Final Report

Demonstrating the benefits of increasing available green infrastructure in residential homes

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Public summary

Australia's housing crisis means greenfield residential development will continue. Urban planning permits smaller lots and larger houses with little space for green infrastructure. However, these new residential developments are expected to be environmentally sustainable, resilient to climate change and livable for new communities. This project seeks to demonstrate and quantify the social, economic and environmental benefits of increasing green infrastructure and how it can help deliver these expectations.

Our research team from the University of Melbourne and NatureCapital set up four work programs. The first sought to understand the values and perspectives of residents of new greenfield developments regarding public and private green infrastructure. We undertook an online survey of >1000 homeowners in new greenfield developments around Sydney, Melbourne and Adelaide, and select one-on-one interviews. A large proportion (49%) of homeowners in new residential developments would prefer a smaller footprint home with greater outdoor space. This preference was dominated by older respondents and female respondents.

Our second work program calculated the 'business case' for increasing green infrastructure and greenspace in new developments in Greater Western Sydney. Through modeling and cost-benefit analysis of house sales data we determined that homes with greater green infrastructure sold at a $120k premium to homes dominated by hard surfaces. This demonstrates a market opportunity to the construction and horticulture industry, and a real market benefit to homeowners when they sell.

The third work program studied the microclimate impacts of different green and blue infrastructure decisions in private outdoor spaces. We studied skin burn risk, air temperature reduction and human thermal stress. Artificial turf presents a very real risk of skin burn on hot, sunny afternoons as surface temperatures can exceed >70°C. Private backyards with natural turf (irrigated or not) presented no skin burn risk and provided cooler air temperatures. Misting private backyards can significantly reduce human thermal stress on hot, sunny summer days, but misting must be frequent to be effective. Adding green facades did not provide cooling benefits to a private backyard, but significantly reduced wall surface temperatures on hot, sunny summer days.

The fourth work program demonstrates a simple method to retain stormwater runoff within the private lot through the installation of an infiltration trench along the front of the property. This blue infrastructure solution can support water requirements of nearby vegetation but also support reduced flood risk and improved stream and waterway ecology.

The project recommends that Hort Innovation work with the developer and construction industry to provide smaller footprint home options in new residential builds. This project has demonstrated the market demand for this and the social and environmental benefits gained from greening the outdoor space. Importantly, this project recommends that the business case provided by hedonic analysis be repeated in Queensland, Victoria and Western Australia as this is likely the most impactful element to change developer an builder behavior and acceptance. This project also recommends that infiltration trenches be demonstrated in other residential developments and soil types to provide a future option for stormwater runoff and flood risk reduction, a contemporary state and federal urban planning issue.

Our project culminated in an industry workshop involving state and local government planners and policy makers, with landscape architecture, engineering, and water industry practitioners. There is demand for project events and publication outputs to guide industry and future policy and planning decisions. The 'Guide to the benefits of private green Infrastructure in new residential developments' will be published in late 2025. Our scientific publications, presentation and industry articles provide a scientific evidence-base platform from which advocates and decision-makers can lobby and encourage greater uptake and consideration of green infrastructure in private residential developments throughout Australia.

Keywords

Greenfield development; resident perspectives; values; hedonic analysis; cost-benefit; house resale premium; human thermal stress; skin burn risk; misting; zero runoff

Introduction

In October 2021, Hort Frontiers released a request for proposal (RFP) GC21000 “Demonstrating the benefits of increasing available green infrastructure in residential homes” to be funded by the Green Cities fund. The request was for:

> “*The research project will undertake demonstration research - the value of an elevated level of green infrastructure in a residential home. This project will assess the potential to elevate exposure to green space and the associated health benefits in a residential environment.*
>
> *Mirvac (developer) and the Green Building Council of Australia (GBCA) have the intent of developing a Future Home at the Olivine Development (Victoria) in 2021/22 with the aspiration that it can play a key role in steering the construction default in new urban developments across the country towards more sustainable outcomes. Their current focus is attaining an 8-star energy rating for the building and the sustainability of construction materials. However, green infrastructure and its potential contribution to improved energy ratings and sustainability outcomes are currently not being considered.*
>
> *Through this project and Hort Innovation involvement the benefits that can accrue from an increased level of green infrastructure over the current default could be included in the overall Future Home initiative.”*

The University of Melbourne, School of Agriculture, Food and Ecosystem Sciences submitted a proposal that following negotiations with Hort Innovation was accepted and funded over a year later in December 2022. The research team was able to secure co-contributions from three Victorian water authorities (South East Water, Yarra Valley Water and Greater Western Water) two state government entities (Victoria – DELWP; New South Wales – DPI) and both The University of Melbourne and the University of Technology Sydney.

The proposal was focused upon understanding the benefits of green infrastructure in private lots of new residential developments in outer greenfield locations of state capital cities. Greenfield residential estates on the outskirts of Australian cities are often the first step on the housing ladder for younger people and new immigrants to Australia (Keane & Birrell, 2010; Urban Development Institute of Australia, 2023). These new residential estates are unique in several ways. They form an entirely new community of residents. The green infrastructure in these new estates (parks, street trees, and private gardens) are typically grown anew from juvenile plants (Parsons et al., 2023) and are typically surrounded by construction activity for many years. Additionally, these new greenfield residential estates are often disconnected from other suburbs and commercial centres unless residents have private vehicles. In Australia, greenfield residential estates are also often culturally and linguistically diverse communities (Australian Bureau of Statistics, 2021).

The proposal was structured around assessing four potential types of benefit from increasing green infrastructure in outdoor spaces of private homes in greenfield developments. These formed the four work packages of the project and the four sections of this Final Report.

1. Health and well-being benefits (Work Package 1)

1.1 Homeowner greenspace preference and wellbeing research:

Anecdotal evidence from a developer (Mirvac) following their engagement with new communities, suggests that a large percentage (20-40%) of new homeowners would prefer to have purchased a home with a smaller building footprint on the lot. Within this group, we hypothesised that many homeowners will state a desire for larger private greenspace and green infrastructure as the driving factor in wanting a home with a smaller footprint.

We hypothesised that level of education and family income will significantly correlate with the desire for more green infrastructure in the public or private realms of new residential developments. Furthermore, that level of education and income will significantly correlate with the level of satisfaction with, and nature connection to public and private greenspaces in new residential developments (Kendal et al., 2022; Saldarriaga et al., 2020).

1.2 Private and public green infrastructure for well-being and nature connection research:

We hypothesised that there will be a section of the community in new greenfield residential estates that highly values private greenspace and local public streetscapes and green spaces for the restorative benefits and nature connection that they provide. Our hypothesis is that the socio-economic status, level of education and cultural diversity of homeowners will correlate with the use of, well-being ratings and nature-connection associated with both private and public green infrastructure (private gardens, streetscapes and local parks) (Kendal et al., 2022; Saldarriaga et al., 2020). For those sections of the community that do not value, or are dissatisfied with their public and private greenspaces, we hypothesised that this will correlate with expressions of safety and overall wellbeing (Li et al., 2021).

2. Market and industry benefits (Work Package 2)

In an era where community environmental sentiment is at an all-time high, planners, developers and property purchasers are faced with the question of whether they should "go green". If property developers had a better understanding of the monetary cost and benefits of including sustainability features such as green infrastructure in their projects it may encourage greater inclusion. This project aims to increase and accelerate the use of green infrastructure in residential buildings by demonstrating a financial benefit to developers.

Economic researchers have long used hedonic modelling to understand the role that various property attributes play in determining the overall property value. Many previous hedonic studies, including our own, have found that environmental amenity (proximity to greenspace or other natural features) can increase property prices. Our understanding of the impact of green infrastructure situated within a residential property is more limited.

This study will use hedonic modelling to determine how green infrastructure impacts on the marketability and pricing of residential properties. It will provide an estimate of the price premium that purchasers are willing to pay for green infrastructure in residential properties. It will also provide new information on consumer preferences and guidance on how green buildings can be configured to align with consumer preferences, as well as the profit margins that can be expected by developers who implement different types of green infrastructure.

3. Microclimate and cooling benefits (Work Package 3)

3.1 Artificial turf versus natural turf research:

Artificial turf is commonly used in private green spaces because it is believed to require little maintenance and no inputs of water and fertilizers. However, artificial turf has been reported to pose a risk of skin burns and heat stress in children's playgrounds and sports grounds in summer. In this part, we aim to quantify the risk of skin burns and heat stress of artificial turf as compared to unirrigated and irrigated natural turf in a backyard environment.

We set up experimental plots at the Burnley Campus of the University of Melbourne to enable the direct comparison of the three treatments: artificial turf, unirrigated and irrigated natural turf. The turf surface temperature and human heat stress were monitored continuously in each plot for 51 days in the 2023/24 summer to quantify the risk of skin burns and heat stress. We hypothesised that artificial turf would pose higher risks of skin burns and heat stress than unirrigated and irrigated natural turf. The results will have strong implications for the safety of using artificial turf in backyards.

3.2 Private green space microclimate research:

Private front yards and backyards in new greenfield residential developments are surfaced with a mixture of traditional grass turf, paving, gravel or artificial turf. The type of surface cover in these outdoor spaces can have a large impact upon the microclimate and amenity of the outdoor space during summer months. The area and orientation of front yards and backyards can also influence their microclimate. In this part, we aim to understand the impacts of different design factors such as surface type, area, and orientation on the air temperature and human heat stress in private front yards and backyards in summer.

We recruited nine homeowners at the Olivine Estates in Donnybrook, VIC, to participate in this research. We installed climate stations in their front yards and backyards to continuously measure air temperature and human heat stress in February 2024. We hypothesised that backyards and front yards that have irrigated vegetation, are large, and unexposed to the east and west aspects would have lower air temperature and human heat stress. The results will help identify the design factors of private front yards and backyards that are conducive to reducing air temperature and human heat stress in summer.

3.3 Misting and green façade cooling research:

Courtyard areas in private residential areas are often referred to as the outside room. In summer, depending upon wall and courtyard aspect to the sun, they can become excessively warm leading to less use. We hypothesised that west- or north-facing courtyards and patios will be 2-3 °C cooler when the walls are covered in green facades and misted from above, as compared to bare paved and bare wall courtyards. The smart misting of potable water in response to air temperature thresholds (e.g. >28 °C) will use very little water to provide direct and well-timed cooling benefits to home-owners using the courtyard on summer days, and the addition of green facades will provide two benefits – i) reduced solar warming of courtyard walls that would otherwise re-radiate heat into the courtyard, and ii) leaf and twig surfaces for the misted water to settle on and evaporate from, thereby further cooling the plant and air within the courtyard.

Combining the air and vegetation cooling benefit of misting with green facades mean courtyards can become a more amenable and valued outdoor space all year round. This will leverage previous learnings from the deployment and study of this method and associated technology at the Aquarevo Demonstration House of South East Water undertaken in collaboration with this University of Melbourne research group.

4. Water cycle benefits (Work Package 4)

In new residential developments, the impervious roofs of houses can cover >60% of the land surface. These roofs therefore create the majority of stormwater runoff that can damage urban waterways and lead to localised flood risks. By retaining roof runoff within new residential buildings, we can reduce waterway damage and flood risks and at the same time provide a valuable water resource to maintain and support the performance of private green infrastructure systems.

This is the WIN-WIN environmental business case that blue-green infrastructure can provide. We hypothesised that we can reduce roof rainwater runoff over a 12-month period to 10-20% of a standard private home, simply by integrating two rainwater tanks for appropriate indoor (e.g., toilet flushing and hot-water showers), and outdoor uses (smart irrigation of turfgrass areas with deep soil substrates and overflow trench retention systems). By creating space in rainwater tanks using smart technology (such as Tank Talk®) that is integrated to rainfall forecasts, increased retention can be achieved compared to passive systems, and the benefit used for the house and landscape instead of loss to stormwater. This approach will work towards a *net zero additional runoff* (i.e., maintain runoff at the volume that would have occurred naturally) and provide huge environmental benefits to downstream waterways.

Irrigation is a valuable resource but requires specific design of soil, substrate, and vegetation in supporting green infrastructure systems, to realise these benefits. This will also leverage the smart tank (Tank Talk®) technology developed by South East Water which has to-date demonstrated 10-20% run off reduction across the estate.

Project delivery

The project milestones were similarly structured around these four work packages. Project monitoring and evaluation led to some revisions to work packages (two contract variations) in response to changes in industry support and time delays associated with finding alternative industry support for demonstration sites. However, the vast majority of the above proposal has been delivered and this Final report remains structured according to these four work packages.

1. Health and well-being benefit

Methodology (Work Package 1.1 & 1.2)

Perspectives on private and public green infrastructure in new greenfield developments

Understanding how residents value and interact with green infrastructure in these new greenfield estates is crucial for future urban planning. Effective green infrastructure planning on private and public property can better foster a sense of community and belonging, and positively contribute to the wellbeing, social cohesion, and quality of life of the residents. Understanding this in new residential communities is important given their greater socio-cultural diversity. There are recognised differences among culturally diverse communities in how they value nature (Egerer et al., 2019; Ordóñez Barona et al., 2023). In a systematic review of how different cultural groups value the urban forest, Ordóñez-Barona (2017) identified that, in general, ethno-culturally diverse people value the social attributes of urban areas and find the functional aspects and social integration more meaningful. Private gardens are most valued for recreation, relaxation, socialisation, connecting with nature, aesthetics, and ecological function (Coolen & Meesters, 2012; Hanson et al., 2021; Šiftová, 2021).

Nature connection – which has often been treated as a key aspect of wellbeing and life satisfaction (Barragan-Jason et al., 2023; Pritchard et al., 2019) – differs among cultural and demographic groups so is worth examining in culturally diverse communities (Barthelmess et al., 2013). In the UK, large survey results have shown that nature connection dips in teenage years and then increases across the lifespan (Richardson et al., 2019). In Melbourne, Australia, researchers have found that nature connection differs among demographic groups: for example, younger adults with part time work and who have lived in Australia for a short period of time are the most connected to nature, while students who are long-term residents in Australia are least connected with nature (Selinske et al., 2023).

In this social research (qualitative and quantitative) work package, we aimed to:

1. better understand the influence of socio-cultural factors and natural, social and experiential values on green infrastructure preferences and future home preferences of residents in new developments.
2. capture the perspectives of these residents ‘in their own words’, to honestly represent the ways they value public and private green infrastructure in these newly created communities.

To deliver the first aim, we undertook a quantitative approach through an online panel survey of more than 1000 residents of new greenfield estates in Sydney, Melbourne and Adelaide. We collected responses from people living in recently developed (<15 years old) greenfield residential estates across the outer urban suburbs identified by postcode. We collected responses from 1041 participants through an online survey panel managed by a market research company (Pure Profile, www.pureprofile.com). Human ethics approval was granted by the University of Melbourne (Project ID 27430). The full online panel survey questions and response options are provided in Appendix 1.

