GRWFs and (2) collaboration for rapid innovation. Our results highlight collaborative learning and link this to phases of sector evolution through government-led research partnerships, policy, and incentives; a national body advocating, and supporting, engaging, and developing expertise; and cross-sector co-leading for alignment and building sector capacity and knowledge. We integrate these into our model, revealing adoption, legitimation, and diffusion and sector growth phases, finding stalled progress and new initiatives signalling recent change. This work is relevant to GRWF and other forms of green infrastructure in cities where these technologies are new or not widely implemented.

1. Introduction

New forms of green infrastructure such as green roofs, walls, and facades (GRWF) are an important component of sustainable and liveable cities (e.g. Shafique et al., 2018; Tassiker et al., 2016; Williams et al., 2019). They can provide access to, or views of vegetation that may support the health and wellbeing of workers and residents (e.g. Williams et al., 2019), manage stormwater, provide habitat, reduce building energy use and urban heat through thermal control (Fleck et al., 2022; see Shafique et al., 2018 and Williams et al., 2021 for overviews). Such external 'green infrastructure where vegetation is planted on building roofs or facades, does not require land reallocation (Irga et al., 2017) and therefore provides a way of incorporating green infrastructure in high density cities. More generally, city green spaces are part of the move towards nature-based solutions and eco-cities (e.g. Bush & Hes, 2018) and may support the climate, environment, and people. For example, they may provide opportunities for enhancing biodiversity—with a global meta-analysis highlighting the key role of habitat patches and connected corridors in cities (e.g. Beninde et al., 2015)—and for health and wellbeing—although reviews highlight the complexity of these relationships, with a range of environmental and personal variables involved (e.g. Hartig et al., 2014; Lee & Maheswaran, 2011). Frameworks linking green spaces and health highlight pathways through reducing harm (e.g. noise reduction), restoring (e.g. stress reduction), and building capacities (e.g. exercise) (e.g. Markevych et al., 2017). As such, they are critical for liveable and resilient cities and recognised internationally in the Sustainable Development Goals.

As such, GRWFs are proliferating globally; for example, there is a 13.5 million m^2 yearly increase in green roofs internationally (Shafique et al., 2018). The Australian GRWF sector is much younger than its international counterparts and has been slower to develop, grappling with constraints such as the harsh Australian climate, long distances from established international product suppliers and lack of knowledge (Williams et al., 2010). We define this sector as part of society working with GRWFs, including those directly involved in researching, constructing, maintaining, and using green roofs and cities more broadly including those working in sustainability and urban planning.

Governments and institutions around the world are progressing ambitious green infrastructure programs focused on engaging multi-stakeholder collaborations in ways that are better equipped to tackle

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complex problems (Lafortezza et al., 2018; Lähde & Di Marino, 2019; Pauleit et al., 2019; van der Jagt et al., 2019). These programs seek to better understand current barriers to progress, create multifunctional spaces, and develop effective collaborative networks to continue delivering green infrastructure (Lafortezza et al., 2018; Lähde & Di Marino, 2019; Pauleit et al., 2019). Often the focus is on collective learning, recognising urban green infrastructure as complex social-ecological systems requiring input and collaboration from people working at multiple scales (van der Jagt et al., 2019). Surprisingly, there has been far less consideration of how stakeholders collaborate—the interactions and dynamics of collaborative relationships—even though this is valued by government partners (Le Feuvre et al., 2016).

Effectively planning and delivering green infrastructure is difficult and involves a range of different stakeholders (Bissonnette et al., 2018; van der Jagt et al., 2019); as such, enhancing collaboration between multiple diverse stakeholders is key. Twin reviews on green roofs in Australia and internationally, provide some indication of the range of relevant stakeholders and disciplines co-creating knowledge and GRWF. These include, for example, industry and academicians in building operations, construction and building, contracting, design, ecology, engineering, horticulture, psychology, urban planning, as well as end-users, government, owners (Williams et al., 2021; Zhang & He, 2021), and specialist installers. This highlights the multi-disciplinary, and in some cases transdisciplinary collaborations that are taking place between organisations across the GRWF sector.

In this work we aim to better understand how to foster learning and collaboration between organisations for GRWF sector evolution in Australia, drawing out lessons for other countries. To do this we first develop a framework for sector learning and collaboration, linking this with phases and narratives of sector evolution in transitions to sustainability and nature-based cities. GRWFs are “redefining the traditional edges and boundaries between ‘nature’ and the city” and associated “narratives and values on what kind of ‘nature’, and what kind of green roof, is desirable and appropriate in the city” (Loder, 2007, p.22). There is also evidence that greening traditionally non-greened elements of cities such as GRWF, for example, through inner-city laneways, are one part of innovative policy and action towards sustainable, equitable, and resilient cities (e.g. Bush, 2020).

We use an Appreciative Inquiry methodology (AIM; Cooperrider & Srivastva, 1987) to engage with stakeholders from government, academia, industry, and community, to better understand the GRWF sector in Australia and the learning and collaboration required for growth. We see this as an advance on existing approaches as we focus at the sector level and provide a framework for evolution in complex, multi-organisational sectors (e.g. Bissonnette et al., 2018; Lavie et al., 2010). This highlights how organisations within the sector can work and make meaning together as they progress the sector in their move towards green cities. This is consistent with previous work focusing on deep collaboration to address wicked problems related to sustainability (e.g. Moosavi & Brown, 2021) and with the breadth of work using participatory approaches to meaningfully engage stakeholders (e.g. Bissonnette et al., 2018; Le Feuvre et al., 2016; Moosavi & Brown, 2021).

1.1. Green roofs, walls, and facades in the Australian context

The global GRWF market is estimated to be worth $AU 7 billion (Wilkinson & Dixon, 2016). Despite this, there is no national policy to drive the sector in Australia. The market requires codes, mandates, and incentives to progress (Wilkinson & Dixon, 2016) but these are largely absent. Internationally regulations and incentives, along with falling costs for GRWF have driven their global market expansion and this has significant implications for the sector and for collaboration here in Australia. Using a local GRWF case study in Sydney, researchers have found support for the studied environmental and building benefits, suggesting that they are highly cost effective and, if adopted widely, could have synergistic effects, thus supporting sustainable cities (Irga et al., 2021; see Fig. 1 for selected GRWF images).

This highlights that the Australian sector has great potential for growth, but the perplexing slow uptake of green infrastructure in Australia (Matthews et al., 2015) suggests the sector may face unacknowledged barriers which are stalling progress. Most Australians live and work in increasingly dense cities, with 40 % of the population concentrated in the south-eastern cities of Sydney and Melbourne (Australian Bureau of Statistics [ABS], 2019). Australia has three levels of government: local, state, and national, and both Sydney and Melbourne have developed policies and guidelines at the local government level (see Supplementary Table 1). These guidelines have been developed to help stimulate GRWF uptake by addressing previously identified barriers (e.g. Williams et al., 2010) and since then, have experienced a modest increase in GRWF (Irga et al., 2017). Despite this, only a small fraction of available surfaces has been greened (Wilkinson et al., 2018; even though in Melbourne, approximately 64 % of city rooftops could be greened; City of Melbourne, 2014), and there is significant scope for growth in the sector. There is significant interest in catalysing transformational change, with both City of Melbourne and City of Sydney councils setting ambitious targets for achieving green sustainable cities and significant increases in greening (Wilkinson & Dixon, 2016).

In recent years, interviews and workshops with the Australian GRWF sector have provided insights into opportunities and barriers to growth. These have highlighted roles for government and the national industry or peak professional body, and for actions via research, demonstration projects, education programs, and incentives to share risks and benefits in the move to mainstreaming (Tassiker et al., 2016). Alongside this they have accentuated the importance of building collaborative knowledge and developing metrics/tools and of building capacity via forming and maintaining strategic collaborations in green infrastructure (Lin et al., 2019). While these workshops have often been conducted with experts, there is increasing focus on involving the community in these collaborations and decisions for “democratizing the design, management, and governance of public spaces” (Campbell-Arvai and Lindquist, 2021, p. 1). These findings draw attention to barriers to sector growth and opportunities for delivering green infrastructure solutions and building collaborative learning across organisations through dynamic processes of discovery and implementation as the sector evolves.

1.2. Learning and collaboration for GRWF sector evolution

Our research focuses on collaborative learning across organisations, and how this operates in the GRWF sector in Australia. We draw on, and adapt, theoretical accounts of learning and collaboration between organisations (Holmqvist, 2003; March, 1991). Next we provide an outline of the collaborative learning literature to provide a conceptual underpinning for our paper, one that helps understand the evolution of GRWF sector in Australia.

Learning between organisations (inter-organisational learning) includes processes of opening up during discovery and focusing during implementation; balancing these processes is critical for “system survival and prosperity” (March, 1991, p. 71). One way to achieve this balance is through sequential phases where implementation follows discovery (Brix, 2019; Choi & Chandler, 2015) for sustained learning and collaboration that would occur with an evolving GRWF sector. Our consideration of learning and collaboration is consistent with recent localised (Bissonnette et al., 2018) and large-scale collaborative and engaged green infrastructure projects (e.g. Pauleit et al., 2019; van der Jagt et al., 2019). These have been directed towards resilient and sustainable cities (Brown et al., 2018; Moloney & Doyon, 2021) and reflect a broader focus on social learning beyond this field (e.g. Pahl-Wostl, 2009).

Collective discovery involves jointly innovating, and risk-taking, drawing in novel experiences through networks, and collaboratively exploring new trajectories. Collective implementation involves jointly refining the best discoveries for consistent and repeatable results

Fig. 1. Selected images of green roofs and facades in Sydney and Melbourne.

through capitalising on established trajectories and process innovations (Holmqvist, 2003; Westerlund & Rajala, 2010). Neither process alone is desirable: while discovery can provide novel solutions, the search for these—and the associated failures—sacrifices immediate performance; and while implementation can provide immediate stable performance, lack of exploration—and associated novel solutions—sacrifices future competitiveness (Lavie et al., 2010; March, 1991).

We use Jones et al.'s (2019) model of industry transition to sustainable practices to consider how organisations can collaborate for sector evolution. This responds to calls for understanding how learning through discovery and implementation contributes to GRWF sector evolution (Lavie et al., 2010). We focus on phases of the transition; *adoption* "of new practices through voluntary standards", *legitimation* "of new practices through framing", and *diffusion and growth* through commercialization "of new practices through new market entries and alternatives" (Jones et al., 2019, p. 426). Importantly, this model provides a path to sector evolution through complementary actions across multiple diverse organisations. Applied to green infrastructure, and specifically the GRWF sector, this model can help us to understand how sector learning and collaboration may operate. We draw on narratives in the GRWF sector as a framing device to help us understand these processes and to build a model of sector evolution. Narratives support meaning-making towards building a collective identity (Jones et al., 2019) and so we use stories told by GRWF organisations to illustrate the learning and collaboration taking place. There is broad evidence that fragmented and competing narratives are slowing the move to 'nature-based cities' and that a consistent and collective narrative vision is critical in shifting from a 'business-as-usual' approach (Bush & Hes, 2018). But this change requires a validating shift through stories of developing sector success (Jones et al., 2019). These narrative shifts are likely associated with learning and collaboration underway, and to phases of sector evolution and development which is important when considering the progression of the GRWF sector. This approach has been used in other sectors such as urban water in their move towards sustainability (e.g., Brown et al., 2018) and so we believe it is critical to include here.

1.3. Approach

To help us understand how learning and collaborative dynamics operate, and what they might look like in the GRWF sector we turned to AIM (Cooperrider & Srivastva, 1987), an action research approach from organisational development. AIM can be used for complex issues of social innovation and sustainability and has been successfully implemented at the city level and with closely related issues such as collective visions of sustainability (e.g. Meyer-Emerick, 2012). Summits are a popular tool in AIM as they can create collective agreement on visions and goals (Ludema & Mohr, 2003) and as such, a promising approach for us to use for the GRWF sector. For example, as part of a plan for a sustainable green local economy in Cleveland, stakeholders from business, public and non-profit, sustainability, and community sectors generated environmental, social, and economic goals over two summits. In doing so, the summits generated continuing momentum for shared knowledge platforms, stimulating funding and feasibility actions, new partnerships, and new city initiatives (Meyer-Emerick, 2012). We used AIM summits to engage with GRWF stakeholders, exploring collaborative learning towards evolving the sector. We sought to co-develop a shared vision of what future green cities and GRWFs might look like in Australia, and how to collectively work towards meaningful action.