We hoped to recruit 25% of our respondents from homes that spoke a language other than English. In Australia, 25% of residents speak another language at home, and in greenfield developments this is generally higher (Australian Bureau of Statistics, 2021). Despite concerted efforts, we were only able to recruit 11% of participants who spoke another language at home (Table 1). The survey consisted of demographic and socio-cultural attributes (age, gender, education, income, languages spoken at home, country of birth, ownership of residence), public and private green infrastructure interactions (frequency and activity), core nature values, valued attributes of these landscapes, nature connection and life satisfaction.

We created a single measure to explore preference for choosing a hypothetical future home. We asked respondents to “Imagine you are buying a new house to move into in the area where you currently live, on a 450 m^2 block of land”. We presented three options of site plans with varying dwelling to plot size ratios, based on existing options in new greenfield residential estates in Australia (Figure 1). We asked respondents which of the site plans would be most preferable to purchase. A follow up question asked about factors that motivated their choice, including cost of maintenance, desire for more/fewer plants, and space for activities.

To deliver on the second aim we undertook a qualitative approach through one-on-one interviews of residents of the Mirvac Olivine estate off Donnybrook Road, Wallan. The interviewees values associated with public and private green infrastructure covered 1) psychological and experiential values, 2) natural and ecological values, and 3) social values.

Table 1. Online panel sample characteristics

	Frequency	Percent
State/territory		
Victoria	563	54.0
New South Wales	352	33.8
South Australia	127	12.2
Missing	0	0.0
Ownership of residence		
Owned outright	180	17.3
Owned with a mortgage	552	53
Rented	300	28.8
Occupied rent free	6	0.6
Other	3	0.3
Missing	1	0.1
Gender		
Male	330	31.7
Female	706	67.8
Non-binary	3	0.3
Prefer not to say	2	0.2
Missing	1	0.1
Age		
18-20	36	3.5
21-29	181	17.4
30-39	376	36.1
40-49	228	21.9
50-59	119	11.4
60-69	63	6
70 or older	36	3.5
Missing	3	0.3

	Frequency	Percent
Household income ($AUD)		
Nil or negative income	25	2.4
$1 - $7,799	8	0.8
$1 - $15,599	18	1.7
$15,600 - $25,999	34	3.3
$26,000 - $51,999	137	13.4
$52,000 - $77,999	172	16.8
$78,000 - $103,999	223	21.8
$104,000 - $155,999	228	21.9
$156,000 or more	204	19.6
Missing	1	0.1
Education		
Less than Year 12 or equivalent	121	11.6
Year 12 or equivalent	204	19.6
Vocational qualification	228	21.9
Undergraduate degree	295	28.3
Postgraduate degree	183	17.6
Missing	11	1.1
Country of birth		
Australia and New Zealand	717	69
West Europe	39	4
East and South Europe	18	2
West Asia / Middle East	26	2
South Asia	93	9
Southeast and East Asia	69	7
Other	80	7
Language spoken at home		
English only	902	89
Other language or English	110	11

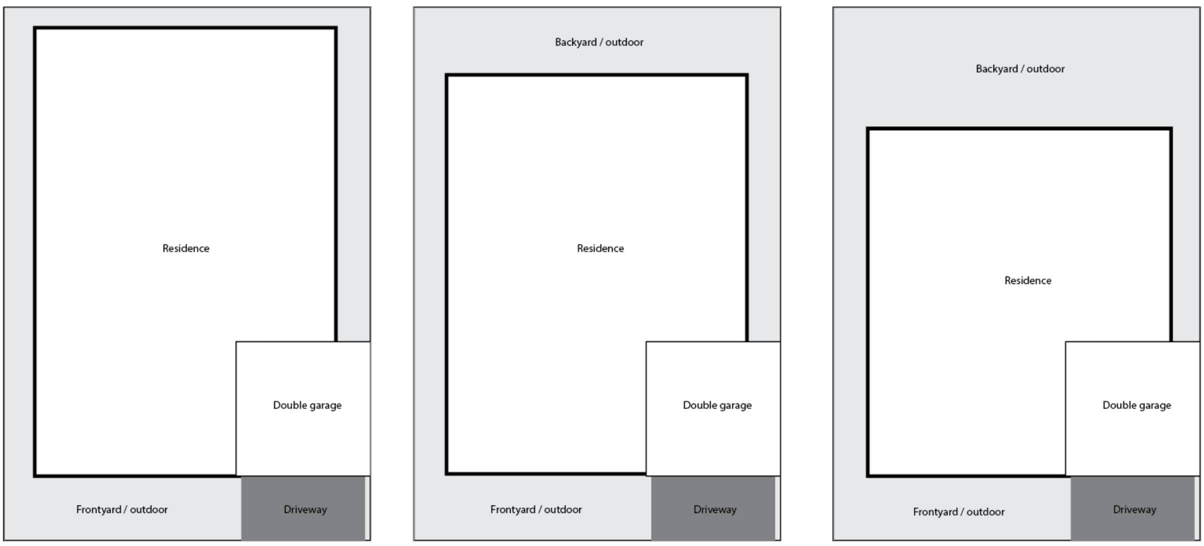


Figure 1. Survey question asking respondents which of the three options they would choose if buying a new house in their estate

Results and discussion (Work Package 1.1 & 1.2)

Socio-cultural factors and values influence green infrastructure and future home preferences

Respondents spend more time in their backyards than in their neighbourhood green space. 52% of respondents visit neighbourhood green space frequently, at least once per week, and 64% spend time in their backyard at least once a week (Figure 2). 19% visit neighbourhood green space rarely or not at all and 14% spend time in their back yard rarely (a few times a year or less) or not at all. Overall, respondents valued the attributes of public green space more than private green space (Figure 3).

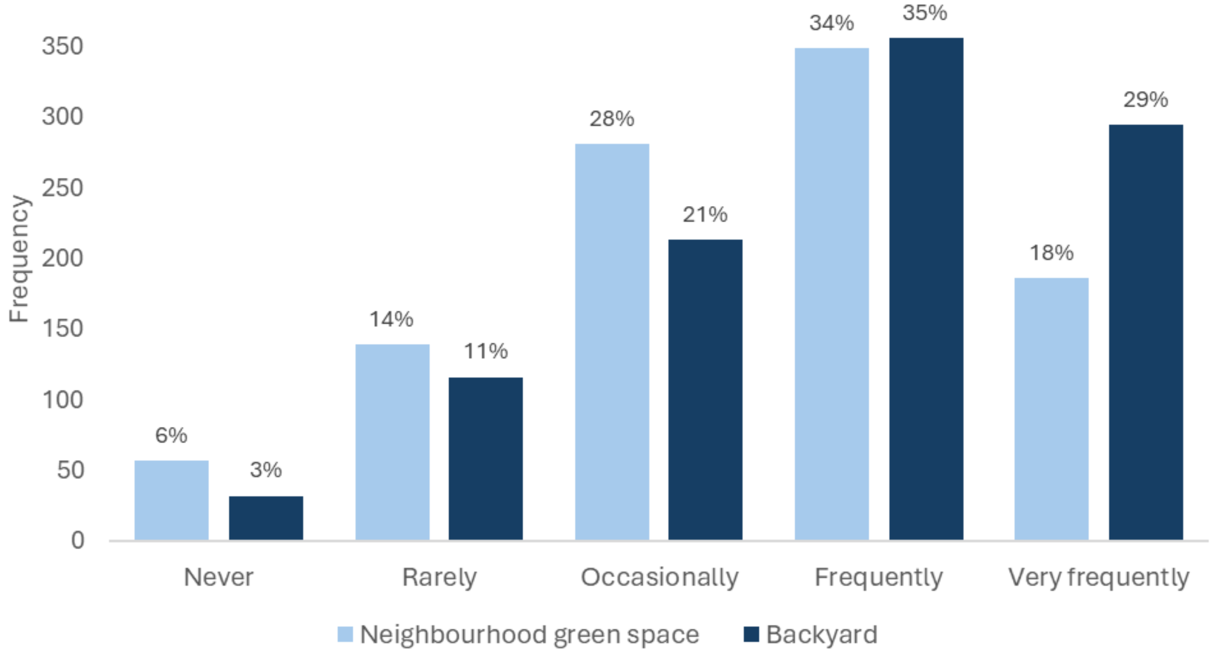


Figure 2. Frequency of spending time in backyard (for more than 10mins) and frequency of visiting public green space in the neighbourhood. Note: Rarely = a few times a year or less; Occasionally = monthly to fortnightly; Frequently = weekly; Very frequently = daily or multiple times per week.

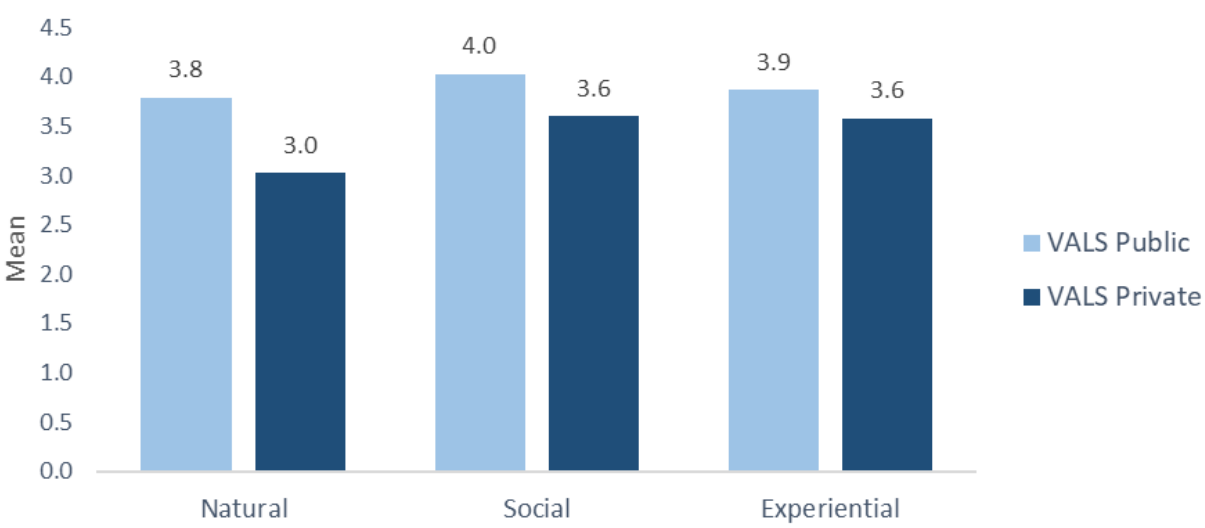
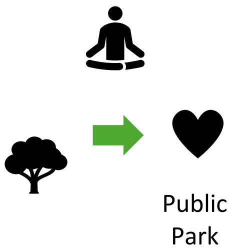


Figure 3. Mean scores of valued attributes (VALS) of public and private green infrastructure.

Regression analyses were used to predict Nature, Experience and Social value attribution for both public and private green space, as well as the frequency of interacting with both public and private green space.

The intrinsic value of green space



Valuing nature for its spiritual value and existence is highly and positively associated with valuing attributes of natural, social, and experiential attributes of both private and public green space.

Intrinsic valuing of nature (that is, valuing nature beyond its use and benefit to humans) was positively associated with valuing the natural attributes of public green space.

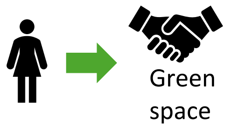
However, this intrinsic valuing of nature was negatively associated with valuing the natural attributes of private green space.

Similarly, this intrinsic valuing of nature was also negatively associated with experiential attributes of both public and private.

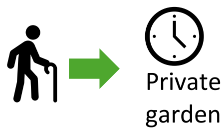
This can be interpreted as meaning that those residents who value nature intrinsically consider natural features (native plants, animals, large trees) in public spaces as important, but not so important in private space. Furthermore, they do not consider the human experience of public or private space to be important attributes (aesthetic appreciation, rest and relaxation).

Some socio-cultural differences

There were some significant socio-cultural effects in the analyses.



Women value the social attributes (such as space for interaction, socialisation, and safety) of both public and private green space more than men.



Older people value the natural attributes and experiential attributes of public space more than younger people, and older people spend more time in private green space than younger people. There were no effects of household income.

Finally, those with lower education value the natural attributes of public green space slightly more, and those with a higher level of education visit public green space more frequently.

There were some inconsistent but interesting results for country of birth. Compared to people born in Australia or New Zealand: people born in West Europe and Southeast Asia/East Asia value social attributes of public green space less; those born in West Asia/Middle East value experiential attributes of public green space more; and people born in South Asia value natural and experiential attributes of both public and private green space more.

Future home size and private green space preferences

Nearly half of the 1041 respondents (49%) would prefer to buy a property with a small residence and large outdoor area if they were buying a new house in the same neighborhood (Table 2). Key motivators for this choice were having space for outdoor activities, and a desire for more plants and trees in outdoor space. Cost of maintenance was a key motivator for respondents who would prefer a large residence and small outdoor area.

Table 2. Response frequency to question on preference for future home and backyard size.

Preference	Number of respondents	Percentage (%)
Large Residence with small outdoor area	101	10
Medium residence with medium outdoor area	416	41
Small residence with larger outdoor area	495	49

Regression analyses were able to identify that:

- Respondent age and gender had significant effects on future home preference.
- Older people and women were more likely to choose a smaller house size with a larger backyard.
- Respondents who spend more time in the garden, feeling more connected with nature, and valuing nature for its intrinsic value, were also more likely to choose a smaller house size and larger backyard.

Unexpectedly, there were no effects of the valued attributes of private green space on future home preference. There were also no effects of country of birth or other demographic factors.

'In their own words' - Values expressed for public green infrastructure

The interviewees values associated with public green infrastructure covered:

1) psychological and experiential values,
2) natural and ecological values,
3) social values

Psychological and experiential values

All participants reported valuing psychological and experiential qualities of their interactions with public green infrastructure in the estate. Several interviewees reflected on how interacting with the public parks in the estate contributed to their overall wellbeing or quality of life

> *"gives me this positive feeling, the openness and, it's the happiness that it brings in you."* (P13).

There were several aspects to wellbeing that were raised by participants, such as mental health, happiness, freedom. This included the sense of calmness and relaxation felt while in the park or open space:

> *"And they do have a very calming effect on myself because I do like to do the, just sit there do a deep breathing, just calm and relax because it's such a tranquil place and invariably there aren't a lot of other people there."* (P02)

Having the space for recreation, exercise, and simply getting a break and "escaping" from indoor environments also fostered a sense of wellbeing and relaxation in the public parks.

> *"So I think if we didn't have these green spaces, I'd be like either stuck inside watching TV or just in a corner rocking. So it's nice to have an outlet like just to go somewhere different."* (P07)

Feeling connected with nature in public green space was important for several participants. A key value for many participants was the sense of identity, belonging and place that the public green spaces afford. This was described in different ways, including having a sense of ownership over the green space or estate:

> *"It genuinely feels like it's part of our estate… it makes you feel like it's your place"* (P07)

Natural and ecological values

Only one participant, who was particularly passionate about biodiversity and wildlife in the estate, emphasised the importance of natural values for the sake of ecological health and wildlife conservation:

> *"To me, nature is really important, the diversity in it. And there needs to be more of that, that importance impress on people so that they understand that putting down fake grass is of no benefit…. It produces no habitat for any insect or creature and it doesn't reduce maintenance"* (P2)

Other mentions of natural and ecological values were raised in the context of interactions and experiences in nature. Several participants discussed the importance of wildlife habitat due to their desire to increase the frequency of interactions with wildlife:

> "*I suppose just the other thing that's missing it's just the native bird life as well. That would be good if you could wake up and have rosellas in your backyard and things like that."* (P11).