We use two research questions to guide this work:

Who are the stakeholders and how can they collaborate for sector learning?

How is this related to sector evolution?

2. Method

2.1. Appreciative inquiry

AIM is a form of action research with a theory of collective change for "organising and [a] method for changing social systems" (Bushe, 1999, p. 61). It explicitly affirms and develops positive images that people hold, and harnesses these to provide a method for transforming an entire system (Bushe, 1999; Cooperrider & Whitney, 2005). It focuses on developing new knowledge, understanding, and language creating "a new lens for seeing old issues…[so that] people have new ways to think about and discuss their organisation" (Bushe & Kassam, 2005, p. 164). This is likely to be particularly critical in diverse sectors such as GRWF where multi-actor and multi-organisational collaborations are required, and as such, also more likely to create change (e.g., Hanleybrown et al., 2012).

AIM draws on five key principles. First, that people are "constantly involved in understanding and making sense of the people and the world" around them and that involving all related stakeholders is critical to enact change (Cooperrider & Whitney, 2005, p. 49). Second, that inquiry and change occur together. Third, that people are constantly engaging in "learning, inspiration, and interpretation" in creating the story of their organisation (p.51). Fourth and fifth, that positive visions inform positive actions and that mobilizing and sustaining this requires positive emotions which generate energy and social connections (Cooperrider & Whitney, 2005). The third principle highlights narratives shape and reflect the system and this also forms a basis of our findings and model building. These principles were embedded throughout this work from the process developing the summits, their format, and the activities on the day and we discuss this further in the following sections.

2.2. Summit context

Summits are a popular tool in AIM as they can create collective agreement on visions and goals (Ludema & Mohr, 2003), an outcome we hoped to achieve for the GRWF sector. We ran our day-long summits in two major Australian cities, Sydney (11th March 2019) and Melbourne (9th April 2019). Their GRWF context is summarised in the Supplementary materials (see Supplementary Table 1). In 2014, both cities introduced significant initiatives supporting urban greening which have continued to be developed in Melbourne and reaffirmed in Sydney. Both cities have supported the growth of the GRWF sector with research funding, industry networking forums and government-led demonstration projects, although support appears to be significantly greater in Melbourne. However, GRWF still only cover a tiny fraction of the total roof and wall area available in both cities.

2.3. Summit planning

In line with the principles of AIM, we focused our summits on two affirmative topics defined by the design team with the vision set for 2030 to inspire action. We selected 2030 based on guidance from our design team as a timeframe that could catalyse motivation and action, while also being relevant for planning and policy.

1. Actions to achieve a flourishing of green roofs, walls and facades in Australia, and
2. Collaboration that fires rapid innovation and adoption

Our summit design team consisted of nine key stakeholders of the GRWF system from academia, local government, industry, and an AIM facilitator. Over approximately four months the design team co-designed and delivered the summits. Summits were designed to be generative and inclusive, encouraging contributors to share personal stories and diverse perspectives. Both summits followed a similar agenda (1) a welcome and overview of the sector, the AIM process, and the day, (2) summit activities working through the AIM process, and (3) wrap up of the day and next steps.

Contributors were selected to maximise generative discussions through capturing diverse perspectives, first through existing networks and broadening to encompass as many related groups as possible. Contributors were invited in successive rounds and design team members were able to update this with new contacts they identified or that were recommended from other invitees. Overall, 66 people participated across both summits: 57.5 % from industry, 24 % from government, 17 % from academia, and 1.5 % from community (see Table 1).

2.4. Summit activities

Summit activities progressed through the stages of AIM and from paired discussion (see Table 2), focused around our affirmative topics. This was to maximise generativity through the number of interviewers and interviewees, to build interest and relationships for "a collective experience that catalyses that conversation" (Bushe, 2007, p. 4–5). The questions and scenarios used in the summits were developed from materials created by the design team during the design phase. In line with key AIM recommendations, they were designed to provoke novelty and surprise, engage the heart and spirit, build relationships, and reframe reality (Bushe, 2007).

The latter sessions were initiated around five different 'data stations', with discussion sparked by eye catching posters that summarised the sector and standout examples from across the sector (e.g. policies, networks, cases) (see Table 2). To encourage novelty and diversity we asked contributors to form new cross-sector groups. We made minor adjustments to the agenda to help the Melbourne summit run more smoothly: an icebreaker to immediately engage and connect contributors; stronger focus in two sessions to enhance clarity, energy, and time for end-of-the-day report back to support change; and a state-of-the-industry poster partly informed by comments and material generated in Sydney. Fig. 2 provides an overview of the different steps in the design and delivery of the summits.

2.5. Data collection

We collected four sets of qualitative data. The first was group-level data generated from the small-group and large-group summit activities. The second was individual-level data on milestones towards the collective vision of the future which informed our discussions and interpretation but was primarily incorporated into a post-summit sector roadmap (Bathgate et al., 2020). Third was individual-level data on evaluations of each summit from participants. We used all these texts to analyse the thematic outcomes of the summit, additionally drawing out powerful quotes or responses from the small group data that would help to illustrate or expand on the large group data. We also collected observational data from a member of the research team related to notable comments, tone and engagement throughout the summits.

2.6. Data analysis

The data analysis involved two phases. The first phase involved collating the textual data from the summit and conducting a thematic analysis for our two affirmative topics. We focused on the large group text and noted patterns relating to collaborations between sector organisations, mechanisms for rapid adoption, and how to grow the sector through to 2030. A researcher identified key topics emerging from the textual data and after discussions with a second researcher, aggregated this into broader codes (cf. Miles & Huberman, 1994). Two researchers analysed the text, using an established thematic coding protocol. Where there was disagreement, researchers met to discuss their approach and to resolve. During the analysis stage emerging themes and summaries of results were discussed with members of the design team and their

Table 1
Summary of summit contributors.

	Industry						Government		Academic			Community	Total
	Developer	Spatial Design	Hort. & Installers	Water & Engineer	Mgmt.	Advocacy	Local	State	Social science	Natural science	Built Environ		
Sydney	4	3[a]	8	1	1		3	7		2	3		32
Melbourne	2	5	5	4	2	3	3	3	3	3		1	34

[a] Includes Indigenous design firm.

Table 2
Description of the appreciative inquiry process.

	Discovery	Dream	Design	Destiny
Description	"Mobilizing the whole system by engaging all stakeholders in the articulation of strengths and best practices."[a]	"Creating a clear results-oriented vision in relation to discovered potential and questions of a higher purpose…"[a]	"Creating possibility propositions… magnifying the positive core to realize the newly expressed dream."[a]	"Strengthening…capability of the whole system…build hope and sustain momentum for ongoing positive change…"[a]
Objective	Sharing the best of what is.	Envisioning what's possible.	Co-constructing based on what's possible.	Sustaining and maintaining.
Activity	Contributors interview each other using questions and scenarios provided in summit booklet. Sharing stories and responses with small groups and the large group. • Stand out examples of GRWF • Stand out examples of collaboration	Contributors interview each other using questions and scenarios provided in summit booklet. Sharing stories and responses with small groups and the large group. • Imagining flourishing GRWF in 2030 • Imagining the collaboration to get there	Small groups rotate around key data stations and consider key opportunities and barriers. Sharing stories and responses in small groups and overall top 2 for the large group. • Golden opportunities to leverage • Critical barriers to remove	Individuals noted their milestones for 1–2 years (short-term), 4–5 years (medium-term), and 8–10 years (long-term). Main themes shared back with the group for strategic alignment.
Outcome	• Analysis of partner interview with top 2 picks for each • Small group consensus on top 2–3 picks for each • Large group notes top 2–3 picks for each	• Small group consensus on top 2–3 picks for each • Large group notes top 2–3 picks for each	• Small group consensus on top 2 picks for each • Large group votes across shared responses	• Individual milestones for short-term, medium-term, long-term • Large group review of main themes for each timeframe (Melbourne only)

[a] Cooperrider & Whitney, 2005, p.16.

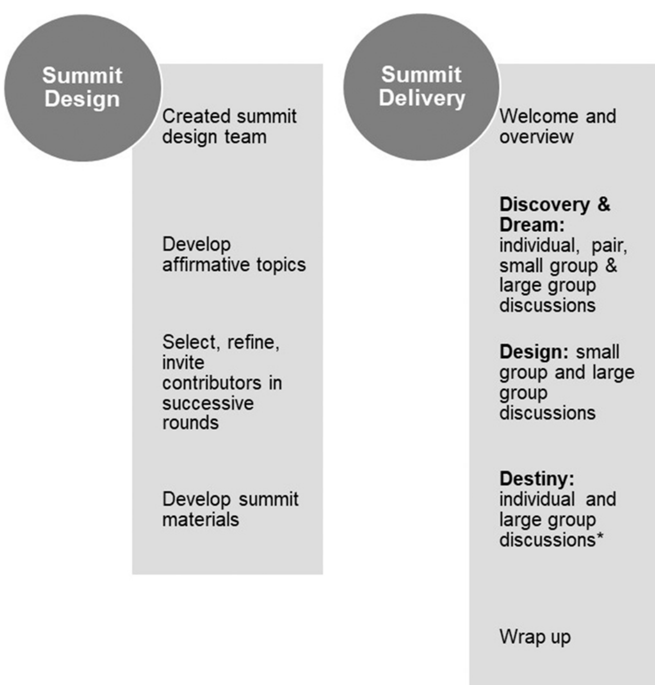

Fig. 2. Steps in designing and delivering the GRWF summits.

observations and clarifications reported to the research team.

The second phase involved interpreting the data in line with our conceptual model. We analysed the text for evidence of collaborative learning through engaging in collective discovery through exploring new trajectories, and implementation through capitalising on established processes (Holmqvist, 2003). We also applied a temporal lens to the data, looking for evidence of key shifts in the sector through narratives emerging from the language and stories used by contributors. We use these as devices to better understand how the sector is evolving through indicating changing collective identity (e.g., Czarniawska-Joerges, 1994). This allowed us to identify the current state of the GRWF sector as well as key elements for continued sector evolution (e.g., Jones et al., 2019).

3. Results

We first present evidence of sector learning, exploring who are the stakeholders involved and how they envisioned collaborating. We then identify narratives that emerged from the summits and use these as a device to explore how collaborative learning is related to sector evolution. We interpret these elements to develop a model of evolution for the Australian GRWF sector. We finish by examining the potential for these GRWF summits to support this evolution.

3.1. Who are the stakeholders and how can they collaborate for sector learning?

This section responds to our first research question highlighting the stakeholders involved in learning and ways they envision collaborating and provides evidence with which to build our model of sector evolution in the following section. Contributors reported collaborative learning taking place, identifying that government had a role to play through "government-led research development…", via "demonstration" projects with broad research collaboration partnerships, for example, through "living labs". Demonstration projects can facilitate "public/private" joint "researching", make successes and failures evident, and engage the public. Alongside this they saw governments as developing policy as a way of moving "beyond awareness" and voluntary adherence and towards "mandatory requirements and incentives combined with a clear planning process and guidelines for implementation". Contributors called for a "carrot-and-stick" approach with compliance as well as incentives, building codes and standards with "integrated national co-ordination on policy" as this is currently lacking.

Activating the national body, strategy, and key advocates, was recognised as critical, with contributors calling for a co-ordinated "living infrastructure national strategy". There were differing views on whether to "approach the existing body to be the champion", activate the current peak body or other professional bodies or create a "new national body to be an effective voice for green roof advocacy, knowledge hub, leadership" (the latter primarily in Melbourne). This lack of national body leadership and lack of clarity about who this should be appears to be a significant problem in the sector. One potential role of this body would be to create a "live" "central repository", an online platform for sharing data and knowledge for the "…public and industry". The importance of this hub appeared to be creating a single source of truth, with unbiased information that told the full story of success and failure (critical for learning) and that managed the challenge of integrating commercial knowledge. This became evident through comments calling for "key honest learnings" alongside a need to "…work out models for how to deal with commercial sensitivities" for example, through "co-opetition".

Strategic alignment in the sector was seen to require "governance arrangements for collaborative partnerships", with key stakeholders making ongoing and strategic contributions at multiple government levels as the sector evolved, supported to "align commercial interest with political aspiration". However, some collaborations were described as "a bucket of crabs" and so it is not clear that these forms of alignment have been established. Clear sector alignment and co-leadership were seen as critical to address contributors' desire to "embed [sic] green roofs, walls, facades into curriculum for many disciplines." They emphasised using "global best practice to facilitate" "growth and improvement" through developing "education, accreditation, and training…" with "certifications…" for industry professionals as well as "creating a new workforce…". This appeared important for supporting "a shared vision with a multi-faceted team with an integrated design process, know their job, & are free to do it".

3.2. How is this related to sector evolution?

We next draw our findings of into a model specifying the elements of sector evolution for GRWF in Australia, towards sustaining balanced collaborative learning cycles for flourishing in 2030 (see Fig. 3). We identified three distinct GRWFs sector narratives that appeared to indicate a shift from fragmented and competing narratives consistent with *adoption*, validating through success consistent with *legitimation*, and sharing a collective vision, aligning with an evolving sector consistent with *diffusion and sector growth*.

In the *adoption* phase, our findings show that *collective discovery* occurs through demonstration projects with a role for government working alongside stakeholders. Establishing partnerships, building new knowledge together, and consultation to develop policy highlights *exploring new trajectories* to build capacity in the sector. We characterised this phase through the lens of shifting from *fragmented narratives* about the sector and how it is perceived, dominated by generating awareness and developing knowledge. Contributors were concerned that high-profile projects may simply be acting as expensive showcases giving the perception of "green bling". They also noted the "persistence of myths" including the "assumption the [sic] green roofs [are] universally useful" which may have arisen through "cowboys" in the sector, or "green washing". Contributors called for an "awareness-raising campaign (branding of industry)", that could "use current issues to create opportunities…", emphasise their value, and highlight important benefits. Communicating thematically to ensure that "the words really describe the experience", capture the imagination, and make people think would support this. This may provide a way to transition through this phase, with contributors embedding their collective vision of the future, and potentially, drawing along those outside the sector.

In the *legitimation* phase, our findings show that *collective implementation* can occur through a national body for advocacy and co-ordination drawing on high-quality knowledge and experience developed in the previous phase. Developing a knowledge hub, as well as regulation and standards such as a certification rating system are key aspects in building learning and collaboration and capitalising on *established trajectories*. We characterised this phase through the lens of

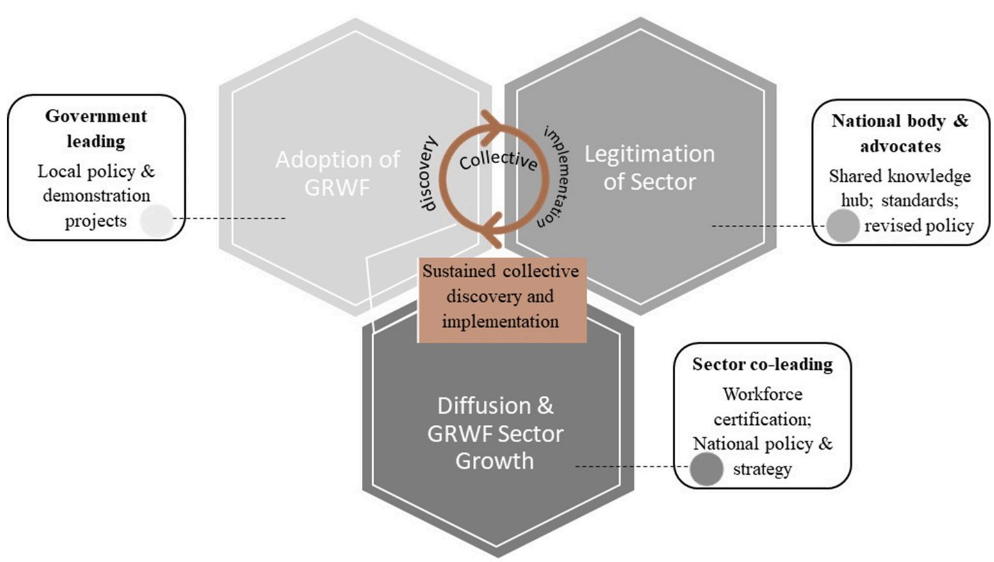

Fig. 3. A model of collaborative learning for the evolving Australian GRWF sector. Grey shapes represent phases of sector evolution, with the feedback loop indicating sustained balancing of adoption and legitimation activities for diffusion and growth. White boxes indicate members of the sector leading and examples of activities occurring in each phase.

validating narratives about the nature of the sector and the role of evidence. Contributors felt an "urgent need for metrics (evidence)" and "… for different co-benefits" to "develop empirical evidence around different objectives of green roofs". Contributors called for different forms of localised knowledge, for example, developing the "…'local' evidence base", with case studies, and qualitative evidence to complement metrics, "co-creating, sharing research & knowledge across sectors, communities, customers". Some contributors suggested "using existing data to identify opportunity [sic] for present green roof installation, proactively identifying useful sites", and this could support transition through this phase. However, addressing challenges with the national body will be critical in this endeavour and we discuss this in the next section (see Discussion).

Sustaining learning and collaboration will be critical if the sector is to evolve by 2030 towards the *diffusion and growth* phase. In this phase, widespread certification would need to become a sector norm, with novel industry practices shared, and a comprehensive approach including specialist and multi-disciplinary training. We characterised this phase through the lens of *multi-functional narratives* reflecting participants' anticipation of a proliferation of nature-based solutions built on considerations of developing evidence of multi-functionality and 'co-benefits". For example, contributors imagined a city "as a forest" a "mini-jungle" or "as a garden" where "living infrastructure" is "nature embedded into built form". Contributors saw GRWFs as a path to blurring the line between nature and the built environment through site-specific, multifunctional, self-sustaining, and biodiverse spaces. Possible new market entrants and practices were identified such as using indigenous vegetation and attractions for green tourism, where "on the roof experiences" and "biodiversity tours are part of Melbourne's nightlife".

3.3. Evaluating the GRWF summits

We examined our summits for their potential to support GRWF sector evolution (see Supplementary Table 2; and see calls for critical evaluation from Van der Haar & Hosking, 2004; Grant & Humphries, 2006). First, contributors appeared to value sharing across the like-minded and multidisciplinary group, commenting, "we are all in this together and that everyone has a valuable contribution from many fields". Contributors saw opportunities for change through partnerships, advocating and sharing knowledge, to "get things moving and connect essential players", including "within my company" and felt that the summits helped generate "a collective desire to help guide the industry", "getting together with all the GI [green infrastructure] players and working together towards a shared vision for the future". Contributors seemed to share critical insights across the sector and to engage with these challenges, acknowledging "that we are really behind the 8-ball. We face huge regulatory challenges … but that the people in this room are engaged and committed to make it happen" through making sure "no ideas off the table" and "begin [sic] challenged to consider why not! How this might look in the future for greener cities". However, there was also evidence of tensions, with one contributor commenting others "… were more interested in telling the group than sharing insights". Further, contributors at each location appeared to emerge differently from the summits, highlighting possible differences in their constructions of the local sector. Although not universal, two comments help to illustrate this difference: in Melbourne one contributor commented "the best ideas are in this room", while in Sydney another contributor commented "Australia has a long way to catch up and we are likely to take a lot of effort to catch up".

4. Discussion

Building an action approach to collaborative learning provides a way to progress the GRWF sector, develop strategic networks for facilitating knowledge translation for policy, overcome critical barriers to 'establishing long-term institutional collaborations' (Lin et al., 2019, p.30), and translate real-world experimentation to stakeholder experiences and outcomes (van der Jagt et al., 2019). We contribute to the international literature on participatory approaches to green infrastructure. For example, research exploring stakeholder perceptions of green infrastructure implementation in Montreal identified multiple narratives for planning including the need for coherent frameworks and collaboration across scales (Bissonnette et al., 2018). We extend this work by drawing on AIM and learning across GRWF organisations, new theoretical and methodological lenses that explicitly incorporate dynamic collaborative processes of discovery and implementation into a temporal model of transitions to sustainability. This provides an organising framework for the sector, providing possible pathways forward. It also highlights challenges to evolving the sector, and through the generative and appreciative approach of AIM, aims to support contributors in taking a new perspective, thus shifting the normative narrative. Next, we discuss these aspects in more detail.

Results from our GRWF summits highlight that the sector appeared to be engaged in elements of adoption and legitimation but had not yet reached diffusion and growth. There is evidence of early demonstration projects which supported collective discovery, particularly around technical components (Rayner et al., 2010; Growing Green Guide, Department of Environment and Primary Industries, 2014) and these include a number of government-led projects across both cities (see Supplementary Table 1 for more detail). Beyond this technical focus, research in other sectors has identified shifting roles for demonstration projects, moving towards large projects building sector-wide capacity (Brown et al., 2018). In GRWF these collaborations would include range of stakeholders across different stages of the project; from designers, engineers, construction, contractors, building operators, owners, end-users, and government (Zhang & He, 2021). There is some evidence that this form of demonstration is occurring, but such projects—which typically involve government, industry, and research organisations—are more complex and therefore, difficult to implement. For example, a recent retrofitted demonstration project in Melbourne's CBD has faced unforeseen regulatory barriers resulting in repeated delays and cost increases.

There is evidence of policy progression at state and local government level in Melbourne and Sydney (see Supplementary Fig for policy standards and guidelines). This appears to continue adoption in both locations, and legitimation in Melbourne, through developing and updating guidelines, policies and codes, and strengthening green infrastructure requirements and the planning system (e.g. City of Melbourne, n.d.; City of Sydney, 2021; State of New South Wales, Department of Planning, Industry and Environment, 2020; The State of Victoria Department of Environment, Land, Water and Planning, 2020). Alongside this, the City of Melbourne have developed an online 'Green Factor' tool for optimising green infrastructure design which can be adapted for use Australia-wide, including in Sydney (Bush et al., 2021). With other adjoining Local Governments identifying their intention to follow suit in Melbourne, this shows continued growth, although there are further elements to address in transitioning through the legitimation phase and these are emerging alongside policy. It is possible that these differences in policy and regulatory development could be linked with differences in how contributors emerged from the summits, for example, with a Sydney contributor commenting they have work to do to catch up.

It is interesting to note that in Australia these policy advancements have been occurring while the national body has been relatively inactive. This is surprising given their key role in the legitimation phase of our model, and so this raises questions about their role in sector evolution. However, delivering on contributor calls for a nationally coordinated policies and GRWF strategies will be challenging in the absence of an overarching body advocating at the national level and drawing collaborators together in this phase. We specifically identified their role in building and sharing knowledge and publishing industry standards and this is consistent with established GRWF sectors internationally where non-government associations play an important function in communicating research, credentialing technical standards, or certification (Irga et al., 2017). This body could become an effective bridging structure in the sector, acting to support transformation early on by building deep knowledge, and later, by translating "new practice into action" (Brown et al., 2018).

It is possible that stakeholders have navigated these challenges with the peak body by forming a new Community of Practice (CoP) across government, industry, and academia, with a shared agenda for research, governance, and education for GWRFs (Green/living infrastructure community of practice meeting 1, personal communication 30th September 2021). The CoP working groups are progressing their agenda, including through developing an industry body, sector responses on issues that affect the sector, and fill gaps in guidance and skills in the industry (Green/living infrastructure community of practice meeting 2, personal communication 17th November 2021). These activities are consistent with our model of sector evolution and suggest that this group is seeking to mature the sector. CoPs are learning communities that build shared meaning through collective resources and language, supporting joint progress towards common goals (e.g. Wenger, 1998). Formal and informal CoPs can advance discovery, support collaborative learning, and progress visionary narratives for transformation (Brodnik & Brown, 2018). Early on, these partnerships may have been established, in part, through Australian Research Council and Co-operative Research Centre grants with multiple industry, government, and academic partners (see Supplementary Table 1).