Similarly, for participants who spoke to the value of having large old trees in the estate, these were mostly framed around the experiences or feelings they afford:

> *"We've got very old trees over here in this park. As you can see, I don't know, more than 200 years some of them and it's just beautiful, amazing, brings a different feeling."* (P13)

Open green space in the public parks was valued by many of the participants, for different reasons. For some participants, the open space in the estate encouraged a sense of connection to community or reduced the feeling of loneliness:

> "*[this park] is much more open. And it's not too shady at the same time. You can just keep an eye on the cars, and you have some sort of sound going around you as well which doesn't make you feel like you're lonely… it's nice to be here. Just in the open space".* (P01).

Other participants valued the openness of green spaces for recreation:

> *"I love open spaces…. Because since my childhood I've been playing in the play field. I used to play hockey, used to play cricket, I used to go out for a long walk in the stadium, I used to go round and around, back home in India. So since then, I'm very much fond of open spaces."* (P16)

Social values

Social values associated with public green infrastructure were most frequently raised and so probably hold most importance for participants. The most common social value was as a space to spend time with friends, family, children, and neighbours:

> *"…we'll just meet here with the neighbouring people. I know the neighbours just across the road across the park… just an unplanned meeting usually and it's nice to have the kids and families here in the evening."*

The other major theme relating to social interactions was that public green spaces in this new residential estate supported community connectedness and relationships. This was expressed in several ways. First, public parks enable opportunities to meet new people (neighbours) and form friendships:

> *"When you're in a park, you're probably can understand that mostly people that are going to be coming here are going to be from around here as well. So it's easier to introduce yourself and I guess get to know exactly where the other person is from."* (P08)
>
> *"At least once you come across and you exchange a greeting, the next time they will stop and exchange a greeting, and third time…. If I go back the last three months or so, I think I have made friends with at least 10 new people, which is good, through the parks."* (P15)

The second way that public green spaces support community connections is by giving a "common connection" (P10), a space where residents can see and spend time around other members of the community*:*

> *"it just makes this community feel more alive because there's people around."* (P03); "*sometimes we don't even play – she doesn't play at the park. We just go down there and see what's happening down there."* (P10).

For other participants this community connection was more explicit, and particularly important for new members of the community:

> *"From a migrant's point of view, and also a new migrant's point of view, a common place like a park is very important. Because then they feel as if they have got a common connection. That gives them a common connection that they are at the same place. And people are not very comfortable inviting the new acquaintances to their homes, but then they come to know about each other, meeting in the park, talking, playing games or something or even story sharing, or talking about their difficulties at home that they're facing. So it's gradual trust building happens in these green spaces."* (P15).

'In their own words' - Values expressed for private green infrastructure

Values for private green infrastructure were discussed less than public green infrastructure in the interviews. This may be due to the interviews took place in public spaces. In general, private green space was considered most important for psychological and experiential values (in particular wellbeing and relaxation) and for socialisation. Private green space contributes to wellbeing through simply being able to have access to the outdoor environment to "*just get some fresh air and enjoy some nature"* (P04), and to have a space that promotes relaxation:

> *"Definitely just makes me feel relaxed. When I'm in the garden, whether with the girls or alone, generally there's no worry about anything else that I need to do. It's just me relaxed and just enjoying whatever is happening."* (P09)

Participants described these benefits occurring through the enhanced sensory experience of being in the outdoors in their home environment:

> *"It lifts the spirit… I struggled with winter this year, it really didn't help with my mood at all… And I really found that as soon as that sun came out, it lifted the beat in my feet. Days like today where you've got that breeze, where you've got that sun, and just the smell as well. That's a big thing for me. Just having certain smells and, that's one thing that I'll put in, just a couple of shrubs or something that will generate a smell. Jasmine is big for me. I love the smell of jasmine. That's a childhood thing. So yeah, if your backyard can entice you out then it does lift your spirits."* (P11)

Socialisation was another key value of private green space. Outdoor green space at home provides a space to spend time with friends and guests, but is also an important space to connect with family members living in the same home:

> *"That's how we feel connected with the family. That's the only time when we sit together, having some drinks together or having a dinner together sitting in the backyard space, or even doing gardening together. The three year old will come and water the plant. Because he himself gets wet also. But he's still doing it with us. And then he'll call his dad too and mom too, he'll say, Come here I'm doing watering. Yeah, it brings a family thing together in the backyard."* (P15)

Naturalness and green were noted as important for some participants, but this was less about ecological values, and more about aesthetics (e.g., flowers and greenness, "*It's just nice to see colourful flowers or trees*", P01) and provision of services, such shade and temperature ("*I would think of something more natural around the house, otherwise it gets a bit hot*" P05).

Care was also an important factor for why individuals value private green space. In contrast to how individuals valued care in public green space, at home this is expressed through caring for and growing plants (including lawn, vegetables and fruit trees) and nurturing gardens over time. Participants expressed relations with their gardens, with expressions like, "*it's like our baby*" (P09).

> *"I always enjoyed growing plants and just seeing them grow in the period of time and watering them... And kids enjoy that as well when it's time to water the plants and they would help me out which is nice and yeah, just to have them growing and don't give out vegetables straightaway. They might not give out in couple of months because the season but it's just nice to see them grow in your backyard and something's growing and just getting healthier."* (P01)

'In their own words' - Interaction between public and private green infrastructure values

Interviewees expressed some interrelationships between values for public and private green infrastructure in the estate. Some interviewees spoke of how the private and public spaces complemented one another, while for others there were conflicting values or trade-offs between the two.

A recurring theme was that nearby and available public green space made up for and balanced out the small backyards that are the norm in the estate. Participants noted that without the public green space they would not have space for activities such as barbequing or playing sport. And because of the proximity to local neighbourhood parks, there is a reduced need for private space to afford other activities like exercise. However, if there was limited access to public green space, participants acknowledged that there would be a need for more private outdoor space for these social and recreation activities.

> *"Yeah, so we make use of both spaces. If [the backyard] was even smaller, there's enough green space out here that we could use. I think we'd probably use it more for barbecues and things like that, if we didn't have backyard space."* (P03)

> *"Initially, I thought I was going to put a little gym area where the barbecue is going to go. And I thought, why? Nature's my gym. I'll go for a run, there's all this equipment… I don't need a playground for when my baby's born. I've got playgrounds down the road. So we're just setting it up as a way that is a space that we're going to use that isn't so much something that we need to go out for."* (P04)

> *"We just come here just to use the space, the grass sometimes. As you know, the houses are like boxes. The backyard is very small. So these are very, very essential and important, these green spaces, because otherwise you can't do anything in your house because the yards are too small now. So we utilise it a lot."* (P10)

> *"Absolutely. If we didn't have access to the parks, I guess we would have more green in the backyard. So we're benefiting from these parks. And having our house as low maintenance."* (P13)

While the spaces afford different activities, some participants also felt that private and public spaces suit different moods, energy levels, or weather conditions.

> *"It's more of a preference to come to the park and then the weather was good. But if it's just breezy or it's, it's cold, then we'll just play in the backyard."* (P01)

> *"If come back home from work. I might be too tired to come here to the park. I'll sit at the back yard. If I have the energy I would prefer coming out here. Spending time walking and going throughout the parks."* (P05)

There were also some tensions between the public and private spaces. For participants whose homes were very close to the park, the noise and activity in the parks in the evenings disturbed the peace of their private space.

> *"We know that 930 to 1030 there's still going to be kids in the park. Young children. So like that house next door to us, they've got young kids and like most summer nights we're out here asking people to be quiet. Because we just like we can't settle. We can't have our windows open. We can't, you know, can't relax at night until people are out of the park."* (P07)

Due to these overlapping values and affordances, and that the neighbourhood parks are so close to people's homes, several participants commented that the parks feel like an extension of the backyard and feel a sense of ownership of the neighbourhood parks.

> *"So, yeah, just simply, it doesn't even feel like you're going to the park, it feels like part of the house. You know? Yeah, we're here all the time. We don't have to decide that we're going to the park or anything special. We just walk here, walk around."* (P13)

2. Market and industry benefits

Methodology (Work Package 2)

Hedonic modelling of market benefits from green infrastructure

Hedonic modelling is widely used for valuation in various economic contexts, particularly in real estate markets where it is used to assess how different property attributes contribute to overall value. Hedonic modelling quantifies how specific characteristics, such as location, size, and amenities, influence housing prices, allowing for a nuanced understanding of market dynamics (Chau & Chin 2003, Branzini et al. 2008). While hedonic pricing models initially gained traction in understanding residential property values, their application has extended to include environmental factors, especially greenspace, as urban planners and economists recognize the importance of green areas in enhancing urban lifestyles (Adamu et al. 2023).

Hedonic modelling has been extensively used to quantify price premiums associated with greenspaces. For example, Loomis et al. (2024) report a 10% price premium for houses within 2km of a national park in the US. Research conducted in Melbourne suggests that properties within 400 meters of a significant park can achieve premiums ranging from 6% to 15% compared to those farther away (Fernández & Martin 2020), and in Sydney, the presence of well-maintained parks has been linked to price premiums of approximately 10% (Copiello & Coletto 2023). But smaller urban greenspaces (front and backyard, nature strips and street trees) that also contribute to neighbourhood amenity have not been as well considered in hedonic modelling. By explicitly quantifying the economic benefits associated with all urban greenspaces and green elements, hedonic modelling studies can help to encourage the provision of greenspace in new residential developments (Widłak & Tomczyk 2010).

There are three key challenges to implementing hedonic modelling into the urban development planning process. First, hedonic studies need to consider greenspace configuration, and account for potential differential impacts of small and large, private and public greenspace and other green elements on property prices (e,g, Czembrowski & Kronenberg 2016, Pearson et al. 2002, Li et al. 2024). Including multiple types of greenspace in a single hedonic analysis enables price premiums to be compared and contrasted and may help to identify opportunities to optimise greenspace design within a relevant context. Second, hedonic modelling should consider aspects of greenspace quality (Li et al. 2024). Without information on the impact of greenspace quality on property values, homeowners, planners and developers are unable to justify effective landscape planning strategies (Sun et al. 2021). Hedonic models that explicitly include key elements of greenspace quality – like configuration, accessibility and vegetation type – may help to provide more specific and practical advice for developers, local councils and other landscape planners. Third, property price premiums reported from hedonic modelling cannot be considered in isolation. Effective landscape planning requires that price premiums are implemented into the formal planning decision-making processes, like cost-benefit analysis - where greenspace price premiums are weighed against the costs of greenspace provision to determine whether specific greenspace options are likely to deliver a net cost or a net benefit.

Recent studies indicate that lower-income communities often have inferior access to quality greenspaces, further contributing to socio-economic disparities in urban environments (O'Regan et al. 2021, Ghanem & Edirisinghe 2024). As urban areas expand into fringe regions often underserved by greenspace, it becomes imperative for municipalities to adopt evidence-based strategies that address these disparities and promote equitable access to nature for all residents (Adamu et al., 2023). In this study we focus on recent greenfield developments in Greater Western Sydney to develop a hedonic model that includes eight different greenspace measures that account for greenspace configuration, accessibility and vegetation type. We then incorporate the information on greenspace property price premiums into a formal cost-benefit analysis framework, alongside the costs of greenspace provision, to identify specific opportunities for targeted greenspace design to deliver net positive outcomes.

Study sites

This study included seven Local Government Areas (LGAs) within the Greater Western Sydney region. All are high growth areas located on the urban fringe to the north-west, west or south-west of Sydney, and were selected in consultation with Planning NSW (Figure 1).

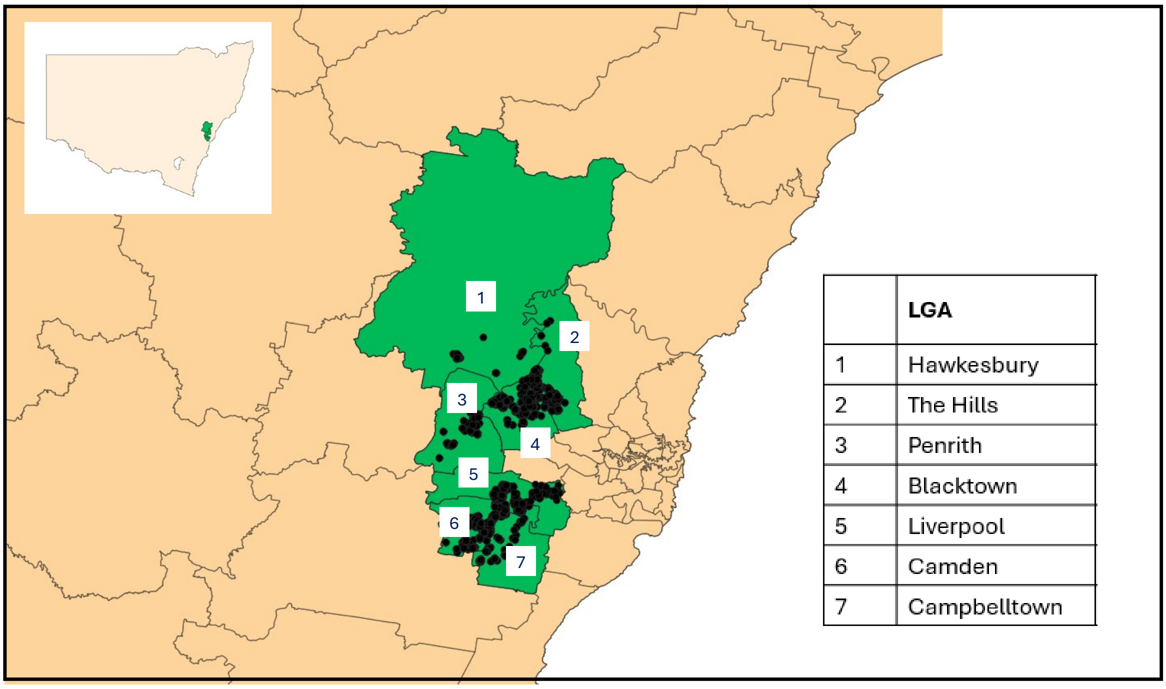


Figure 1: Map of Local Government Areas (LGAs) included in the Greater Western Sydney study region

These LGAs were selected because they are expected to experience the high rates of population growth 2041: in combination, they are expected to experience population increase of more than 650,000 residents, representing one third of all population growth in NSW to for the period 2021 - 2041 (Planning NSW, 2024).

House sales and attribute data

We purchased data relating to house sales in our study region from a residential property data company CoreLogic (https://www.corelogic.com.au). We restricted our analysis to houses, with a land area <1000m, and include sales of new properties only – defined as those sold in the same or subsequent calendar year to the year of build (Table 1). This supports the study focused on design of new residential dwellings within the Greater Western Sydney. We further restricted our analysis to sales over the period 2021 - 2023 to coincide with the timing of satellite imagery relating to NSW vegetation cover mapping.