It remains to be seen whether this CoP, the national body, or another actor in the sector can also advance a knowledge hub for sharing the evidence base that will be key for legitimation. Consistent with our findings, an international review of green roofs (Shafique et al., 2018) highlighted challenges with limited local research to inform climate, and context, appropriate designs and plantings which may suggest that local evidence and specialised models are required. They also suggested that constrained collaborations, for example, between architects, engineers, and residents, pose challenges for green roof construction and maintenance. While our contributors focused on building and sharing technical knowledge, cultural and experiential knowledge, and accompanying implementation tools are also likely to be important for supporting evolution as shown in the related sector of water sensitive urban design (WSUD; Rogers et al., 2015). A recent review of green roofs recommended greater knowledge of "attitudes, preferences, and willingness to pay" to support policy and incentives, and full modelling of economic, social, and environmental benefits to support decision-making, for greater green roof implementation, alongside technical guides and checklists for designers, engineers, and building operators (Zhang & He, 2021).

One key challenge with sharing knowledge across the sector will be in managing summit contributors' concern for addressing commercial sensitivities. One approach to this is "co-opetition" which has been linked with positive outcomes such as performance, innovation, learning, and sustainability. This form of interaction has been identified as key for enabling urban partnerships (Le Feuvre et al., 2016), but managing these interactions and relationships are critical, because organisations are collaborating for shared value whilst competing for individual gain. As such, they should perceive that they are receiving individual value so that they do not limit information exchange (Gernsheimer et al., 2021). This is likely to be particularly important for the GRWF sector in Australia where there is a small market and relatively few established specialist installers who appear to have design, building, research and development, and environmental expertise in-house. As such they may see limited value in sharing their knowledge with competitors or new market entrants, particularly with high initial and ongoing costs associated with GRWF (Shafique et al., 2018). It remains to be seen whether the sector can develop mutually acceptable approaches to developing and sharing knowledge, and whether the CoP or proposed peak body can act as bridging mechanisms to support this.

Our focus on sector evolution is consistent with the broader focus on transitions towards sustainable cities and related sectors including WSUD (Brown et al., 2018). This sector has gone through a similar process of change, developing shared understanding, building and diffusing knowledge and policy, and stabilising emerging practices in the move towards widespread adaptive and multi-functional solutions. This sector has been established longer than GRWFs and provides a helpful comparison for our sector and model. The later WSUD transition phases of knowledge dissemination, diffusion, and embedding (2000-present) appear similar to our proposed GRWF sector evolution phases. Looking at this sector also provides helpful guidance for our final phase of diffusion and growth, as they have moved beyond multi-agency strategic alignment to a formalised institution with a political mandate and leading a new research strategy (Brown et al., 2018). This suggests a subsequent phase for our model and may represent a mature Australian GRWF sector in the future.

4.1. Future directions

The nature of this study meant that we were engaged as active participants in this process, collaboratively co-constructing knowledge with summit contributors. As such we brought our existing experiences and expectations of the GRWF sector to bear in this process, and summit contributors also came with different backgrounds and experience. Indeed, these are design features of AIM. In general, contributors appeared to feel that the key stakeholders were present and value the diverse perspectives from like-minded people that enabled them to engage in challenging, yet expansive, conversations. Conversely, a small number of comments suggested that some contributors did not feel heard or that they perceived the sector to be falling behind. Past research has shown that awareness of sustainability and climate initiatives can differ widely across countries and geographic area, stakeholder group, and familiarity with relevant codes and regulations (Lenzholzer et al., 2020; Wang et al., 2021). As such, the specific actions identified through our summits may be most relevant for similar sectors and contexts, but our model, developed through established models across sectors and academic fields, is likely to provide a useful approach for other complex system-level topics or sectors seeking to enact change internationally, such as blue infrastructure, and this should be examined in future research.

Summits were comprised primarily of expert stakeholders and involved only one member of the wider community. Future work should focus on engaging and co-creating alongside community for greater success in driving and sustaining multifunctional and inclusive public landscapes (Campbell-Arvai and Lindquist, 2021) and including private and civil participation in decision-making has been identified as a key part of transformative leadership in other sector transitions (e.g. WSUD; Brodnik & Brown, 2018). Recent work has developed platforms to support community input and collaboration into designing, managing, and governing public places at scale and these may support broader and more extensive forms of engagement (Campbell-Arvai and Lindquist, 2021). This is likely to be increasingly important for GRWF, particularly in advocating and in continuing to support transitions to future eco-cities, and in increasing market demand (e.g. Zhang & He, 2021). More specifically, mapping of green roofs in Melbourne shows a steep increase on apartments (Williams et al., 2021) and this trend suggests a key role for potential users of these spaces as well as surrounding residents and workers.

While our summits included past members of the board and key sponsors from the current peak industry body, no current members were involved. This was a decision made collectively by the design team, but as the future role of a national body emerged prominently, it is difficult to know the extent we can really push for transformational change with their absence from the conversation. By not involving a key member of the green roofs, walls, and facades system, we highlight a tension between our summits and appreciative inquiry principles, and this may impact on their capacity to catalyse change. Because of the prominence of this issue and role in our model, future work could consider models of sector structures and alliances internationally to identify which might work best in the relatively small Australian GRWF context. We should note that we do feel assured that at least some summit contributors are enacting change, as a small number co-authored a subsequent roadmap industry alongside the research team and members of the design team (Bathgate et al., 2020), and a larger number have formed a new Community of Practice. However, we have not yet gone back to the sector to assess the transformation of contributor visions into further action, and this is an additional avenue for future research.

5. Conclusion

We have developed a framework for collaborative learning for GRWF sector evolution in Australia. We drew on AIM to collectively inquire into the sector, envisioning the future GRWF and the sector and associated narratives, to build a model of sector evolution, drawing from existing transitions to sustainable cities and theoretical understandings of learning across organisations. The AIM process supported contributors at our summits to create shared visions of the future, drawing from their best current experience, dealing with challenges and opportunities, and developing pathways to move towards this new future. This revealed: (1) a government role in developing research partnerships, policy, and incentives, supporting discovery and exploring new opportunities for adoption (2) a national body role in advocating, and in supporting, engaging, and developing expertise, for implementation through capitalising on existing processes to legitimate, and (3) cross-sector co-leading for multi-institutional alignment, and building sector capacity and knowledge, for sustaining collaborative learning cycles for diffusion and sector growth (an envisioned future state). This highlighted a pathway for sector evolution from adoption, to legitimation, and to diffusion and sector growth, providing evidence that the Australian GRWF is engaged in adoption and legitimation activities and may be initiating change to overcome challenges and continue progression to diffusion and sector growth. This model and approach provide a useful contribution that can extend beyond the Australian context and GRWF sector to other complex system-level topics or sectors seeking to enact change internationally. Appreciative Inquiry provides a robust, industry-engaged and action-oriented approach that can be tailored through the co-design process, and this is a powerful new contribution to the field. Our model provides a way forward for sustainable, resilient, and green Australian cities of the future.

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CRediT authorship contribution statement

Lee, K.E: Conceptualization, methodology, analysis, investigation, writing original draft, review and editing, project administration, funding acquisition. Sargent, L.D: Conceptualization, methodology, analysis, investigation, writing original draft, review and editing, project administration, funding acquisition. Williams, K.J.H: Conceptualization, methodology, validation, investigation, writing review and editing, project administration, funding acquisition. Hall, G: Validation, investigation, writing review and editing, project administration. Williams, N.S.G: Conceptualization, methodology, validation, investigation, writing review and editing, project administration, funding acquisition.

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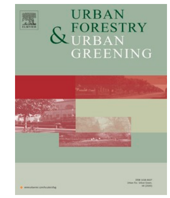

Green roofs sown with an annual plant mix attain high cover and functional diversity regardless of irrigation frequency

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ABSTRACT

Annual plant species have great potential on green roofs as many are highly attractive, fast and cheap to establish via sowing and can provide rapid cover and growth, which is important for ecosystem service provision. While irrigation is essential for survival and growth of annual plants in seasonally hot or dry climates, it is also important to minimize water use as availability is often limited. Therefore, we evaluated how irrigation frequency affects plant cover, species abundance, richness and diversity, plant traits and functional diversity of a 16 species mixture of Australian annual species (4 g $m^{-2} \sim 2100$ seeds m^{-2}) sown onto thirty 0.25 m^2 green roof modules. The experiment was carried out in Melbourne, Australia, from January (summer) to July (winter) 2020. After a 2-month irrigated establishment phase (to ensure germination and seedling establishment), three irrigation treatments (2, 4 and 6 days between irrigation) were applied to the modules for three months. Plant cover was reduced at lower irrigation frequency (6 days), but $\geq 80\%$ plant cover was achieved in all irrigation treatments. There was no effect of irrigation frequency on species abundance and richness; however, abundance, richness and diversity reduced over time, likely due to competition effects. Plant height and leaf area were also reduced by lower irrigation frequency. At the community level, functional diversity was unaffected by irrigation frequency. Our results indicate that green roofs sown with a mixture of annual plants can achieve good plant coverage, as recommended by green roof guidelines, and maintain high diversity when minimally irrigated in their first growing season.

1. Introduction

The environmental and social benefits green roofs provide (Mesimäki et al., 2019; Shafique et al., 2018) depend on a healthy vegetation layer with good coverage (Cook and Larsen, 2021; Lee et al., 2014; Williams et al., 2019). However, the harsh environments of green roofs limit the types of plants which can survive hot and dry summer conditions (Rayner et al., 2016; Vahdati et al., 2017). Due to their adaptation to shallow substrates, low water usage and high stress tolerance (Getter and Rowe, 2006), succulent plants, especially *Sedum* species, are commonly grown on extensive green roofs (Van Mechelen et al., 2014). Unfortunately, green roofs composed of only succulents have relatively low biodiversity and limited ecosystem services such as cooling, stormwater management, habitat provision for local flora and fauna, and aesthetic value (Blanusa et al., 2013; Cook-Patton and Bauerle, 2012; Lee et al., 2014; Li et al., 2018). In terms of aesthetic value, White and Gatersleben (2011) compared people's preferences for different vegetation types and found that a "Sedum roof" was not attractive, while a "Meadow roof" was more preferred. Similarly, Lee et al. (2014) showed that Australian office workers preferred taller, green grassy and especially flowering vegetation compared to succulent vegetation. More diverse, prairie style or grassland green roofs have also been shown to promote greater fascination, sense of calmness and well-being, and creative, meditative thinking than sedum-style green roofs (Loder, 2014).

To expand the number of plant species used on extensive green roofs beyond the regularly used succulents, researchers have attempted to find plant species originating from natural habitats with analogous conditions to those on extensive green roofs (Caneva et al., 2015; MacDonagh and Shanstrom, 2015; Van Mechelen et al., 2014). This process called the habitat template approach (Lundholm, 2006), suggests that plant species appropriate for green roofs can be found in microclimates or habitats with similar biotic and abiotic conditions to those on extensive green roofs (Lundholm, 2006). This approach has

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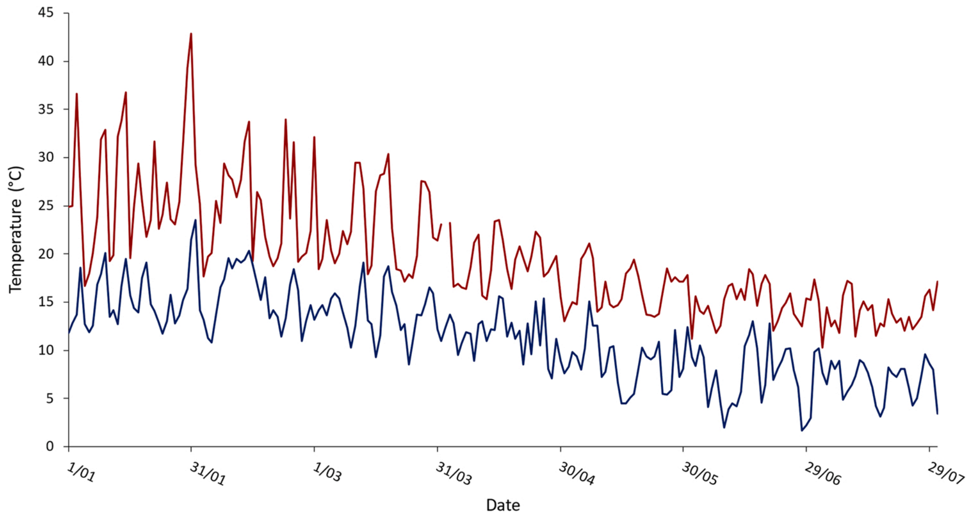

Fig. 1. Daily maximum (red) and minimum (blue) temperatures during the green roof module experiment from January (summer) to July (winter) 2020, measured at Olympic Park weather station, Melbourne. Data for maximum temperature on 2 April 2020 is missing.

been used by researchers in various regions with different climates (Ksiazek-Mikenas et al., 2021; Nagase and Tashiro-Ishii, 2018; Sutton et al., 2012) including Mediterranean-type climates (Cáceres et al., 2018; Caneva et al., 2015; Farrell et al., 2012) and has resulted in suggested plants, particularly native species, suitable for green roofs. However, these species are mostly perennials and few studies have evaluated annual plants despite their potential to perform well on green roofs (Van Mechelen et al., 2014).

One way to increase the diversity and aesthetic appeal of green roofs is to use more flowering species, including annual wildflower species. The flowers of many annual species provide nectar and pollen for pollinators and have been shown to add visual attraction to extensive green roofs (Dunnett, 2015). As annual plants complete their life cycle within one growing season; they germinate, grow, bloom, and set seeds under favourable conditions and are dormant as seeds during adverse conditions (Mulroy and Rundel, 1977), they are likely to persist on green roofs. Few studies have investigated the establishment of annual plants (including native species) on green roofs (or in green roof module experiments) as mixtures solely of annual species (Nagase and Dunnett, 2013; Vasl et al., 2019) or along with *Sedum* species (Kircher, 2004; Schindler et al., 2019; Vasl et al., 2017) or herbaceous perennials (Bates et al., 2013; Benvenuti, 2014; MacIvor et al., 2013; Ondoño et al., 2015). For example, Nagase and Dunnett (2013) found that it is possible to establish a 3–4 month flowering annual plant mix (non-native) on unirrigated extensive green roofs in the maritime climate of Sheffield, UK. Vasl et al. (2017) also demonstrated the possibility of improving green roof performance and services (cooling effect and storm water runoff mitigation) in Mediterranean climates, by combining local annuals and *Sedum* species. Using annual plants on green roofs can also have economic advantages as they can be quickly sown across large roofs. For example, Sutton (2013) found 40% lower labor costs for seeding native grasses compared to direct planting of small *Sedum* plants (plugs) on green roofs, in addition to the lower cost of seeds. Annual plants can also provide rapid coverage of substrate and prevent weed invasion. Long-term studies have shown that in the absence of regular maintenance, vegetation communities on green roofs shift towards annual species (or ruderals) (Catalano et al., 2016; Köhler, 2006; Thuring and Dunnett, 2019), indicating that annual species are likely to persist on green roofs over multiple generations (Vanstockem et al., 2018).

In natural environments, annual plants germinate following sufficient rainfall, with further precipitation after germination promoting survival and growth (Brown, 2002; Gao et al., 2014). In artificial environments, irrigation can trigger seed germination in annual plants under favourable growing temperatures (Funk et al., 2015; Wolf and Young, 2016). In green roofs, irrigation is critical for the survival and growth of non-succulent plant species in regions with Mediterranean-type climates (Du et al., 2019; Guo et al., 2021; Vandegrift et al., 2019; Zhang et al., 2014). For example, Rayner et al. (2016) showed that in Melbourne, Australia, all 17 forb and grass species died during summer on an unirrigated 12 cm deep green roof due to hot and dry conditions, whereas in Sheffield, UK, annual meadows can be established on extensive green roofs without irrigation due to greater and more regular precipitation of their maritime climate (Nagase and Dunnett, 2013). Therefore, in climates with seasonally hot and or dry seasons, irrigation will be essential to grow annuals on green roofs. However, as water resources available for irrigating urban green areas can be scarce, especially in drier environments, it is important to minimise irrigation, but at the same time ensure green roofs have good coverage and diversity (Van Mechelen, Dutoit et al., 2015; Williams et al., 2010).

Differences in plant response to water availability due to differences in drought resistance and traits (Azeñas et al., 2019; Vandegrift et al., 2019) will affect species abundance, diversity and cover (Miranda et al., 2009; Vahdati et al., 2017), and consequently community structure and function (Azeñas et al., 2018; Nunes et al., 2017). Green roofs with higher species and functional trait diversity are more resilient to environmental stress (Heim and Lundholm, 2014; MacIvor et al., 2016; Nagase and Dunnett, 2010) and provide greater aesthetic value (Lee et al., 2014; MacIvor et al., 2016) and ecosystem services (Lundholm, 2015; Van Mechelen, Van Meerbeek et al., 2015; Xie et al., 2018). Plant height and leaf traits have been used to explore variation in functional diversity in natural (Midolo et al., 2021; Spasojevic and Suding, 2012) and green roof ecosystems (Vanstockem et al., 2019; Xie et al., 2018). Plant height has been found to increase competitive and dispersal ability and negatively respond to environmental stress (Garnier and Navas, 2012; Nunes et al., 2017), whereas leaf traits are associated with light capture and photosynthesis, water and nutrient acquisition and resistance to water stress (Onoda et al., 2017). These traits also contribute to green roof functioning (Lundholm et al., 2015). For example, lower plant height was found to be associated with cooler substrate temperatures (Xie et al., 2018), while greater plant height was positively related to higher stormwater capture (Lundholm et al., 2015).

The suitability of using annual species on extensive green roofs in seasonally hot and/or dry climates, and the lowest frequency of irrigation needed to result in an acceptable coverage and diversity is largely unexplored. Therefore, we conducted an experiment using green roof modules sown with a mixture of 16 annual plant taxa in Melbourne,

Table 1
Characteristics of the 16 Australian annual species used in the seed mix including family, germination percentage, number of seeds used in the seed mix for each module, and their climate of origin: mean values (± standard deviation) and ranges (min - max) of mean annual temperature (MAT) and annual precipitation (AP) for species occurrence records in the Atlas of living Australia (ALA, 2018). Germination pre-treatments were applied to six species to maximize germination.

Scientific name	Family	MAT (°C)		AP (mm)		Germination (%)	Number of seeds	Germination pre-treatment
		Mean (± SD)	Range	Mean (± SD)	Range			
Brachyscome iberidifolia	Asteraceae	18.8 (± 2.3)	11.9–27.1	492 (± 261.6)	155–1216	84%	25	–
*Craspedia variabilis**	Asteraceae	13.5 (± 2.5)	4.1–22.6	799.7 (±256.8)	197–2190	91%	25	–
Goodenia vilmoriniae	Goodeniaceae	23.4 (± 1.9)	19.1–27.2	353.1 (±103.7)	198–1488	63%	50	Karrikinolide
*Heliotropium tenuifolium**	Asteraceae	25.1 (± 2)	17.8–28.5	520.5 (±229.1)	156–1788	59%	50	Gibberellic acid
Podotheca gnaphalioides	Asteraceae	18.9 (± 1.4)	15.3–23.6	414.4 (±169.5)	198–1111	90%	25	Karrikinolide
Rhodanthe chlorocephala subsp. *rosea*	Asteraceae	19.3 (± 1.4)	13.7–25.2	331.1 (±131.1)	172–1030	90%	25	–
Rhodanthe humboldtiana	Asteraceae	22.5 (± 1.8)	16.8–27.1	263.4 (± 66.8)	182–801	83%	25	–
Rhodanthe manglesii	Asteraceae	18 (± 1.6)	11.9–21.4	456.7 (±186.6)	230–1280	80%	25	–
Rhodanthe margarethae	Asteraceae	25 (± 1.5)	21.7–27.6	369 (± 53.2)	203–443	65%	50	Karrikinolide
Rhodanthe stricta	Asteraceae	20.4 (± 1.8)	14.1–27.1	253.3 (± 89.5)	139–1245.7	85%	25	–
Schoenia cassiniana	Asteraceae	20.3 (± 1.6)	15.4–27	270.4 (± 71.6)	154–1030	49%	50	–
Schoenia filifolia subsp.*subulifolia*	Asteraceae	19.7 (± 1.1)	16.3–20.4	426.9 (±190.5)	329–1038.7	90%	25	–
Schoenia macivorii	Asteraceae	24.2 (± 0.8)	21.3–24.8	249.7 (± 29.1)	215–327	92%	25	Gibberellic acid
*Swainsona formosa**	Fabaceae	20.5 (± 2.9)	13.2–27.9	249.5 (± 83.4)	148–1030	52%	50	Karrikinolide
*Trachymene coerulea**	Araliaceae	18.1 (± 1.5)	14.1–22.8	762.1 (± 196)	195–1151	93%	25	–
*Xerochrysum bracteatum**	Asteraceae	16 (± 3.2)	3.4–27.7	753.2 (±374.6)	157–3197	95%	25	–
Total number of seeds							525	

—, no germination pre-treatment has been used for these species
* Occurs in both annual and short-lived perennial forms

Australia. While Melbourne has a maritime temperate climate with warm summers and cool, wet, winters, it often can experience prolonged summer heat waves and drought periods. These hot and dry conditions are exacerbated on green roofs, where substrate temperatures can exceed 65 °C and evaporative demand regularly exceeds rainfall for long periods of time (Rayner et al., 2016). We applied three different irrigation frequencies (days between irrigation) to evaluate how irrigation frequency affects: 1) plant cover, species abundance, richness and diversity; 2) plant traits of individual species and 3) plant traits and functional diversity at the community level. Another aim was to determine the lowest irrigation frequency which results in an acceptable coverage and diversity of annuals on green roofs.

2. Materials and Methods

2.1. Study location and climate

A green roof module experiment with a complete randomized block design and three irrigation frequencies (2, 4, and 6 days between irrigation) was established at the Burnley Campus, University of Melbourne, Australia (37°82' S, 145°02' E). The experiment was conducted from January (summer) to July (winter) 2020, where daily mean minimum temperature ranged from 1.7° to 11.7 °C and maximum temperature from 17.4° to 42.9 °C (Fig. 1). Previous germination trials with the annual plant species used in this experiment showed optimal germination at 20 °C (Saraeian et al., unpublished). Therefore, we commenced the experiment in January at when temperatures were optimal, approximately 20 °C monthly mean temperature (Bureau of Meteorology, 2020).

2.2. Experimental design

Thirty experimental green roof modules (HDPE boxes, 50 cm × 50 cm × 20 cm depth) were installed under a rainout shelter. Each module consisted of a 30 mm deep drainage layer (VersiCell® 3050, Elmich Pty Ltd), a layer of geotextile and 100 mm deep scoria-based green roof substrate (60% scoria ≤ 8 mm, 20% 7 mm scoria, and 20% coir) (Farrell et al., 2013), to mimic the construction of a typical extensive green roof.

Seeds of 16 Australian annual species, from a range of different climates (Table 1, Supplementary fig. S1) were sourced from two commercial seed suppliers "Nindethana" (http://www.nindethana.net.au) and "Australian Seed" (http://www.australianseed.com). The germination rate of all species was quantified by germinating the seeds on agar at 20 °C for four weeks. All seeds had germination rates greater than 50% (Table 1).