The CoreLogic dataset provided data on the sale price, as well as basic property attributes such as location, land size, floor area, number of bedrooms, number of bathrooms and number of garages. These attributes were included into our (preliminary) hedonic model (Appendix 2). We also used CoreLogic data relating to land size and floor area to generate an additional housing attribute: 'House-to-block ratio'. This parameter sought to explore the possibility that property purchasers may be preferencing smaller homes on account of the associated running costs and/or to allow space for private greenspace.

Our preliminary dataset contained 4796 sales for the period 2021-2023. We then excluded any sales with a swimming pool (n = 45) and any sales with missing or zero data relating to house location, land size, floor area or number of bedrooms (n = 410). Our final dataset contained 4341 house sales data points (Table 1).

Table 1: Number of house sales by Local Government Area (LGA) by year. 'Map ref' see Figure 1.

Map ref	LGA	House sales data points included in the analysis		
		2021	2022	2023
1	Hawkesbury	20	3	37
2	The Hills	313	100	233
3	Penrith	33	18	37
4	Blacktown	884	377	504
5	Liverpool	261	119	167
6	Camden	508	165	243
7	Campbelltown	166	69	84
	Total	**2185**	**851**	**1305**

Greenspace quantity, quality and type

Greenspace quantity variables used in valuation studies typically fall into two categories – proximity or distance-to-greenspace measures like distance to national or urban park (e.g. Pearson et al. 2002, Bottero et al. 2022), or quantity-within-radius measures like total area of greenspace within a set radius from the property of interest (e.g. Czembrowski & Kronenberg 2016). In this study, we consider quantity-within-radius to provide a comprehensive picture of urban greenspace within and surrounding a home sale.

Greenspace quality is most often included in hedonic models using classification schemas. For example, Pearson et al. (2002) differentiate between urban parks and national parks; Bottero et al. (2022) differentiate between urban parks, recreation parks and sports parks; and Czembrowski & Kronenberg (2016) differentiate between 9 different greenspace types, including large, medium and small parks, large medium and small forests, cemeteries and garden allotments.

In our study, we classify greenspace quality based on three aspects:

1) accessibility (public or private),
2) vegetation configuration at four spatial scales (Table 2), and
3) vegetation type

Data was sourced from NSW Government's 'Six Maps' data service to calculate the quantity and quality of private and public greenspace on the home lot, adjacent lots, streetscape and within a 500 m radius. (NSW Government Land and Property Information, 2025). Greater methods detail and justification is provided in Appendix 2.

The third greenspace attribute, vegetation type, was calculated using height stratified vegetation cover data mapping created by ArborCarbon (2025), also supplied by the NSW Government. This data set enables us to classify: i) ground areas without vegetation (hard surfaces); ii) grass and shrubs <3m high; iii) trees 3-10m high; iv) trees 10 - 15m high, and v) trees >15m high. Data exploration identified a high degree of spatial correlation for areas with trees 3-10m high and trees >10m high. Accordingly, these two vegetation classifications were combined to a single measure for trees >3m. There was also a high degree of correlation between vegetation types within a 200m buffer and a 500m buffer (Appendix 2). Accordingly, we restricted hedonic modelling to only include greenspace area within the 500m buffer.

The final eight greenspace parameters of greenspace quantity, quality and type that were included in the hedonic modelling are presented in Table 2.

Table 2: The eight final greenspace parameters used in hedonic modelling and their percent distribution across 4341 house sales

Attribute	Unit	Percentile		
		25th	50th	75th
House lot - low veg <3m	%	1.32	6.50	15.27
House lot - trees >3m	%	0.00	0.00	0.73
Adjacent lot - low veg <3m	%	1.40	10.56	22.63
Adjacent lot - trees >3m	%	0.00	0.05	1.13
Streetscape - low veg <3m	%	7.18	10.64	16.71
Streetscape - trees >3m	%	0.08	0.58	3.02
500m buffer - low veg <3m	%	0.04	1.07	3.87
500m buffer - trees >3m	%	0.00	0.15	1.09

Hedonic modelling

We undertook hedonic modelling using Generalized Additive Modelling (GAM). GAM is a non-linear modelling approach that enables identification of non-linear effects like thresholds, maxima and minima (Beck & Jackman 1998, Zuur et al. 2009). This makes GAM particularly suited to investigations that involve trade-offs – including the trade-off between hard substrates and greenspace that is at the core of our investigation. GAM has been shown to outperform linear or polynomial modelling approaches in a number of comparative hedonic modelling studies (e.g. Chernih & Sherris 2004, Bailey et al. 2022). Greater methods detail can be found in Appendix 2.

Cost benefit analysis

In our study, hedonic modeling is used to explore the possibility that property purchasers may be willing to pay more for houses with particular greenspace features. However, potential price premiums are only one consideration for greenspace planning for new residential developments. Informed decision-making requires a full cost-benefit analysis that weighs price premiums against any associated costs of their provision – including direct costs like materials and labour, as well as indirect costs like land-use trade-offs (e.g. loss of potential building space, reduced house size).

We undertook a cost-benefit analysis on three potential planning scenarios relating to the provision of greenspace in new residential developments. Greater details can be found in Appendix 2.

1) Reducing the amount of hard substrate on a house block and increasing the coverage of low vegetation (grasses and shrubs <3m) and trees (>3m).
2) Providing increased amounts of low vegetation (grasses and shrubs <3m) and trees (>3m) in the streetscape.
3) Increasing the land area set aside as public greenspace. In this case we consider the trade-off between new public greenspace and the number of residential blocks developed.

For each of the cost-benefit analysis scenarios described above we estimate the greenspace benefits from predictive modelling of house prices using our GAM. We assess the costs using the parameter estimates presented in Appendix 2. Where possible, costs reflect local costs relevant to our study LGAs. We have undertaken sensitivity testing varying all costs and benefits by 10%. Given that the costs and benefits associated with greenspace provision in new housing are close in time (our sample includes only houses sold in the same or subsequent calendar year to the year of build), we do not apply any discounting in our cost-benefit analyses.

Results and Discussion (Work Package 2)

Hedonic modelling

Hedonic modelling identified a significant effect on house prices for seven of the eight greenspace variables modelled. In all cases, the observed trend was non-linear. In all cases, there was a substantive gap between the optimum modelled amount of greenspace and current levels observed within the study area.

In the case of private greenspace, the significant model terms (House lot– low vegetation, House lot – trees, and Adjacent lot – trees) had a negative parabolic relationship with house prices, with maximum property prices observed at 20%, 12% and 30% respectively (Figure 2). Where greenspace parameters have a negative parabolic relationship with property prices, this suggest that greenspace can add a property price premium up to some optimal level, but that further increases in that greenspace feature may reduce the property price via a trade-off with some other element (e.g. house size).

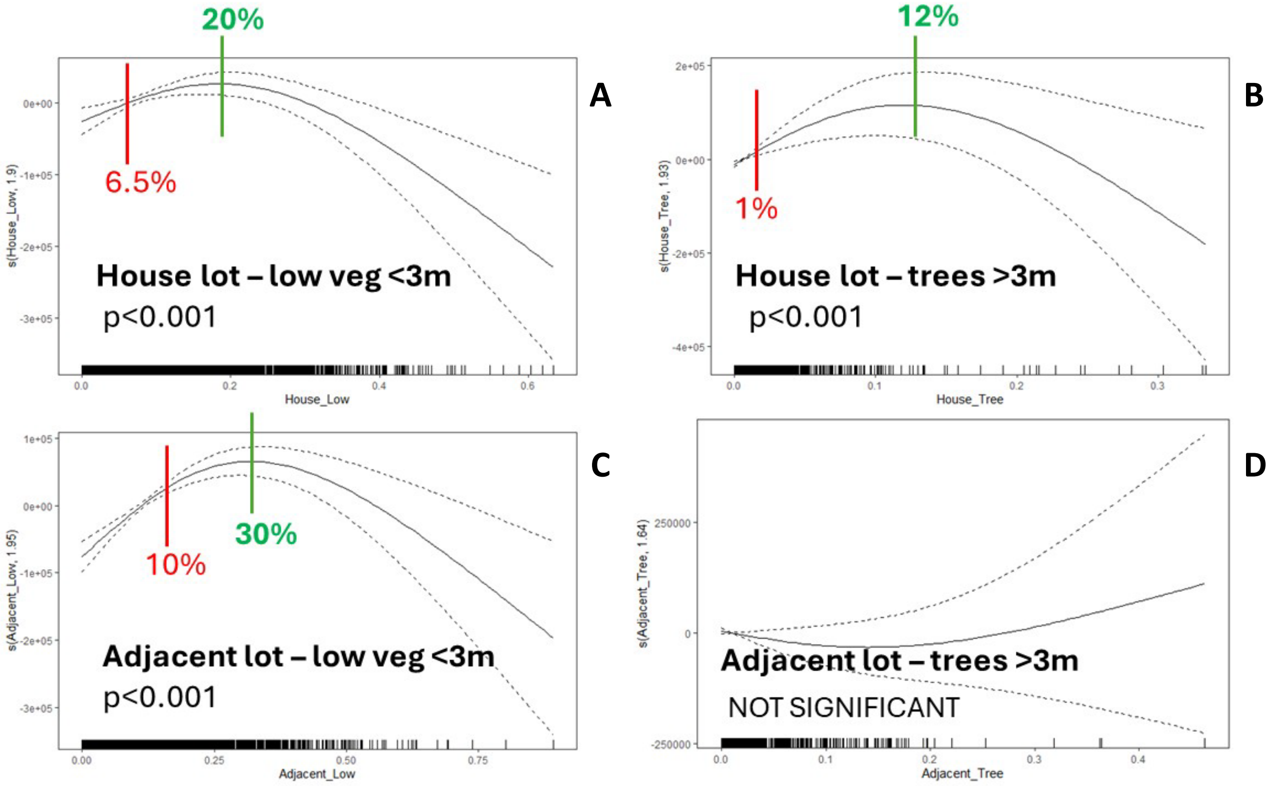


Figure 2: Relationships between house price (y axis) and selected greenspace attributes from GAMs: <3 m grass and shrub cover (A) and >3 m tree cover (B) within the house block, and within the adjacent property blocks (C and D), respectively. Red labels show current mean values. Green labels indicate optimal values.

In the case of public greenspace, two of the significant model terms (Streetscape– low vegetation and 500m buffer – low vegetation) had a negative parabolic relationship with house prices, with maximum property prices observed at 15% and 10% respectively (Figure 3). The remaining two terms (Streetscape – Trees and 500m buffer – trees) had a significant positive relationship with property prices – suggesting that greater levels of tree coverage in public spaces can continue to add value to property prices even up to relatively high levels (30% and 50% respectively; Figure 3).

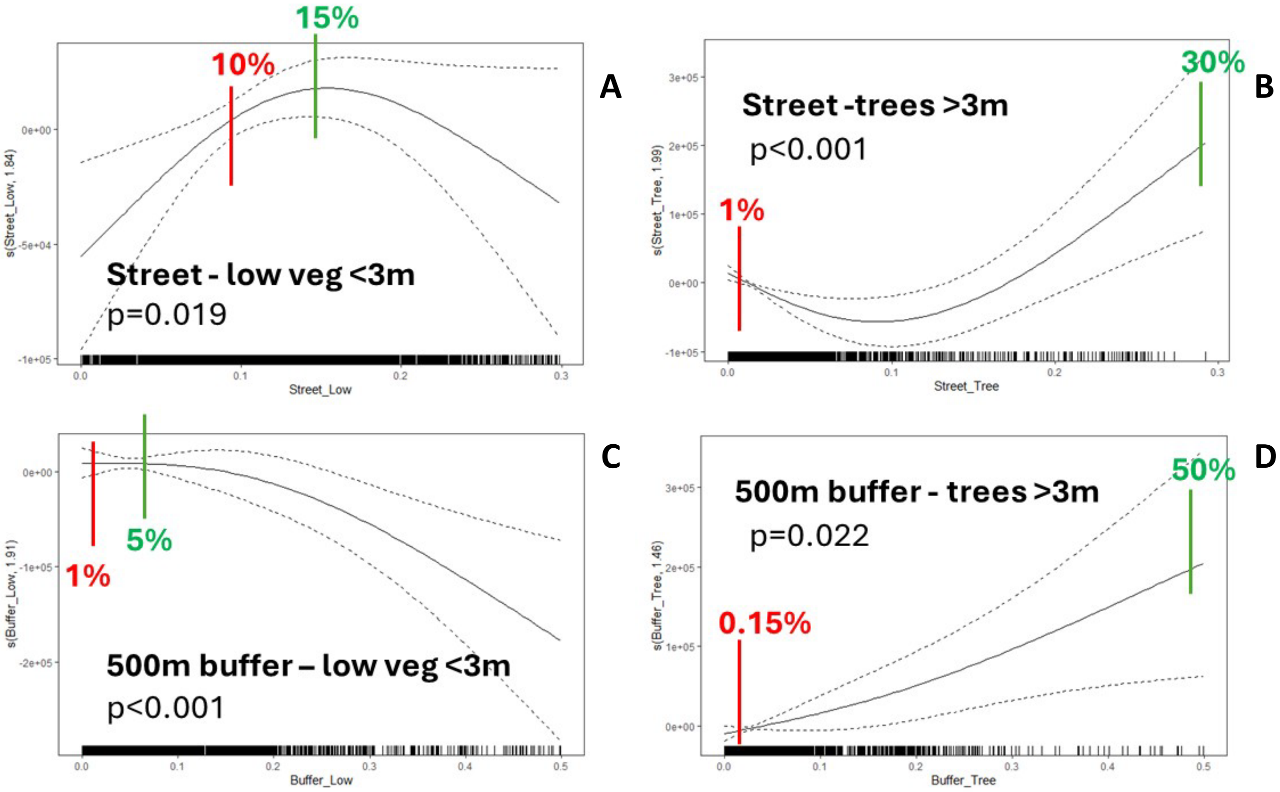


Figure 3: Relationships between house price (y axis) and <3m grass and shrub cover in streetscapes (A) and within 500m of a house (C), and >3m tree cover in streetscapes (B) and within 500m of a house (D). Red labels show current mean values. Green labels indicate optimal values.

The largest effects on house price related to location (latitude, longitude), land area and timing of purchase (Figure4). Greenspace had secondary level impacts; for example, House lot – low vegetation contributed approximately $37k or ~4.3% of median house price; House lot – trees contributed approximately $75k or ~8.7% of median house price (Figure 4). Effect sizes are considered in more detail in the context of cost-benefit analysis in the following section.

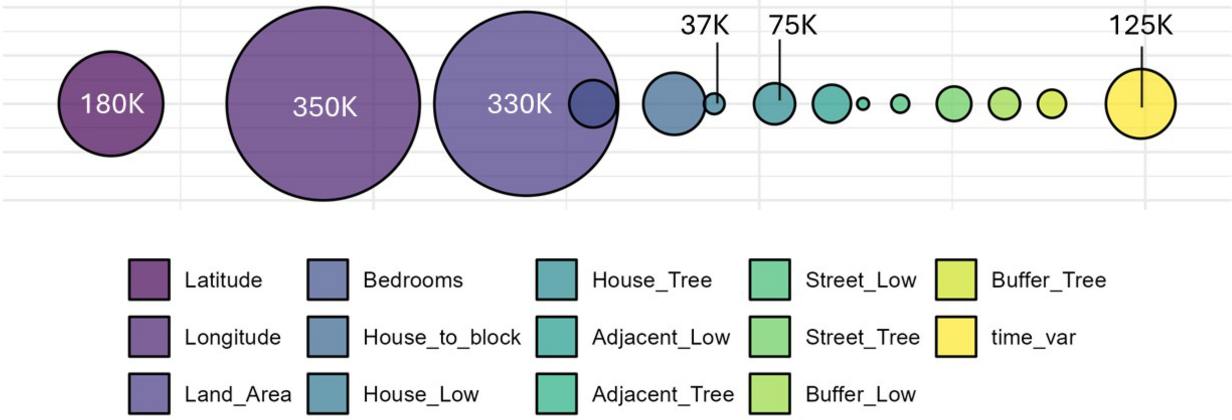


Figure 4: Relative effect size ($ value) of location factors and house and greenspace attributes in the GAM model

Cost benefit analysis

Cost benefit analysis identified a number of opportunities where developers could increase greenspace coverage and achieve higher estimated profits. Greater detail can be found in Appendix 2.1 Results.

In scenario 1 - Reducing the amount of non-house hard substrate on house lots and replacing them with low vegetation and trees (at coverage of approximately 20% and 12 % respectively) yielded an estimated net benefit of ~$120k per house lot (range $105k to $135k).

In scenario 2 - Reducing the number of house lots developed and increasing the land area of greenspace in the streetscape yielded an estimated net benefit of ~$8.8M per 12.5 ha area developed (range $7M to $10.5M).

In scenario 3 - Increasing the area of public greenspace had more mixed outcomes from cost-benefit analysis. The opportunity costs associated with the required land trade-offs (developing a reduced number of house lots) were large – in the order of $30M. The value of greenspace property price premiums only offset this cost if costs associated with greenspace provision were low (i.e. where public spaces are developed by retaining existing trees shrubs and groundcover within landscape and improving only 50% of the low vegetation area available). There was a net loss of ~$5.2M (range -$10.5 to -$1M) in association with the provision of greenspace with full landscaping costs, and a net benefit of ~$2M if public areas make use of pre-existing vegetation as modelled in our Scenario 3B (range -$1.8M to +$5.5M).

Insights into private greenspace features

Our findings suggest that property purchasers are willing to pay more for private greenspace features in new housing developments in the Greater Western Sydney study region. This was particularly the case for greenspace features on the property purchaser's own lot, where greenspace features could add ~$120k or 13% of median house value, to the purchase price. This is consistent with a Melbourne-based study by Farahani et al. (2018), which estimated that residential properties with well-maintained gardens commanded price premiums of 5% to 10% compared to similar properties lacking these features.

The house price relationships with private greenspace features we observed were not simple linear ones. Rather we observed negative parabolic relationships, which suggest that private greenspace on the house (or adjacent) lot can add a property price premium up to some optimal level – in the case of our study area this was a combined greenspace area of 32% of the lot comprising 20% low vegetation and 12% trees - but that further increases in greenspace may reduce the property price via a trade-off with some other element (e.g. house size).

When considered in the context of cost benefit analysis, greenspace provision was estimated to be approximately 50% more expensive than the provision of hard substrates like concrete or gravel when compared on a per m^2 basis. But the net outcome of increasing greenspace, once these costs were weighed against the associated greenspace property price premium, was positive and substantive, providing developers with an estimated net benefit in the range of $104,000 – $135,000 for a single house lot. The effect of greenspace in increasing the value of neighbouring properties observed through the 'adjacent lot' effect in our hedonic model has not been included in this estimate, as it requires property ownership assumptions that will be true in some cases but not all (i.e. that the same developer owns all adjacent lots adjoining a specific property), so we consider this net benefit of private greenspace on the value of new residential properties on our study region to be a minimum bound estimate.

The benefits of greenspace discussed above are reported on a per house lot basis. But it is important to note that total economic opportunity available to developers from increasing private greenspace cannot be estimated by simply multiplying this per house lot value up across the number of new housing developments proposed in Greater Western Sydney areas over coming years. This would be problematic for two reasons. First, the nature of price premiums is that they are temporary. They represent an additional payment made for top-tier products that are differentiated in some way from the rest of the market. If all houses had optimised value of private greenspace, this premium would be competed away. We note however, that the current price premium is large, so it represents a considerable opportunity for early adopting developers to benefit from significant returns. Second, there are other major influences on price in these areas over coming years and decades – including supply shortage, as well as ongoing budgetary constraints associated with the relatively low socio-demographic status of new property purchasers in these areas. Previous research has identified that these factors lead to a higher house price sensitivity in Greater Western Sydney compared to other regions (Kestens et al. 2006). Provision of greenspace, and associated premiums for developers will need to be considered against the broader macro-economic context, as well as the specific socio-demographic profile of specific development regions.

Insights into public greenspace features

Our findings suggest property purchasers are willing to pay more for public greenspace features in new housing developments in our study region. Net outcomes of public greenspace provision were variable once the opportunity costs associated with foregone development were considered. For streetscapes, we estimated a very large benefits from greenspace provision. When low vegetation on the streetscape within 200m of a house lot was increased from current median levels of 10% to optimal levels of 15%, and tree cover was increased significantly from current median levels of 1% to optimal levels of 30%, there was an increase in house price of $66,000 per house lot, equivalent to 7.5% of median house value. When summed across all 225 houses within the 200m buffer (an area of 12.5 ha), this represents a total benefit of ~$14.8M in associated with streetscape vegetation, and a net benefit of ~$8.8M once the costs of providing greenspace, including the opportunity cost of foregone development, were taken into account.

Our hedonic model indicated that increasing public greenspace areas (i.e. parks and open spaces) within a 500m buffer of the house lot from the current median value of 1% to 10% - comprising 5% low vegetation and 5% trees - could add ~$18,000, or 2% of median house value. When summed across all 1900 houses within the 500m buffer (an area of 78 ha), this represents a net benefit of ~$35M. But the costs associated with providing these public greenspace areas are large. We estimate total costs in the order of $40M, including both the cost of foregone development plus materials and labour costs, and a negative net outcome from cost benefit analysis (-$5.2M). If we include only a portion of the materials and labour costs associated with providing greenspace - a scenario that assumes public greenspaces are built around existing vegetation – then the net outcome from cost benefit analysis was positive (+$2M) but with a possibility of negative or positive outcomes (range of -$1.8M to +$5.5M) depending on the cost and benefit assumptions used.

The costs and benefits described for public spaces above should be considered with reference to land ownership and accessibility. If we consider the trend towards developers' provision of quasi-public spaces (i.e. greenspace occurring on lots that are privately held by the developer for exclusive access by residents within a private estate) then all the costs and benefits included in our analysis accrue directly to the developer, and the reported cost-benefit outcomes are directly relevant to landscape planning within new residential estates. But where public greenspace is provided by government and/or is more generally accessible, including to non-residents living outside the 500m buffer used in our study, then a range of other values should be considered in addition to property price premiums. For example, public greenspace has recreational value for non-residents (Heagney et al. 2019) and provides other ecosystem services like water and air filtration, flood mitigation, and, in some cases, biodiversity protection (Bilgili & Gökyer 2012, Dennis & James 2016). In these cases, a full economic valuation (using the Total Economic Value Framework or similar – e.g. Dennis & James 2016) should be applied and is likely to estimate a much larger quantum of benefits from public greenspace. These may outweigh the costs of greenspace provision and deliver a positive cost-benefit estimate.

3. Microclimate and cooling benefits

Methodology (Work Package 3.1)

Human thermal comfort and human skin burn risk from artificial turf as compared to natural turf

Artificial turf, also known as synthetic turf, is a plastic-based surface that is now commonly used in residential landscapes on both the public and private land. The use of artificial turf in private outdoor spaces, such as backyards, because they provide instant 'green' ground cover with a perception of reduced maintenance time, inputs of water and fertilizer. However, there are concerns that in comparison to natural turf, the use of artificial turf leads to a warmer microclimate air temperature and much greater ground surface temperature (Carvalho et al., 2021; Jim, 2016). The greater air and surface temperatures have raised serious concerns over greater heat stress to humans using these spaces (Wardenaar et al., 2023) and a greater risk of skin burns (Buskirk et al., 1971). When artificial turf surfaces are installed in private green spaces, they may be accessed by all family members. Infants, children, the elderly, and people with existing medical conditions are all more susceptible to heat stress and skin burns (Martin & Falder, 2017). In addition, artificial turf is now commonly used as a backyard surface for pet play and toileting areas. Animal paws are also susceptible to burns at high temperatures (Wohlsein et al., 2016).

The existing evidence for increased human heat stress from artificial turf primarily comes from measured human heat stress or its constituent microclimate variables in sports fields (Singh et al., 2024). Human heat stress is influenced by four microclimate variables:

1. air temperature,
2. vapour pressure of water,
3. wind speed, and
4. mean radiant temperature.

A few studies have reported that the daytime mean air temperatures above artificial turf were ≥1.5 °C greater than above natural turf (use of irrigation not reported) in various climate regions (Koon et al., 1972; Ramsey, 1982; Xiao & Cao, 2013). Greater air temperatures measured above artificial turf may increase the likelihood of human heat stress because of reduced convective heat transfer from the human body to the air (Fiala et al., 2012). The daytime mean radiant temperature above artificial turf has been measured to be 3.4°C greater than above natural turf in Hong Kong, China (Shi & Jim, 2022). Greater mean radiant temperature is likely to increase human thermal stress because more radiant energy will be absorbed by the human body (Fiala et al., 2012). These four meteorological variables should be measured and integrated into a single index to assess human heat stress because they each influence human heat stress simultaneously.

The surface temperature of artificial turf is more frequently measured than the microclimate above, and surface energy fluxes associated with artificial turf systems. Different studies have consistently measured greater daytime mean surface temperatures for artificial turf than natural turf, ranging from 12.4 °C in Hong Kong, China (Liu & Jim, 2021) to 34.2 °C in San Diego, USA (Wardenaar et al., 2023). The daily maximum surface temperature of artificial turf has been measured to be as high as 67.0 °C (Aoki, 2009; Wardenaar et al., 2023), 70.2 °C (Jim, 2016) and even 86.6 °C (Twomey et al., 2016). These extreme surface temperatures pose a significant risk to humans through potential skin burns.

Using a field experiment that consisted of three treatments (artificial turf, unirrigated natural turf and irrigated natural turf) with replications, this study aims to Compare the daytime (10:00–16:59) and night-time (21:00–05:59) microclimate (air temperature, vapour pressure, wind speed and mean radiant temperature) and human thermal comfort and ground surface temperature among three treatments of artificial turf and natural turf (irrigated and non-irrigated). From these measures we are able to quantify and compare both the microclimate and human thermal comfort in plots with these three surface treatments and the risk of human skin burns should contact be made.

Study Design

The study was conducted in Melbourne, Australia (–37.8, 145.0). at the Burnley campus of the University of Melbourne. The experiment consisted of three treatments (artificial turf, natural turf unirrigated, natural turf irrigated 4 mm per day) with three replicates of each treatment (3 × 3 = 9) requiring nine plots (Figure. 1). Each plot was 36 m^2 in area (6 m × 6 m) and enclosed by 1.8-m tall 70 % shade cloth (SOLARSHADE™) to mimic the enclosed environment of a private backyard. The dominant grass species in the unirrigated and irrigated natural turf plots was Kikuyu (*Pennisetum clandestinum*). The artificial turf plot was constructed by removing the top 80 mm of soil, laying and compacting 40 mm of crushed rock, laying 40 mm of fine crusher dust, and rolling out and pinning the artificial turf mats on top (Appendix 3). The artificial turf was a 100 % woven polypropylene backing onto which the 25 mm pile fibers (green) were glued. Drainage holes were punctured 0.1 m apart through the backing to allow drainage. The fibers were made of polyethylene and polypropylene and had a specific weight of 1030 gm^{-2}. The unirrigated and irrigated natural turf plots were mowed to 50 mm tall every two weeks. Hunter MP1000-90 Rotator nozzles were installed at the four corners and one MP1000-360 Rotator nozzle was installed centrally to irrigate natural turf with 4 mm d^{-1} from 14:00 to 14:23 local time.

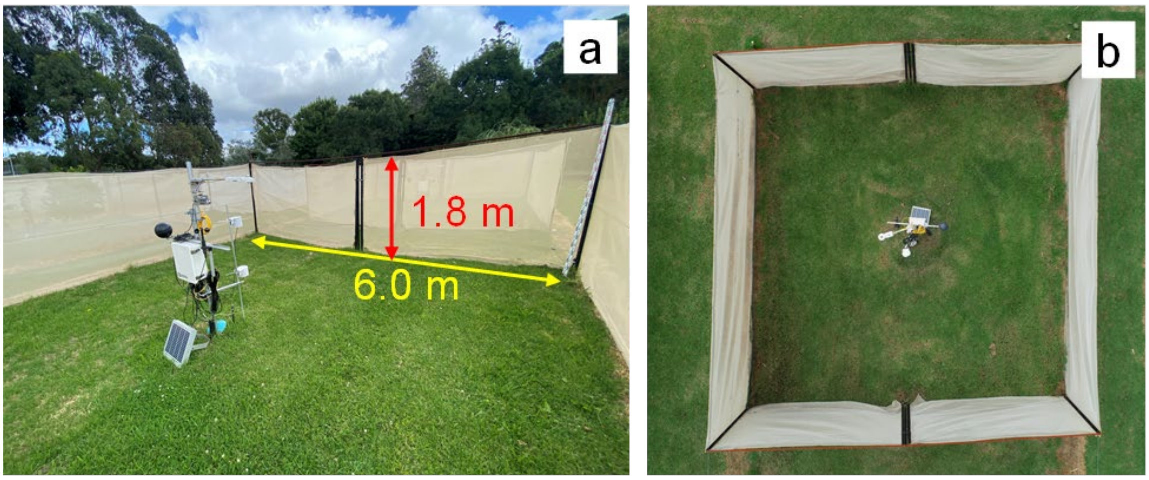


Figure. 1. Ground view (a) and bird-eye view (b) of the 6 m × 6 m plot (36 m^2) enclosed by 1.8 m tall shade cloth. A climate station installed at the centre continuously measures the microclimate and surface temperature in three treatments of 1) artificial turf, 2) unirrigated natural turf and 3) irrigated natural turf.