Germination pre-treatments were applied to the seeds of six species to maximize germination, based on the results of our previous study (Saraeian et al., unpublished) (Table 1). Seeds of *Goodenia vilmoriniae*, *Podotheca gnaphalioides*, *Rhodanthe margarethae* and *Swainsona formosa* were soaked in a 0.67 μM concentration of Karrikinolide (3-methyl-2 H-furo [2,3-c] pyran-2-one, Toronto Research chemicals), for 24 hrs, and seeds of *Heloiotropium tenuifolium* and *Schoenia macivorii* were soaked overnight in a 250 mg L^{-1} Gibberellic acid (GA3) solution and then redried at room temperature for one day prior to sowing.

Thirty seed mixes (one for each module) were made, each containing 25 seeds each of the 11 species that had germination rates > 80% and 50 seeds each of the five species with germination rates 50 – 65% (Table 1). The final sowing rate was 525 seeds per module (~1 g, ≈ 400 germinable seeds), equivalent to ~ 4 g m^{-2} or ~ 2100 seeds m^{-2}. This sowing rate was based on previous studies using seeds of annual or perennial plant species for green roofs (Benvenuti, 2014; Nagase and Dunnett, 2013; Van Mechelen, Dutoit et al., 2015; Vasl et al., 2017). Modules were sown on 8th January (summer) 2020, with seeds combined with 100 ml fine sand to assist spreading across each module surface. Seeds were then covered with an additional 2 mm layer of sand to protect them from drying out. Fifty g m^{-2} of controlled slow release fertiliser (Osmocote® Pro, Everris Australia Pty Ltd.: 15 N:1.3 P:10 K) was added to the substrate surface of each module, six weeks post-sowing.

Irrigation was applied with an automatic irrigation system with four shrubblers® 360° adjustable flow (Antelco Pty Ltd.) placed at four corners of each module to ensure even watering. Modules were irrigated for one minute three times per day (9 L d^{-1} $module^{-1}$) for the first two months after sowing to ensure germination, seedling emergence and establishment. After this phase, ten replicate modules were assigned to one of three irrigation treatments: 2 days, 4 days, and 6 days between irrigation events (irrigation frequencies) and received 1 min of irrigation (approximately 3 L water) per event (Fig. 2). The amount of water applied at each irrigation event was sufficient to restore substrate moisture to pot capacity, as evidenced by drainage from modules after watering.

2.3. Data collection and analysis

Species richness (number of species present) and abundance (number of individuals) were determined during plant surveys using a square sampling frame (50 × 50 cm) which was the same size as the module and divided into 25 quadrats (10 × 10 cm). In each module, plants were identified and counted in six randomly selected quadrats (24% of the module area, excluding the module corners). Surveys were performed twice: two months after sowing prior to starting irrigation treatments (seedling emergence; March 2020), and again five months after sowing at the end of the experiment (June 2020). Species richness and abundance were used to calculate Shannon-Wiener diversity index (H') as a measure of community structure, using the formula:

$$H' = -\sum_{i=1}^{S} pi \ln pi$$

where S is the total number of species (species richness), and p_i is the proportion of individuals of species i (relative abundance). The Shannon index measures the diversity of the community and higher values indicate greater diversity. This index is sensitive to both species richness and abundance and has higher values with greater richness, and/or more even abundance (Pla et al., 2012).

At the end of the experiment, plant cover (percentage of substrate surface covered by plants) was quantified from photos taken 1.5 m above modules surface. Photos were processed using ImageJ software (Rasband, 1997, 2018) and percentage plant cover was calculated by dividing green pixels in the photo divided by the module area.

Plant traits including plant height, leaf area (LA), specific leaf area (SLA), leaf dry matter content (LDMC) and leaf thickness were measured for each species at the end of the experiment following standard protocols (Pérez-Harguindeguy et al., 2013). Individuals with pest damage were excluded from trait measurements. Four species were excluded from analyses as they were completely damaged or lost to pests, drought, or competition, or because they did not grow to an adult plant, and we could not measure their traits.

To evaluate how irrigation frequency affects community trait composition, we calculated community weighted mean trait values (CWMs) and functional diversity (FD) of our plant mixes. CWMs express the mean trait values in communities by the absolute or relative abundance of the species (Lavorel et al., 2008; Ricotta and Moretti, 2011). CWM values were calculated for each trait in each irrigation frequency, using the “weighted.mean” function of *dplyr* package (Wickham et al., 2021) within the R programming language (R Development Core Team, 2018). Functional diversity indices of plant mixes in each irrigation frequency were calculated using “dbFD” function of *FD* R-package (Laliberté et al., 2014). As functional diversity indices including functional richness (FRic), functional evenness (FEve), functional divergence (FDiv), and functional dispersion (FDis) are complementary and describe different features of functional diversity, a combination of these indices was used (Laliberté and Legendre, 2010; Villéger et al., 2008). High levels of functional diversity indicate greater species complementarity in resource use within communities (Mouchet et al., 2010).

All statistical analyses were performed using MINITAB v.19. One-way ANOVA and Tukey-HSD post-hoc tests (P-value < 0.05) were used to compare the abundance of each plant species among irrigation frequencies. Linear mixed effect models (LMMs) and Tukey-HSD post-hoc tests (P-value < 0.05) were used to determine significant differences in all measures among irrigation frequencies, with block as a random factor and irrigation treatments (three irrigation frequencies) as fixed factors. Comparison of abundance, richness, and Shannon index

Fig. 2. Green roof modules at the experimental site of University of Melbourne, Burnley Campus, three (A), six (B) and nine (C) months after sowing (April, July, Sep 2020, respectively).

between the two measurement times (two and five months after sowing) for each irrigation frequency was obtained by performing LMMs for each frequency of irrigation, with time as a fixed factor and block as a random factor. Figures were created using Microsoft Excel and "ggplot" function of the *ggplot2* package (Wickham, 2016) in R statistical software version 3.5.1 (R Development Core Team, 2018).

3. Results

3.1. Seedling emergence, diversity, abundance and richness

Two months after sowing, 51% of seeds had germinated, resulting in 269.8 ± 9.4 seedlings per module (1079 ± 37.5 seedlings m^{-2}). Seedling emergence varied greatly among the 16 species (Fig. 3). *Podotheca gnaphalioides* had the lowest mean seedling abundance (4.0 ± 0.8), followed by *Goodenia vilmoriniae* (10.6 ± 2). While *Xerochrysum bracteatum* and *Schoenia cassiniana* had the highest seedling abundance (22.8 ± 4.3 and 22.0 ± 4.2, respectively) (Fig. 3). These two species were also the most abundant at the end of the experiment (five months after sowing), whereas *Heliotropium tenuifolium* had the lowest abundance at the end of the experiment (Fig. 4). There was no significant effect of irrigation frequency on species abundance at the end of the experiment (Fig. 4). However, regardless of the irrigation frequency there was a significant ($P < 0.05$) loss of individuals (plant death) in five (*G. vilmoriniae*, *H. tenuifolium*, *Rhodanthe margarethae*, *Schoenia macivorii* and *Swainsona formosa*) of the 16 species between the two- and five-month measurements.

Shannon diversity index was highest in the 6 days irrigation frequency and decreased significantly with 2 days irrigation frequency. However, neither abundance nor richness was affected by irrigation frequency. Shannon diversity, abundance and richness all decreased over the experimental period (between two- and five-month measurements) in all irrigation frequencies (Fig. 5).

3.2. Plant cover

Plant cover in all irrigation frequencies was greater than 81%. However, pairwise comparisons found a significant effect of irrigation treatment on plant cover. There was significantly greater plant cover in 2 days (89.3%) than 4 days (83.8%) and 6 days between irrigation (81.7%), however, these differences were minimal (5.4% and 7.6% respectively; Fig. 6).

3.3. Plant traits, community weighted mean trait values, and functional diversity

Plant height decreased significantly in response to irrigation frequency in all species except *X. bracteatum*. For five of the species, height decreased significantly with each reduction in irrigation frequency. In five species, height did not differ significantly between 2 days and 4 days irrigation frequencies but became significantly shorter when the irrigation frequency decreased to 6 days. Whereas the height of *S. cassiniana* decreased from 2 to 4 days irrigation frequency but did not decrease further when irrigation frequency was reduced to 6 days. (Supplementary fig. S2).

Leaf area was not significantly different between irrigation frequencies in all species except for *S. cassiniana* and *Trachymene coerulea*, where LA decreased with increasing days between irrigation, and *Rhodanthe margarethae* where LA was significantly higher in 4 days compared to 6 days irrigation frequency (Supplementary fig. S3). For a small number of species, there were significant differences in specific leaf area, leaf dry matter content and leaf thickness among irrigation frequencies but their changes were mixed (Supplementary figs S4-S6).

Community weighted mean (CWM) plant height significantly decreased (F-value $_{2,17.21} = 27.63$, p-value $= 0$) with 6 days irrigation frequency (Fig. 7). CWM leaf area also decreased (F-value $_{2,25} = 3.3$, p-value $= 0.053$) with reduced irrigation frequency, with the lowest value in 6 days irrigation. CWM SLA, LDMC and leaf thickness did not show significant differences among irrigation frequencies (Fig. 7).

While there were some significant differences in the responses of individual traits to irrigation frequency, there were no significant differences in functional diversity indices among irrigation frequencies (Fig. 8). Functional evenness was around 0.8, which implies a regular distribution of mean species traits within the trait space.

4. Discussion

4.1. Plant cover

High plant cover on green roofs is important to minimize substrate loss and prevent weed invasion and to maximise ecosystem services and aesthetic values (Lundholm and Williams, 2015; Nagase et al., 2013). In our green roof modules sown with a mixture of 16 annual plant species, reduced irrigation frequency resulted in lower plant cover of annuals. Reduced plant cover with reduced water availability was shown in a

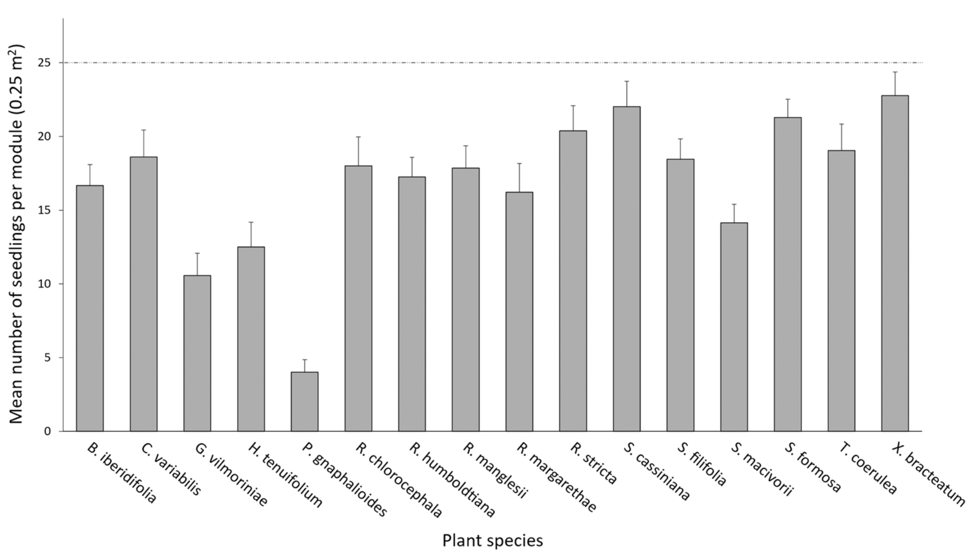

Fig. 3. Mean number of seedlings of each species in each module (0.25 m^2) two months after sowing and before the start of the irrigation treatments. Error bars indicate the standard error of the mean and the dashed line shows the total expected number of seedlings, based on germination testing and sowing rate.