A climate station was installed at the centre of each plot to measure air temperature, vapour pressure of water, atmospheric pressure, black globe temperature (150-mm standard copper black globe) and wind speed at 1.1 m above ground. The experiment started on 2024-01-28 and finished on 2024-03-18 after 51 days of continuous measurement. The sunrise and sunset times on 2024-01-28 were 06:28 and 20:36, respectively. The sunrise and sunset times on 2024-03-18 were 07:21 and 19:34 respectively. All the times presented in this study were local time (UTC+10). The site was unirrigated before the experiment started. The irrigated and unirrigated natural turf plots had similar grass coverage throughout the study period, which was reflected by their similar albedo values (see section 3.1 for albedo data).

Calculation of mean radiant temperature and UTCI

Mean radiant temperature is approximately using the standard equation (ISO 7726, 1998; Kuehn et al., 1970). The University Thermal Climate Index (UTCI), developed by the International Society of Biometeorology (Jendritzky et al., 2012) uses air temperature, vapour pressure of water, wind speed and mean radiant temperature to calculate UTCI using a 6th order polynomial (Bröde et al., 2012) provided in the 'rBiometeo' package in R 4.4.0.

Calculating Skin burn risk and exposure periods

The International Organisation for Standardisation (ISO) has established a surface temperature threshold for plastics (48 °C contact for 10 minutes) above which burns are likely when human skin comes into contact with a hot solid surface (ISO 13732-1, 2006). However, few studies have used this skin burn threshold temperature to estimate the amount of time in a day that the surface temperatures of artificial turf represent a human health risk. The amount of time that the turf surface temperature exceeded the skin burn threshold was calculated for an average 24-h diurnal cycle for each treatment. All the data and statistical analysis were completed in R 4.4.0 (R Core Team, 2024).

Diurnal data analysis

The average 24-h diurnal cycles (in 1-h intervals) of the microclimate, human heat stress, turf surface temperature, and surface energy fluxes in the study period were calculated for each treatment. The variables were plotted to provide a qualitative comparison among the three treatments. Moreover, data was separated into mean daytime (10:00–16:59) and mean night-time (21:00–05:59) periods for quantitative and statistical analysis. These periods excluded sunrise and sunset when shadows cast confounded treatment impacts. Statistically significant differences in daytime and night-time mean microclimate, human heat stress, turf surface temperature, and surface energy fluxes artificial turf were calculated using the Student's *t*-test.

Results and Discussion (Work Package 3.1)

The air temperatures above artificial turf were significantly greater than both the unirrigated natural turf and the irrigated natural turf around midday and at night (Figure 2a). The differences in mean vapour pressure (relative humidity) and mean wind speed were smaller than the accuracy of the sensor (0.5 kPa), so no treatment differences can be detected. However, the daytime (10:00–16:59) mean radiant temperature of the artificial turf (47.0 °C) was significantly ($p<0.05$) greater than that of the unirrigated natural turf (45.8 °C) (Figure 2d). This 1.2 °C difference is small though. A similarly small 1.7 °C increase in midday mean radiant temperature has been reported above artificial turf in comparison to unirrigated natural turf in a playground in Czech (Lehnert et al., 2024). As mean radiant temperature is the greatest contributor to human thermal comfort, it is not surprising that there was only a small but significant 0.5 °C difference in UTCI between artificial turf (33.4 °C) and unirrigated natural turf (32.9 °C) during the daytime (Figure 2e). This 0.5 °C difference in UTCI is too small to change the UTCI human thermal stress category rating.

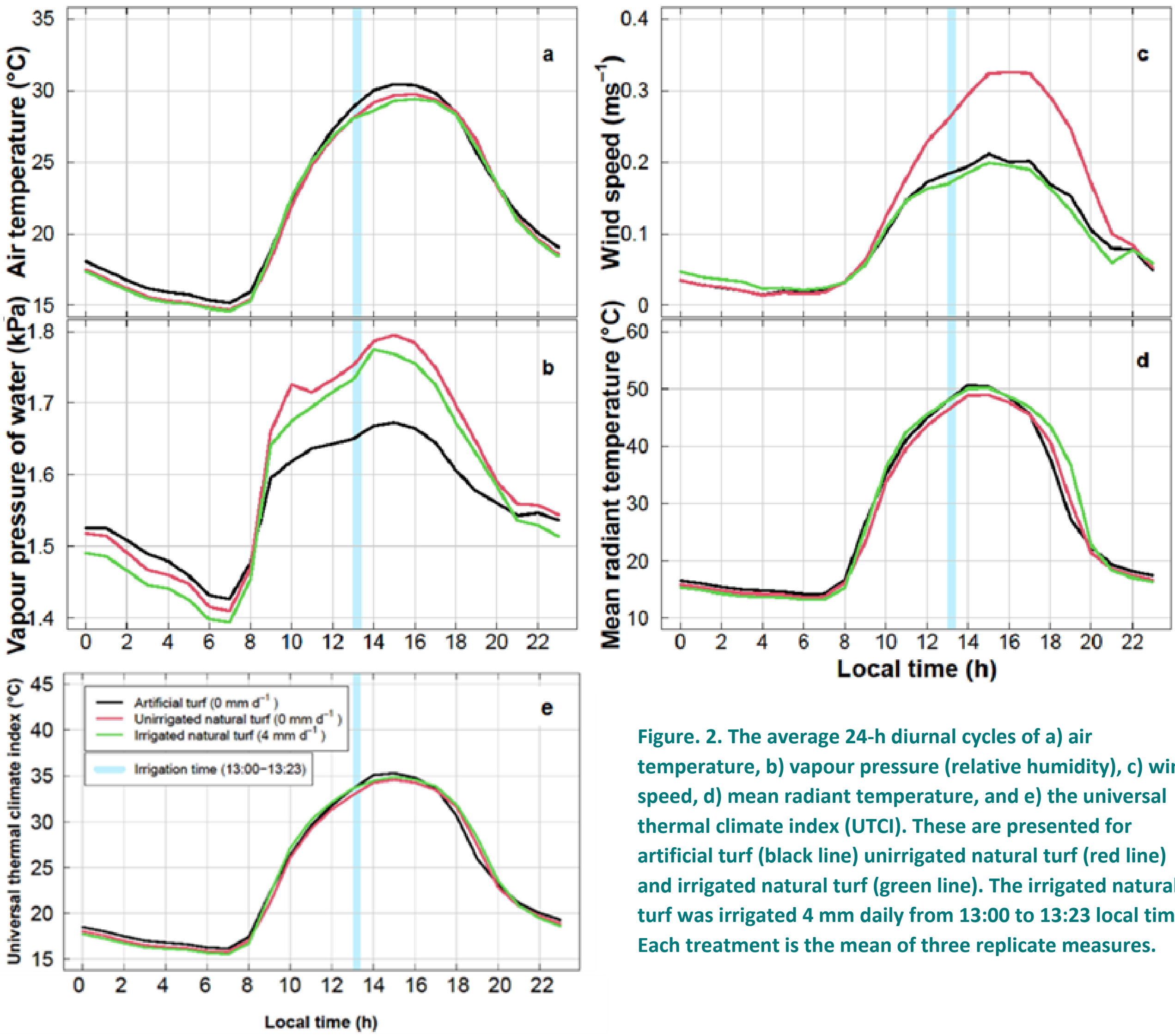


Figure. 2. The average 24-h diurnal cycles of a) air temperature, b) vapour pressure (relative humidity), c) wind speed, d) mean radiant temperature, and e) the universal thermal climate index (UTCI). These are presented for artificial turf (black line) unirrigated natural turf (red line) and irrigated natural turf (green line). The irrigated natural turf was irrigated 4 mm daily from 13:00 to 13:23 local time. Each treatment is the mean of three replicate measures.

The daytime mean ground surface temperature of artificial turf (49.9 °C) was significantly greater than that for unirrigated natural turf (31.7 °C) and the irrigated natural turf (29.9 °C). This ground surface temperature is one of the greatest reported in the literature (Liu & Jim, 2021; Petrass et al., 2015; Xiao & Cao, 2013). The maximum hourly mean turf surface temperature of the artificial turf was 71.6 °C, which is sufficient to cause irreversible skin burns in just 15 seconds (ISO 13732-1, 2006). The amount of time that the turf surface temperature of the artificial turf exceeded the skin burn threshold was 53% during the daytime (10:00–16:59) period (Figure 3) i.e., almost four hours in a day. The hourly mean turf surface temperatures of the unirrigated natural turf and the irrigated natural turf never exceeded the burn threshold during the 51-day measurement period (Figure. 3).

There are two key reasons for artificial turf to sustain such a high turf surface temperature. First, artificial turf has a lower albedo and lower specific heat capacity than natural turf. Low albedo of artificial turf increases its absorption of incoming shortwave radiation, increasing its turf surface temperature. The specific heat capacity of the polyethylene and polypropylene (artificial turf) is approximately 1900 J kg^{-1} K^{-1} (Professional Plastics, 2024). In contrast, the specific heat capacity of fresh leaves (Jayalakshmy & Philip, 2010) and moist soils (Abu-Hamdeh, 2003) of natural turf can exceed 2200 J kg^{-1} K^{-1}. The lower specific heat capacity of artificial turf will lead to a larger increase in turf surface temperature for a given amount of input energy for the same mass. Second, artificial turf has lower evapotranspiration rates than both unirrigated and irrigated natural turf, which reduces the evapotranspirative cooling of the artificial turf surface.

This study has addressed the two limitations identified by Singh et al. (2024) with regards to the measurement and data presentation of turf surface temperature in the existing studies. First, many studies have only measured turf surface temperature for less than one week and the measurements were often not continuous. In this study, we have continuously recorded turf surface temperature every 1 min for 51 days, allowing the variability and night-time conditions to be captured. Second, it was often unclear how long the reported maximum turf surface temperatures in the literature lasted. If the reported maximum turf surface temperature only comes from one measurement in one hour, it is insufficient to determine its burn risk because the 48 °C burn threshold is only applicable if the temperature lasts for 10 minutes or longer (ISO 13732-1, 2006). In this study, we reported the maximum hourly mean turf surface temperature to ensure it is indicative of the skin burn risk associated with the use of artificial turf.

The results of this study suggested that artificial turf does not increase human heat stress in summer in comparison to both unirrigated and irrigated natural turf. However, in the absence of shading, artificial turf can pose a serious human burn risk as surface temperatures can exceed the skin burn threshold for adults for most of the afternoon. The skin burn risk for children is likely greater as their skin is thinner. Furthermore, pet cats and dogs are similarly at risk as their paw pads are similar to human tissue under high temperature contact. Importantly, the hourly mean turf surface temperatures of the natural turf have never exceeded the burn threshold in this study. Natural turf is therefore a safer surface for private outdoor spaces when local climate and sun exposure mean that risks of skin burn are a possibility.

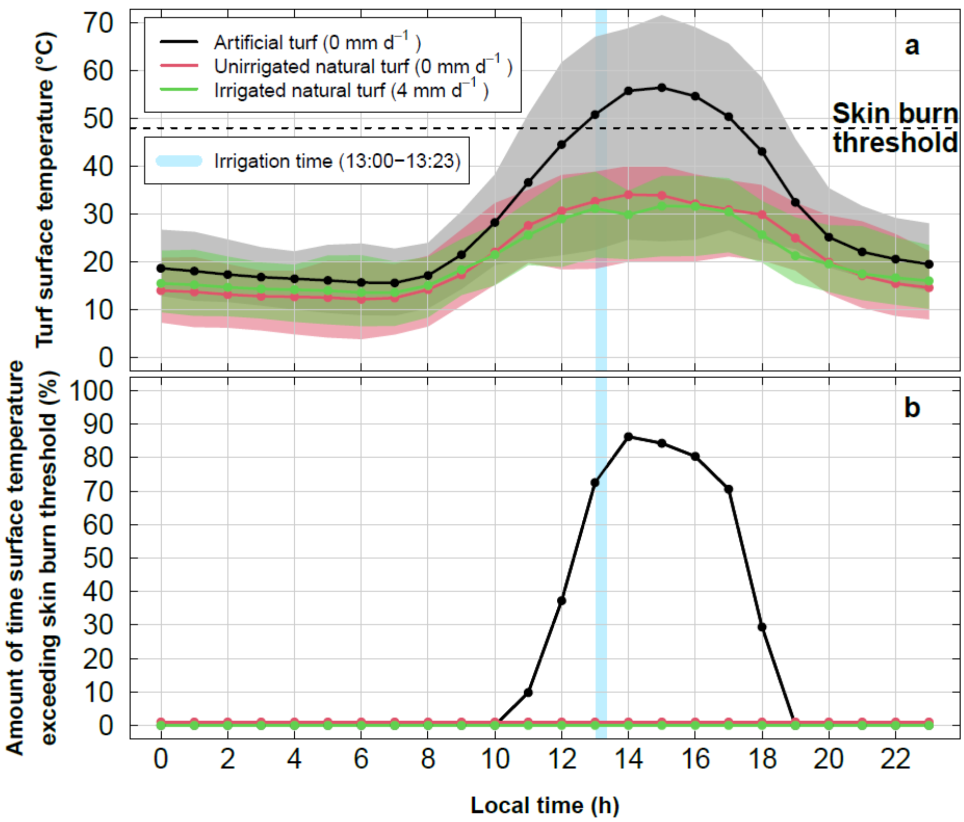


Figure 3. The average 24-h diurnal cycles of (a) the turf surface temperature and its range (shaded area) of the three treatments, and (b) the amount of time the turf surface temperature of each treatment exceeding the burn threshold. The burn threshold is 48 °C for plastics and for a contact period of 10 minutes (ISO 13732-1, 2006).

Methodology (Work Package 3.2)

The microclimate and human thermal comfort of front and back-yards in the Mirvac Olivine estate

Urban heat stress is increasing due to climate change and continued urbanisation (Chapman et al., 2017). Urbanisation leads to stronger heat stress because it converts areas of green and cool vegetation to dark and heat-absorbing surfaces (Thaweepworadej & Evans, 2025). One negative impact of increasing urban heat stress is that it discourages people from using outdoor green spaces (Cheung & Jim, 2018b; Lin et al., 2013). Private residential green spaces, i.e., backyards and front yards, are an important type of outdoor green spaces because they provide urban homeowners with immediate access to an outdoor space for physical and recreational activities (Shanahan et al., 2014). Therefore, it is important to understand how these spaces can be designed to improve human thermal comfort and encourage private green space use.

The design factors that impact human thermal comfort in private green spaces are poorly understood. Only a few studies have considered human thermal comfort in these spaces. Irrigating turfgrass in private green spaces can significantly reduce air temperatures as compared to not irrigating because of the cooling process of evapotranspiration (Bonan, 2000; Cheung et al., 2022). Larger private green spaces may also experience reduced air temperatures because of increased airflow and heat dissipation (Kubota et al., 2008; Lee, 1998). Sky view factor is a measure of how exposed an outdoor location is to the sky and therefore the sun. A smaller sky view factor is associated with lower air temperatures and better human thermal comfort within public green spaces (Cheung et al., 2021a; Zhang et al., 2019). Orientation will play an important role in determining the duration of direct solar exposure in private green spaces. These design factors, and others, will have an impact on human thermal comfort in private green spaces.

Mean radiant temperature is one of the most important climate variables to influence outdoor human thermal comfort (Thorsson et al., 2007). Mean radiant temperature sums up the radiant fluxes of two wavelengths (longwave and shortwave) that the human body is exposed to from the ground (up), lateral (sideways) and sky (down) (Höppe, 1992). Many studies have emphasised the importance of overhead canopy shade in reducing the sky (downward) inputs to mean radiant temperature to improve human thermal comfort (Cheung & Jim, 2018a; Coutts et al., 2016; Rahman et al., 2019). However, the importance of ground surface type in reducing the inputs from the ground (upwards) to mean radiant temperature is less clear. Since various surface types such as natural turf and artificial turf are commonly used in private green spaces, it is important to understand their contribution to mean radiant temperature and thermal comfort.

Apart from human thermal comfort, urban heat also increases the risk of skin burns when skin comes into contact with ground and object surfaces in outdoor green spaces in summer (Pfautsch et al., 2022; Strong et al., 2007). The risk of skin burns in private green spaces is particularly high because homeowners, children and pets can often be barefoot in their private green spaces (Sinha et al., 2006). Irreversible skin burns can occur in adults when their skin is in contact with metal, glass, plastics or wood that are ≥48 °C (skin burn threshold) for ≥10 min (ISO 13732-1, 2006). Children, the elderly, and people with existing medical conditions are more susceptible to skin burns than adults (Martin & Falder, 2017). Most cases of skin burn in children occur in private green spaces (Asquith et al., 2015). Artificial turf is now commonly used in private green spaces but it tends to store more radiant heat than natural turf when exposed to direct sunlight, which can increase its surface temperature and increase the risk of skin burns (Cheung & Livesley, 2025).

This study will focus on the private green spaces in greenfield residential suburbs in Melbourne, Australia. Greenfield development, i.e., development on land that has never been used before, is the main mechanism Australia uses to provide affordable housing for its rapidly growing population. Greenfield residential suburbs are usually built with high dwelling density and small lot size, meaning that many dwellings have smaller backyards and front yards than their older counterparts (Hall, 2010). The potential thermal discomfort and skin burn risks in these green spaces are a significant issue because this type of high-density greenfield development will continue to grow on urban fringe.

i) What design factors influence the microclimate and human thermal comfort in backyards and front yards?
ii) Do choices about backyard ground surface influence mean radian temperatures and thermal comfort?
iii) Do choices about backyard ground surface change the risk of skin burns on hot sunny days?

Study site

Microclimate and human thermal comfort measurements were conducted in private front and backyards in the Mirvac Olivine residential estate off Donnybrook Road, Victoria, Australia (–37.5, 145.0). This residential development is located approximately 30 km north of Melbourne's central business district. This residential development consists of 4,000 homes on 187 ha of land. Most properties are single- or double-storey detached houses ranging in lot size from 50 to 300 m^2.

We recruited nine residents in the Olivine estate through existing contacts and a letterbox drop to provide access to front- and backyards for microclimate measurements. One climate station was installed in the backyard and one in the front yard at each property (Figure. 1). The installation locations did not have direct overhead shading, but the climate stations were shaded in the early morning and the late afternoon by houses, walls or fences. Four microclimate variables were measured at 1.1 m above ground level from 01 February 2024 to 29 February 2024: air temperature (accuracy: ±0.2 °C), relative humidity (accuracy: ±2% @ 25 °C), wind speed (accuracy: ±0.3 m s^{-1}), and black globe temperature (accuracy: ±0.2 °C). These four variables were measured every 10 s and the 5-min means were logged. Mean radiant temperature was estimated from black globe temperature (ISO 7726, 1998; Kuehn et al., 1970). This black globe method allowed us to measure mean radiant temperature in multiple backyards and front yards simultaneously. However, the black globe method does not provide information on the relative contributions of radiant fluxes from the three different directions (ground (upward), lateral (sideways), and sky (downward)).

Universal Thermal Climate Index was used to estimate human thermal stress. from air temperature, relative humidity, wind speed and mean radiant temperature using the "rBiometeo" package in R 4.4.0 (R Core Team, 2025).

Each backyard was characterised for four design factors: 1) area (m^2), 2) orientation (N:S or E:W), 3) irrigated vegetation (resident reported Y/N), and 4) sky view factor.

Sky view factors of the backyards were determined by taking a fisheye image at the same location as the climate station and importing into an urban microclimate model, RayMan 1.2 (Matzarakis et al., 2007).

Microclimate and Human thermal comfort on hot sunny days

Three consecutive warm-hot and sunny days (20, 21 and 22 February 2024) were selected for human thermal comfort analysis. The mean daily maximum, mean and minimum air temperatures over the study period at Melbourne Airport (~15 km) from the study area were 33.9, 25.4, and 18.3 °C, respectively. The mean relative humidity and wind speed (10 m above ground level) over this period at Melbourne Airport were 55 % and 7.0 m s^{-1}, respectively.

The daytime (09:00 – 16:59) mean air temperature, relative humidity, wind speed, mean radiant temperature and Universal Thermal Climate Index over the study period in each backyard and front yards were calculated. Stepwise multiple linear regression was used to quantify the relationship between these four microclimate variables and one human thermal comfort index (dependent variables) and the four design factors (independent variables) (Table 3). The stepwise multiple linear regression aimed to develop a model that only contained the design factors that were useful to predict the microclimate and human thermal comfort variables (Hastie & Pregibon, 1992).

Three dimensional inputs to mean radiant temperature and ground surface temperatures

Three net radiometers (SN-500SS, Apogee) were installed to measure shortwave (385–2,105 nm) and longwave (5,000–30,000 nm) radiant fluxes from two opposing directions. The first net radiometer measured short and long-wave radiant fluxes from the ground (upwards) and the sky (downwards). The second and the third net radiometers measured the contributions from four lateral directions (2^{nd} east and west; 3^{rd} south and north). Short-term (10-min) measurements were made on two warm-hot and sunny days (04 and 11 February 2024) (Figure 3). The maximum air temperatures of these two days were 37.4 and 32.7 °C. The backyards of four properties with four different surface types (irrigated natural turf, artificial turf, mulch, and timber) were measured for 10 minutes in the afternoon when sun-exposed between 14:00 – 15:59. Ground surface temperatures were measured (SI-111-SS, Apogee, accuracy: ±0.3 °C) at the same time for the same four ground surface types. The International Organisation for Standardisation (ISO) has established a surface temperature threshold (in °C) above which irreversible skin burns occur when human skin comes into contact with a hot solid surface. The temperature threshold decreases as contact period (in minutes) decreases. We used the temperature threshold for a 10-min contact period (48 °C) to assess skin burn risks because it is relatable to the time that people spend in their private green spaces (ISO 13732-1, 2006).

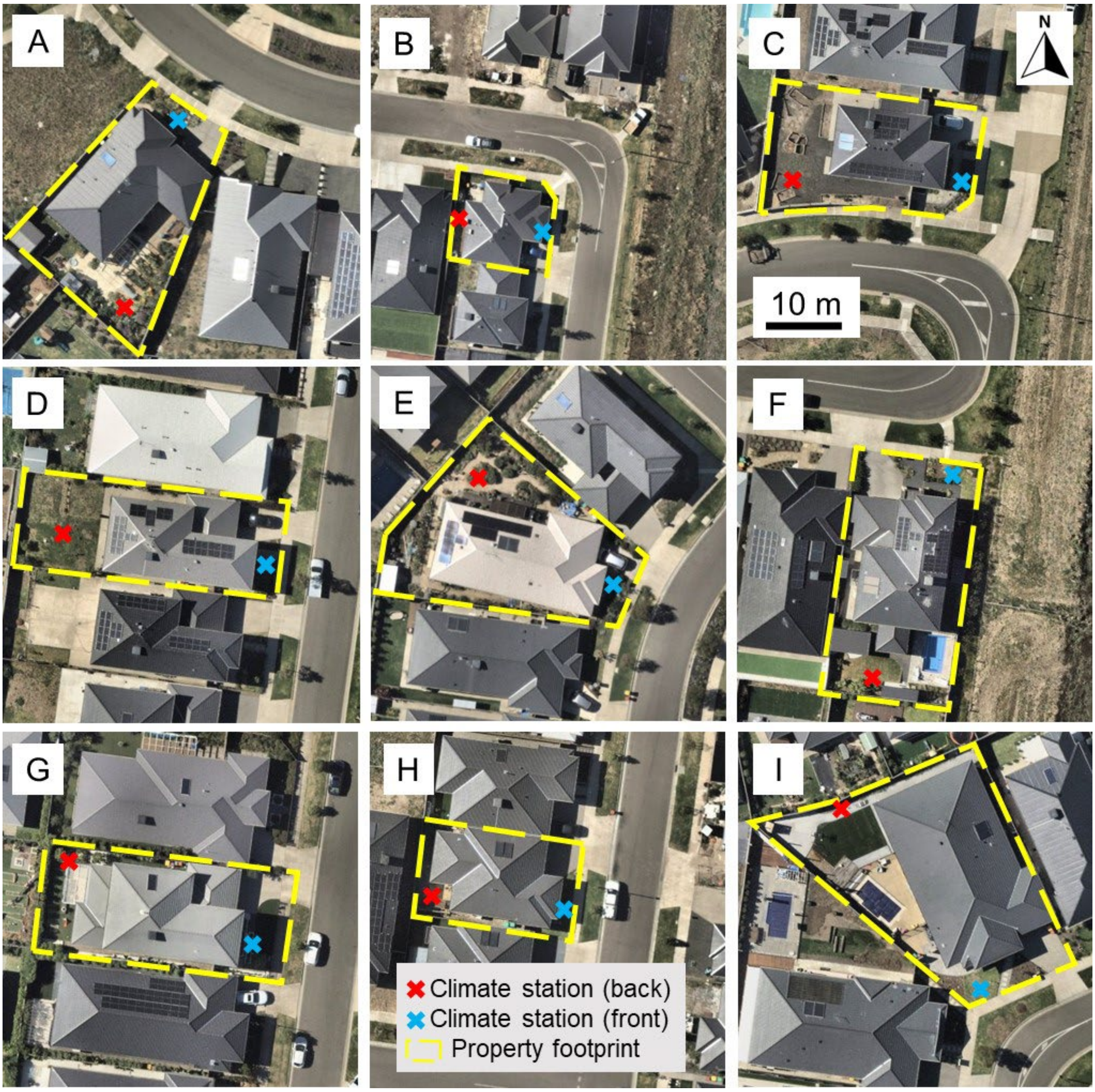


Figure 1. Satellite images (A – I) showing the installation locations of the climate stations in properties A – I. One climate station was installed in each of the backyard and front yards to measure air temperature, relative humidity, wind speed and mean radiant temperature at 1.1 m above ground level.

Results and Discussion (Work Package 3.2)

The impacts of backyard design factors on microclimate and human thermal comfort

The daytime (09:00 – 16:59) mean air temperature and UTCI in backyards were significantly (p<0.05) influenced by three design factors: area, orientation and irrigation (Appendix 3.2 Results).

YES — Compared to a 100 m^2 backyard, the air temperature and UTCI of a 200 m^2 backyard were, on average, 0.7 °C and 1.4 °C lower, respectively.

YES — Compared to backyards open to E:W Aspects, the air temperature and UTCI of those open to N:S aspects were, on average, 0.9 °C and 2.3 °C lower, respectively.

YES — Compared to the backyards without irrigated vegetation, the air temperature and UTCI of those with irrigated vegetation were, on average, 0.6 °C and 1.0 °C lower, respectively.

NO — Sky view factor was not a significant (p>0.05) predicter of air temperature or UTCI.

The three significant design factors (area, orientation, and irrigated vegetation) together explained 74 and 79 % of the variability in air temperature and University Thermal Climate Index, respectively. The relative humidity, wind speed, and mean radiant temperature in the backyards were not influenced by any of these four design factors.

Ground, lateral and sky input components to mean radiant temperature

For the four ground surface types measured in the backyards, the contributions of the six components that contribute to mean radiant temperature were similar (Figure 2). The longwave and shortwave radiant fluxes from the lateral directions contributed approximately 65% and 20% of the mean radiant temperature, respectively. The longwave and shortwave radiant fluxes coming back up from the ground contributed <6% to mean radiant temperature (Figure 2).

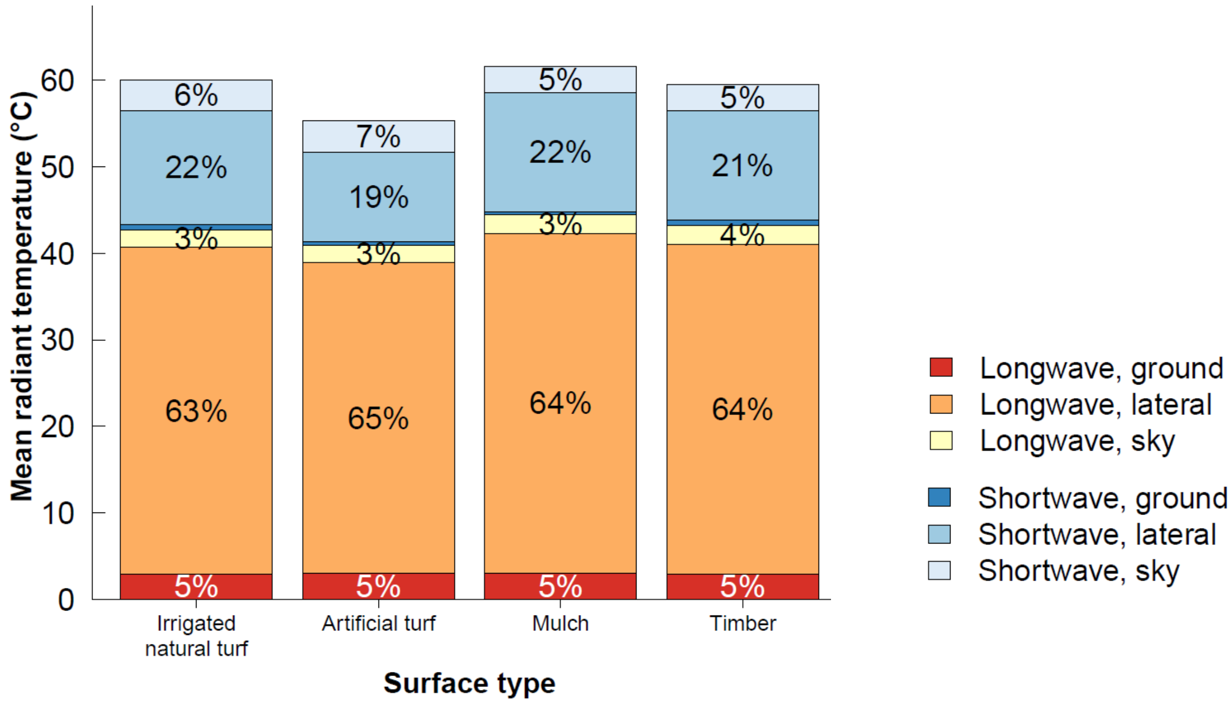


Figure 2. Partitioning the six components of mean radiant temperature measured in backyards of four properties with different surface types. The six components longwave and shortwave radiation from the ground (up), lateral (side), and the sky (down).