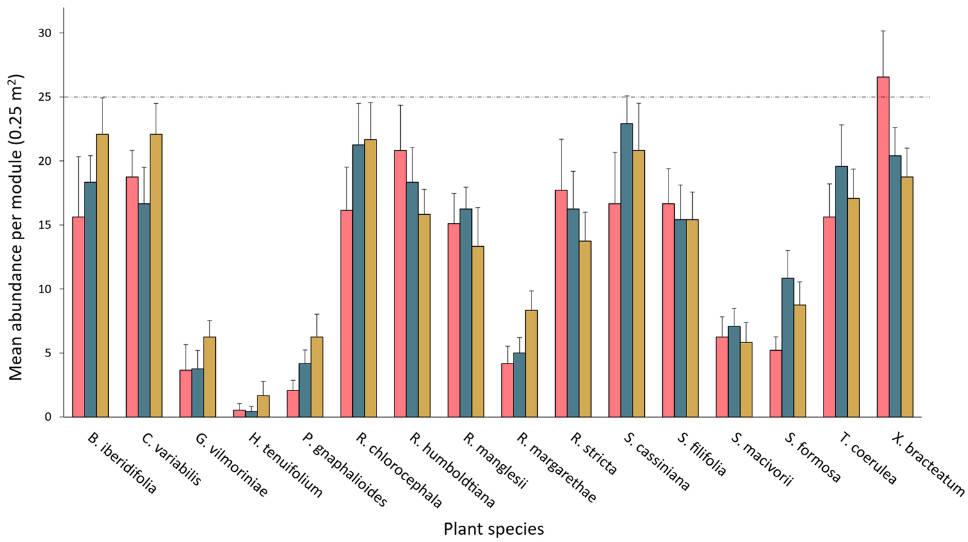

Fig. 4. Mean number of individuals (abundance) of each species in each module (0.25 m^2) five months after sowing (end of the experiment) in response to the three irrigation frequencies: 2 (pink), 4 (green), and 6 (yellow) days between irrigation. Error bars indicate the standard error of the mean. There were no significant differences between irrigation frequencies for each species (Tukey's post-hoc test; p-value < 0.05). The dashed line shows the total expected number of seedlings, based on germination testing and sowing rate.

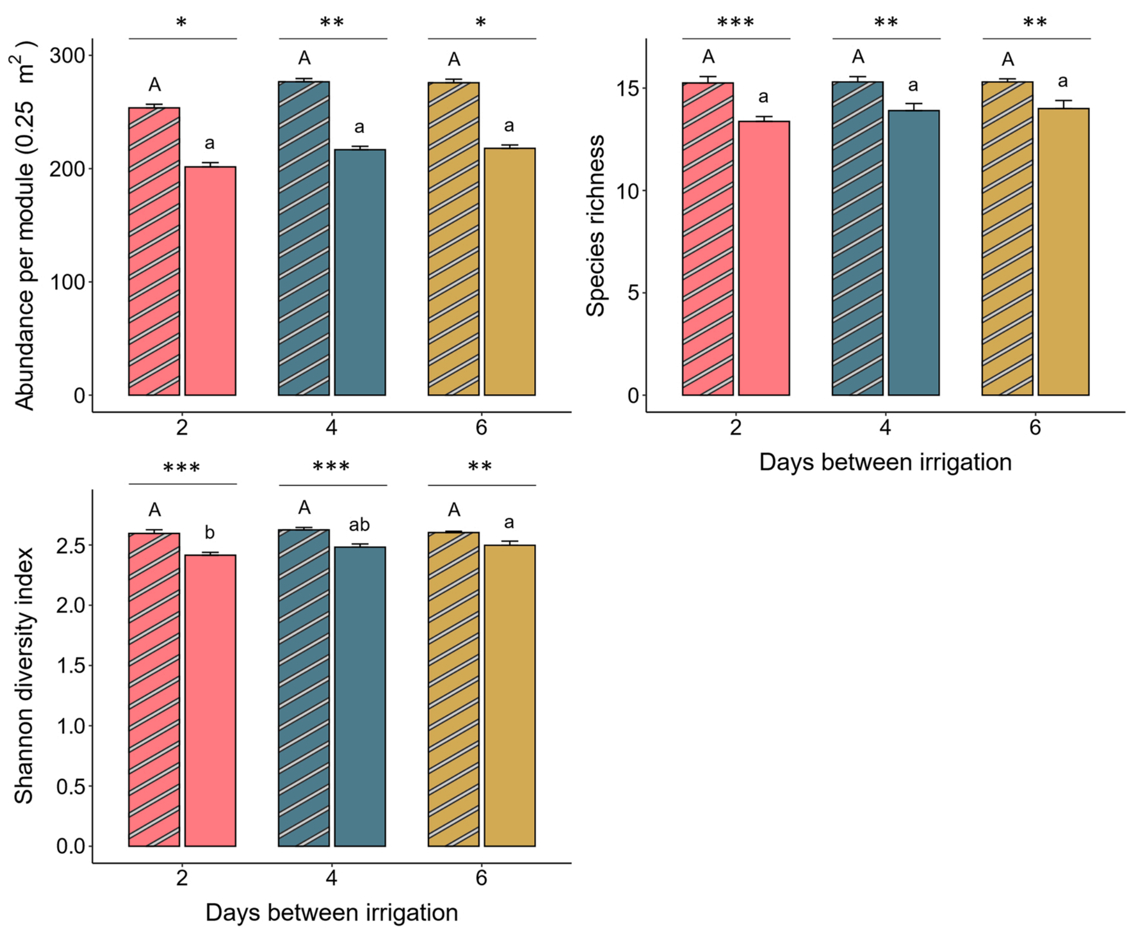

Fig. 5. Species abundance, richness, and Shannon diversity index of the annual plant mix among the three irrigation frequencies: 2, 4, and 6 days between irrigation, measured at two (striped bar) and five (solid bar) months after sowing. Error bars indicate the standard error of the mean. Significant differences are indicated by dissimilar letters above each bar (Tukey's post-hoc test; p-value < 0.05); upper-case letters denote significant differences among irrigation frequencies at two-months and lower-case letters denotes significant differences among irrigation frequencies at five-months. Asterisks indicate significant differences between two- and five-month measurements within each irrigation frequency (Tukey's post-hoc test; *** p-value ≤ 0.001; ** p-value ≤ 0.01; * p-value ≤ 0.05).

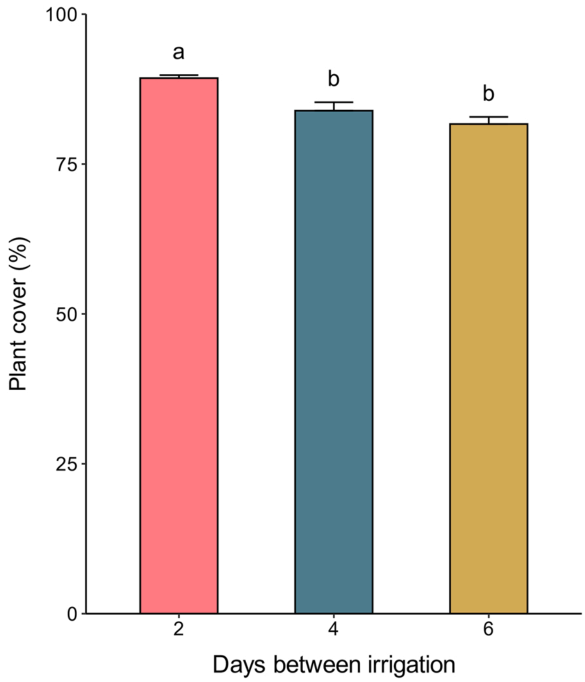

Fig. 6. Plant cover (%) in green roof modules sown with a mixture of 16 annual plant species at the end of the experiment (five months after sowing) with the three irrigation frequencies (2, 4, and 6 days between irrigation). Error bars indicate the standard error of the mean. Significant differences between irrigation frequencies are indicated by dissimilar letters above each bar (Tukey's post-hoc test; p-value < 0.05).

2-year green roof modular experiment with perennial species in a Mediterranean climate (Azeñas et al., 2018). In contrast, MacIvor et al. (2013) found no effect of water availability on plant cover of an annual and perennial grass/forb seed mix in humid continental Toronto, Canada. However, in their study, drought tolerant species became dominant when water was limiting and filled the gaps left by species which had died, and therefore plant cover was maintained. In our study, it is important to note that the reduction in plant cover with reduced irrigation frequency, while significant, was minor ($< 8\%$) and all modules achieved greater than 80% plant cover. The $\geq 80\%$ cover in all of our modules at the end of the experiment satisfies the German FLL and North American guidelines for the recommended vegetation cover on green roofs (Dvorak, 2011) and shows that our plant mix of Australian annual species can provide sufficient cover in their first growing season.

4.2. Plant traits

Plants were shorter and had smaller leaf areas when irrigation frequency was reduced, for both individual species and at the community level. However, the other leaf traits we measured, including SLA, LDMC and leaf thickness, were unaffected by irrigation frequency. Our findings of reduced plant height and leaf area with lower water availability are consistent with other green roof studies. For example, annual plants which had natural rainfall only were shorter than annual plants which were irrigated in the maritime climate of Sheffield, UK (Nagase and Dunnett, 2013). A green roof experiment in Mediterranean Spain also found that lower water availability (50% of field capacity) resulted in smaller leaf area in three out of five perennial species (Azeñas et al., 2019). Changes in plant height and leaf area in our study are also consistent with previous research on annual plants along a natural precipitation gradient in Morgan Hill, California (Lambrecht et al., 2017) or where water availability has been experimentally manipulated (Matesanz et al., 2020). As shorter plants with smaller leaves have reduced water consumption and water loss from leaves (Matesanz et al., 2020), it is likely that reduced height and leaf area enabled the annual plants in our mix to maintain high cover under the lowest irrigation frequency.

4.3. Seedling emergence, diversity, abundance and richness

Greater irrigation frequency (2 days between irrigation) resulted in lower plant diversity in our experiment. In mixtures of grasses, legumes and forbs in experimentally field-grown grassland communities, reduced diversity has been attributed to greater plant cover which creates more shade (Hautier et al., 2009) and intensifies competition for light (Rajaniemi, 2003). In plant communities consisting of both annual and perennial species, faster growing or taller species have also been shown to competitively exclude shorter species (Lamb et al., 2009). This indicates that in our study, greater vegetative cover and canopy height with greater irrigation frequency likely reduced light availability to shorter species, resulting in lower species diversity than 4 days and 6 days irrigation frequencies.

Overall, we observed greater than 50% seedling emergence, resulting in ≥ 1000 seedlings m^{-2} after two months in all of our modules (sown with 4 g seeds $m^{-2} \approx 2100$ seeds m^{-2}). This number of seedlings is greater than reported in other green roof studies (70–1000 plants m^{-2}) with greater sowing rates (5–10 g m^{-2}) (e.g., Benvenuti, 2014; Molineux et al., 2015; Walker and Lundholm, 2018), and is likely due to the daily irrigation of our modules during the first two months of our experiment. However, between establishment (two months) and the end of our experiment (five months), there was an approximate 20% reduction in species abundance in all modules (from ~ 1080 to ~ 800 – 870 plants m^{-2}), likely due to self-thinning. Greater plant density limits access to space, light, soil nutrients and moisture, and increases mortality through competition (Falster et al., 2008). Self-thinning in seed-sown plant communities dominated by forbs has been reported previously. For example, in urban parks in Sheffield, UK, meadows sown with 15 forbs and two grasses showed 72% plant loss over three years in plots sown at high density (sowing rate of 1380 seeds m^{-2}; 2.5 g m^{-2}) compared to 55% loss in plots sown at low density (690 seeds m^{-2}; 1.25 g m^{-2}) due to self-thinning (Hitchmough and de la Fleur, 2006). Therefore, it is likely that lower sowing rates of annuals on green roofs will result in similar species abundance to our study, without loss of species over time due to self-thinning.

Irrigation frequency had no effect on species abundance or richness at the end of our experiment, despite having significantly lower plant cover in the lowest irrigation frequency. However, while significant, the difference in plant cover between the highest and lowest irrigation frequencies was only 7%, which was likely too small to reflect loss of species. Another reason for the lack of difference in species abundance and richness among irrigation treatments is that water availability was not a limiting factor during seedling emergence and establishment, when plants are more susceptible to low water availability, and changes in their abundance have high impact on future community composition (Lloret et al., 2004). It is also likely that the lowest irrigation frequency in our experiment was not severe enough to result in loss of individuals or species. For example, Miranda et al. (2009) showed that 25% reduction in rainfall did not change the abundance and richness of annual species growing along in a wide range of habitats in southeast Spain; whereas 50% reduction resulted in significantly fewer individuals and species. In a green roof experiment with forb and grass mixtures in Sheffield, UK, Nagase and Dunnett (2010) observed decreasing irrigation frequency from watering once every week to once every two weeks after a 6-month irrigated establishment phase did not affect survival. However, significant reductions in survival were observed when irrigation was reduced to once every three weeks, because plants wilted and died (Nagase and Dunnett, 2010). However, in our experiment, weather conditions were relatively benign and it is likely that our lowest irrigation frequency (6 days) would negatively affect plant survival during summer months.

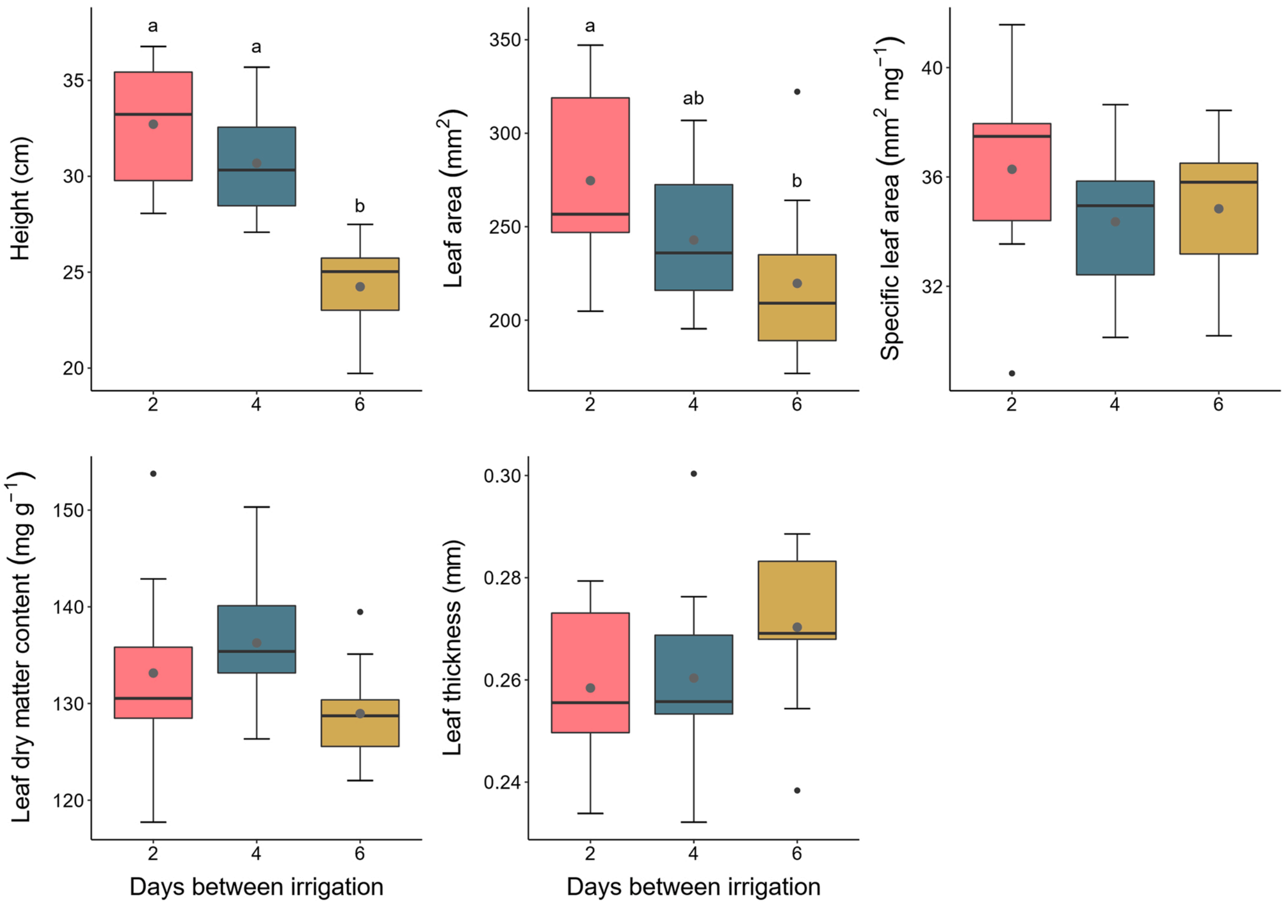

Fig. 7. Community weighted mean (CWM) of plant traits in green roof modules sown with a mixture of 16 annual plant species with the three irrigation frequencies (2, 4, and 6 days between irrigation). Grey circles and black lines inside the boxes show the mean and median (50% quantile) values, respectively. Upper and lower hinges show the 25% and 75% quantiles. Outlying points are shown as black dots. Significant differences between irrigation frequencies are indicated by dissimilar letters above each box (Tukey's post-hoc test; p-value $\leq$ 0.05).

4.4. Functional diversity

Functional diversity of the annual plant mix was unaffected by irrigation frequency, likely because of the lack of any effect on abundance and richness (the two components of the functional diversity indices calculation) (Laliberté and Legendre, 2010; Mouchet et al., 2010; Schleuter et al., 2010). Several green roof studies have suggested that higher functional diversity (or phylogenetic diversity, as a proxy of functional diversity) would likely improve ecosystem services delivery of green roofs (Cook-Patton and Bauerle, 2012; MacIvor et al., 2016, 2018; Van Mechelen, Van Meerbeek et al., 2015). For example, Xie et al. (2018) found that plant functional and phylogenetic diversity was positively related to green roof cooling. Combinations of different plant life-form groups have been shown to optimize summer roof cooling and water capture on green roof compared to monocultures (Lundholm et al., 2010). While green roof studies have not looked at changes in functional diversity in response to different water availabilities, ecological studies have shown variable effects of drought on functional diversity. For example, in Australia, plant species grown under drought stress (extreme or seasonal dryness) had the lowest functional diversity compared to species of wetter and warmer regions (Andrew et al., 2021). On the contrary, in North America, drought has resulted in greater functional diversity in six native grasslands (Griffin-Nolan et al., 2019) and no change in Californian herbaceous plant communities (Copeland et al., 2016). These inconsistencies have been attributed to differences in trait selection and functional diversity indices as well as drought severity (Griffin-Nolan et al., 2019). In our study, as functional diversity of the annual plant mixes did not change with irrigation frequency, it is likely that they will provide the same function on green roofs.

5. Conclusions and recommendations for green roofs

Regardless of irrigation frequency, all modules sown with the mixture of 16 annual plant taxa achieved > 80% plant coverage, high species abundance and diversity. While self-thinning occurred over time, likely due to competition for light and space, irrigation frequency had no effect on species abundance and richness. However, plants had reduced height and leaf area in the lowest irrigation frequency. This indicates that lower irrigation frequency can sustain diverse annual plant mixtures on green roofs during benign weather conditions. However, higher irrigation frequencies are likely to be needed during hot summer months in climates where rainfall is sporadic and/or limited. Irrigation frequency did not change the functional diversity of the annual plant mix in the first growing season. However, plant diversity and cover may change in subsequent growing seasons as the longevity of annual plant communities on green roofs will depend on seed production and their subsequent germination. While some of the annual species failed to establish in green roof modules, most species established well and showed good growth and coverage. Due to the high level of self-thinning we observed, we suggest that a lower sowing rate could be used to establish annual plant mixes on green roofs, which would reduce the cost of establishment. However, plants should be irrigated frequently during germination and seedling emergence. Most species flowered six months after sowing and likely produced viable seeds to ensure persistence on the green roof. However, longer-term studies are needed on green roofs to assess seed germination in the next growing season to

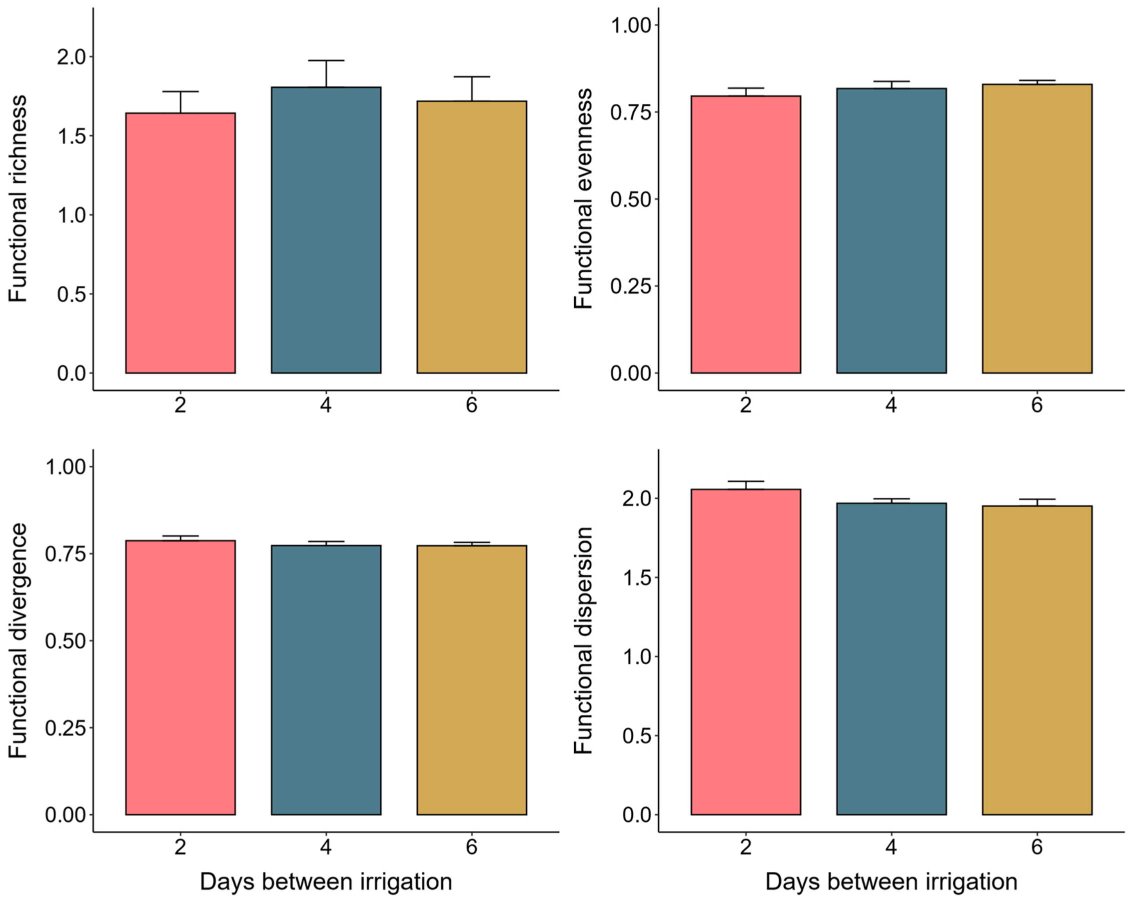

Fig. 8. Functional diversity indices of plant traits in green roof modules sown with a mixture of 16 annual plant species with the three irrigation frequencies (2, 4, and 6 days between irrigation). Error bars indicate the standard error of the mean. There were no significant differences between irrigation frequencies (Tukey's post-hoc test; p-value < 0.05).

determine if re-sowing is needed, or whether annual plant communities can be self-regenerating. Although annuals can provide high coverage and diversity on green roofs during their first growing season, mixing them with perennial plant life forms such as succulents, would provide sustained vegetation cover and flowering when annuals are dormant.

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CRediT authorship contribution statement

Zahra Saraeian: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Claire Farrell:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Nicholas S.G. Williams:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2022.127594.

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