Ground surface temperature and skin burn risks

The ground surface temperatures of artificial turf, mulch, and timber (Figure 3) measured in the backyards between 2 and 4 pm did present a potential risk of skin burns (i.e. > 48 °C). This assumes that skin contact would exceed a contact period of 10 minutes (ISO 13732-1, 2006).

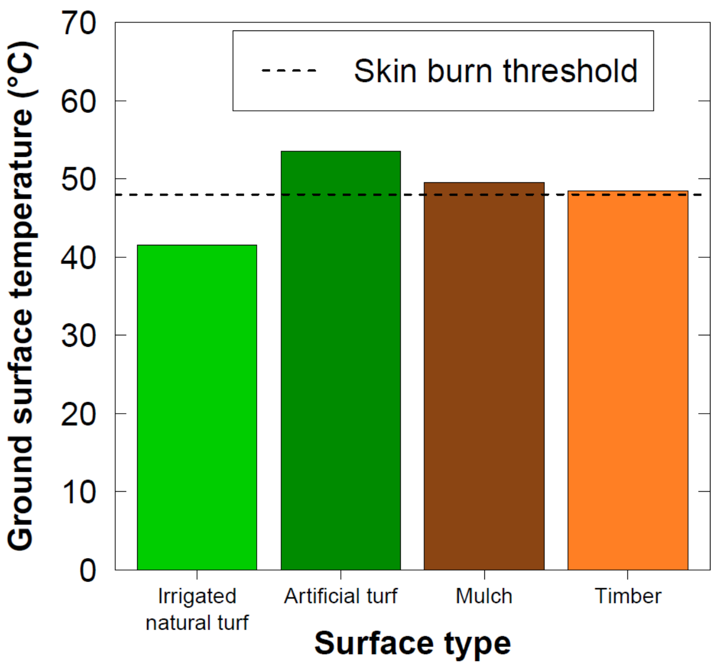


Figure 3. The mean ground surface temperatures measured in the backyard of four properties with four different surface types (irrigated natural turf, artificial turf, mulch, and timber).

The key design aspects that influence the air temperature and human thermal comfort of your backyard are the size (the larger area the better), the orientation (a north:south open aspect is better) and the use of irrigation for vegetation (irrigation is better). The design choices for ground surface did not appear to influence the mean radiant temperature and therefore human thermal comfort in these backyards. However, the choice of ground surface did change the levels of skin burn risk on hot sunny days. The only ground surface that did not present a skin burn risk was irrigated natural turf.

Methodology (Work Package 3.3)

Microclimate and human thermal stress impacts of misting and greening a courtyard in Aquarevo

Private backyards are important to the well-being of urban dwellers because they provide immediate access to urban green spaces (Shanahan et al., 2014). Private backyards offer a tranquil, safe, private place for various activities such as gardening, relaxation, and play. However, heat stress may prevent people from using outdoor green spaces in summer (Cheung & Jim, 2018), including private backyards. It is important to identify measures that are effective in reducing heat stress in backyards to extend the amount of time that people can use their backyards.

Misting has been used in various outdoor spaces to reduce human heat stress such as sports grounds and international exhibition venues (Ulpiani, 2019). Misting systems can emit fine water droplets from above or coupled with a fan to spray fine water droplets onto people to cool them (Wong & Chong, 2010). Misting makes people feel cooler in two ways. First, air temperature is reduced when the fine water droplets evaporate in the air or from the wall or ground surfaces after they land (Oh et al., 2020). Second, people's skin is cooled when the fine water droplets evaporate from it (Vanos et al., 2022). The air temperature reduction can be measured by an ordinary air temperature sensor. The evaporative cooling that occurs on people's skin can be approximated using the standard black globe temperature sensor. The standard black globe temperature sensor consists of a hollow copper globe (150 mm in diameter) painted in matt black and a thermometer inserted into its centre (Kuehn et al., 1970). The evaporative cooling that occurs on people's skin also occurs on the globe surface during and after misting.

Green façades are installed on the external walls of a building to reduce its external wall surface temperature and heat gains (Hunter et al., 2014). Green façades use a vertical support structure such as trellises and mesh structures to allow climbing plants to grow on them (Pérez et al., 2011). The shade provided by the climbing plants can effectively reduce the external wall surface temperatures of a building (Pérez et al., 2017) and reduce indoor air temperature (Zhang et al., 2019). However, the impact of green façades alone on outdoor air temperature is limited (Wong et al., 2010) because the air temperature cooling effect depends on the transpiration of the plants, which is a function of vapour pressure deficit and plant physiology.

Although the impact of green façades on outdoor air temperature is limited, misting with green façades may provide additional air temperature cooling benefits because the leaf surfaces provide a greater area for the mist to evaporate. Using continuous microclimate measurements in a backyard in Melbourne, Australia, this study aims to:

i) compare the impacts of misting with and without green façades on air temperature, mean radiant temperature, and human thermal stress;
ii) compare the external wall surface temperatures of green facades to bare wall on misting and non-misting days.

Study design

This study was conducted at Aquarevo House, Melbourne, Australia (–38.1°, 145.2°). Aquarevo House is a single-storey house (292 m^2) with a backyard (71 m^2) to the west of the house. A misting system (MK31025, Holman) was installed at the centre of the backyard at 3 m above ground level. The misting system consisted of three rows (1.5 m apart) and each row had five nozzles (1.0 m apart). Each nozzle emitted 2 L of water per hour. The misting systems were set to turn on for five minutes at 11:00, 12:00, 13:00, 14:00, 15:00, 16:00, 17:00, and 18:00 on every other day. This timetable enabled measurements for days with misting (Figure 1a), and days without misting (Figure 1b), to be collected in the backyard over the 2024/25 summer. The one-hour interval between misting events ensured that all mist would have evaporated before the next misting event. This misting timetable was operated from 2024-12-25 to 2025-03-23. Since the backyard was unshaded from approximately 11:00 to 18:00, all misting events were conducted in the sun.

A climate station was installed (Figure 2a) to continuously measure air temperature, vapour pressure of water, black globe temperature (Figure 1) and wind speed at 1.1 m above ground. The wall surface temperature was also continuously measured. These variables were measured every 10 s and the 1-min averages were logged. Mean radiant temperature was estimated from black globe temperature using the following equation (ISO

7726, 1998; Kuehn et al., 1970).

After six weeks of backyard climate measurement (from 2024-Dec-25 to 2025-Feb-04) A green façade was installed on the west-facing wall of the backyard (Figure 2b). Wonga Wonga vine (*Pandorea pandorana*) was grown on six metal support mesh sections (1.8 m tall x 1.1 m wide) at the Burnley campus nursery and then installed on the west-facing wall on 2025-Feb-05 (Figure 2b). Climate station measurements then continued for misting every other day operated with a green façade from 2025-Feb-06 to 2025-Mar-18 (41 days).

Hot, cloudless days were selected to analyse the impacts of misting on backyard microclimate, with a 'bare wall' (without green façade) and with a 'green façade' covering the west-facing wall. Six hot cloudless days were selected for analysing the impacts of misting with bare wall, and five days for misting with green façades. This means that there were 48 misting events (6 days × 8 event day–1) with bare wall and 40 events (5 days × 8 event day^{-1}) with green façades (Table 1). The minutely changes in air temperature, mean radian temperature, and Universal Thermal Climate Index in the five minutes before and 55 minutes after a misting event were averaged for those 48 (misting with bare wall) and 40 (misting with green façades) for analysis. Universal Thermal Climate Index was used to estimate human thermal stress from air temperature, relative humidity, wind speed and mean radiant temperature (Bröde et al., 2012). It was calculated using the "rBiometeo" package in R 4.4.0 (R Core Team, 2025).

The same hot, cloudless days were used to compare the wall surface temperatures of green façades to bare wall with misting. Additional hot, cloudless days were selected to compare the wall surface temperatures of green facades to bare wall without misting (Table 1). The hourly average diurnal cycles of wall surface temperatures were calculated for green façades and bare wall with and without misting for analysis.

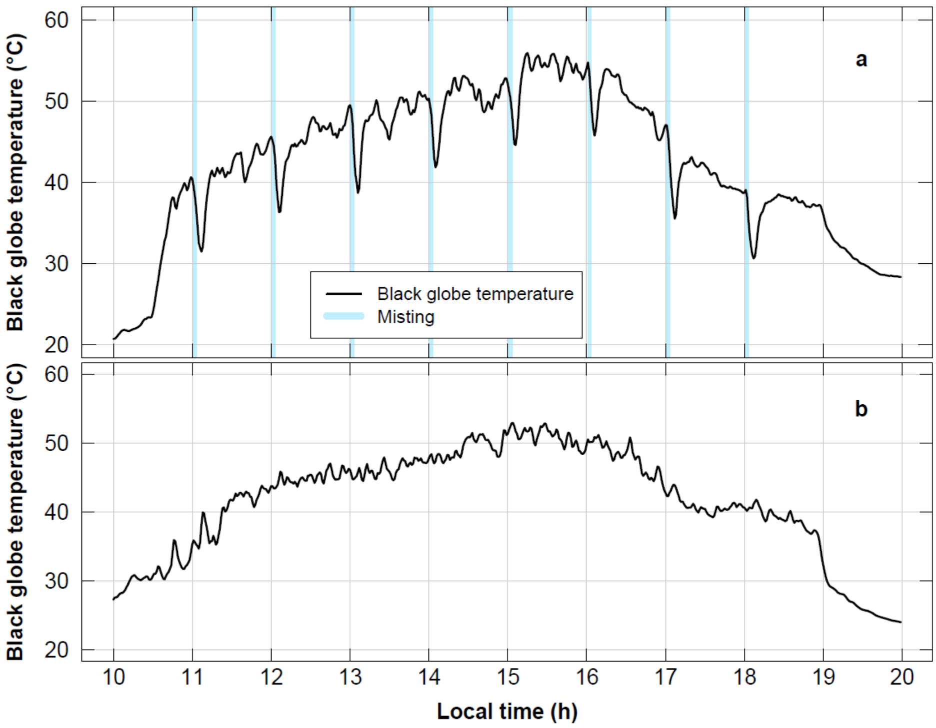


Figure. 1. Misting was scheduled to operate (a) one day on and (b) one day off. On a day with misting, it was scheduled to operate for five minutes at 11:00, 12:00, 13:00, 14:00, 15:00, 16:00, 17:00, and 18:00 h (vertical blue lines). The impact of misting schedules is demonstrated through changes in black globe temperature on two hot cloudless days (a: 2025-Jan-03 and b: 2025-Jan-14).

Figure. 2. Misting system was set up in the backyard of Aquarevo House. The microclimate, human thermal stress and wall surface temperature was measured for 44 days with misting and a bare wall (a), followed by 41 days with misting and a green façade (b).

Results and Discussion (Work Package 3.3)

The impacts of misting with bare wall on air temperature were similar to those with green façades (Figure 3a). The maximum air temperature reduction due to misting was approximately 0.4 °C, which occurred approximately ten minutes after misting started. The air temperatures of both treatments stayed below the pre-misting level for approx. 30 minutes.

The pre-misting mean radiant temperature with bare wall was approximately 10 °C higher than with green façades (Figure 3b) because the background weather was warmer on the days with bare wall. The maximum mean radiant temperature reductions due to misting were 15 °C with bare wall and 12 °C with green façades, which occurred approximately eight minutes after misting started. The mean radiant temperatures of both treatments stayed below the pre-misting level for approximately 15 minutes.

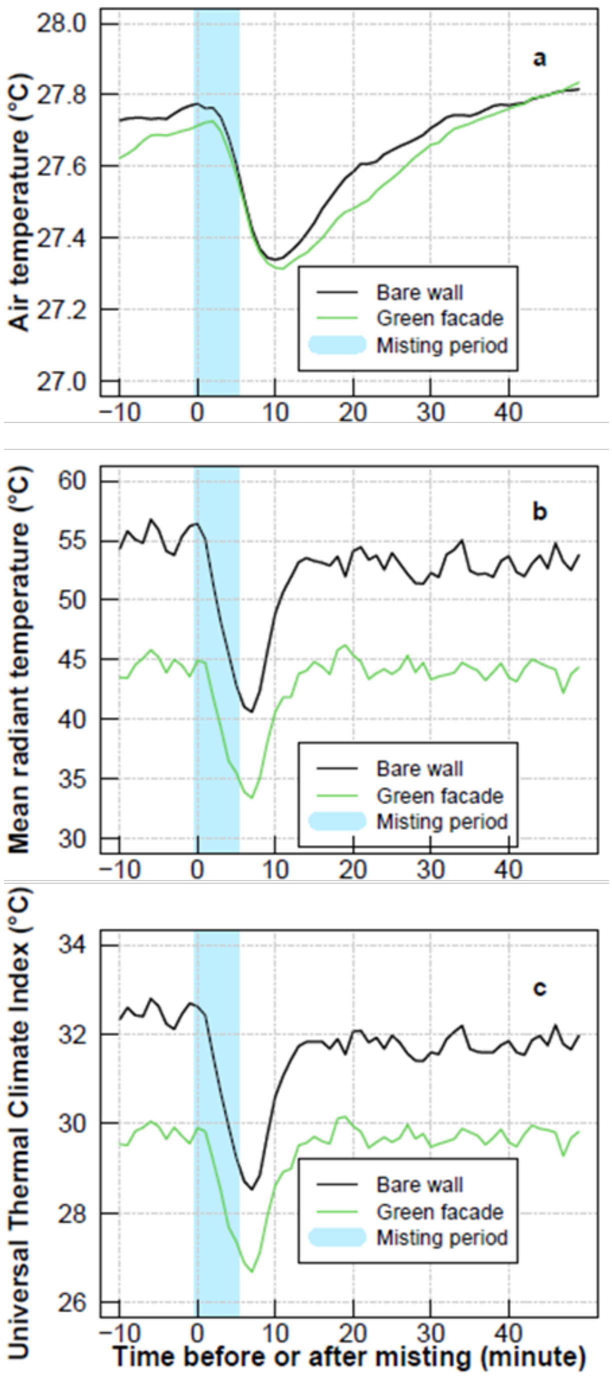


Figure. 3. Impacts of misting on (a) air temperature, (b) mean radiant temperature, and (c) Universal Thermal Climate Index with a bare wall and a green façade covering that wall.

The pre-misting Universal Thermal Climate Index with bare wall was approximately 2 °C higher than with green façades (Figure 3c) because the background weather was warmer on the days with bare wall. The maximum Universal Thermal Climate Index reductions due to misting were 4 °C with bare wall and 3 °C with green façades, which occurred approximately eight minutes after misting started. The Universal Thermal Climate Index of both treatments stayed below the pre-misting level for approximately 15 minutes.

On the misting days, the bare wall always had greater wall surface temperatures than the green facades from 06:00 to 24:00 (Figure 4a). The greatest difference in wall surface temperature between the bare wall and the green façades was approximately 11 °C, which occurred at 18:00. On the non-misting days, the bare wall also had greater wall surface temperatures than the green facades from 06:00 to 24:00 (Figure 4b). The greatest difference in wall surface temperature between the bare wall and the green façades was approximately 19 °C, which occurred at 19:00.

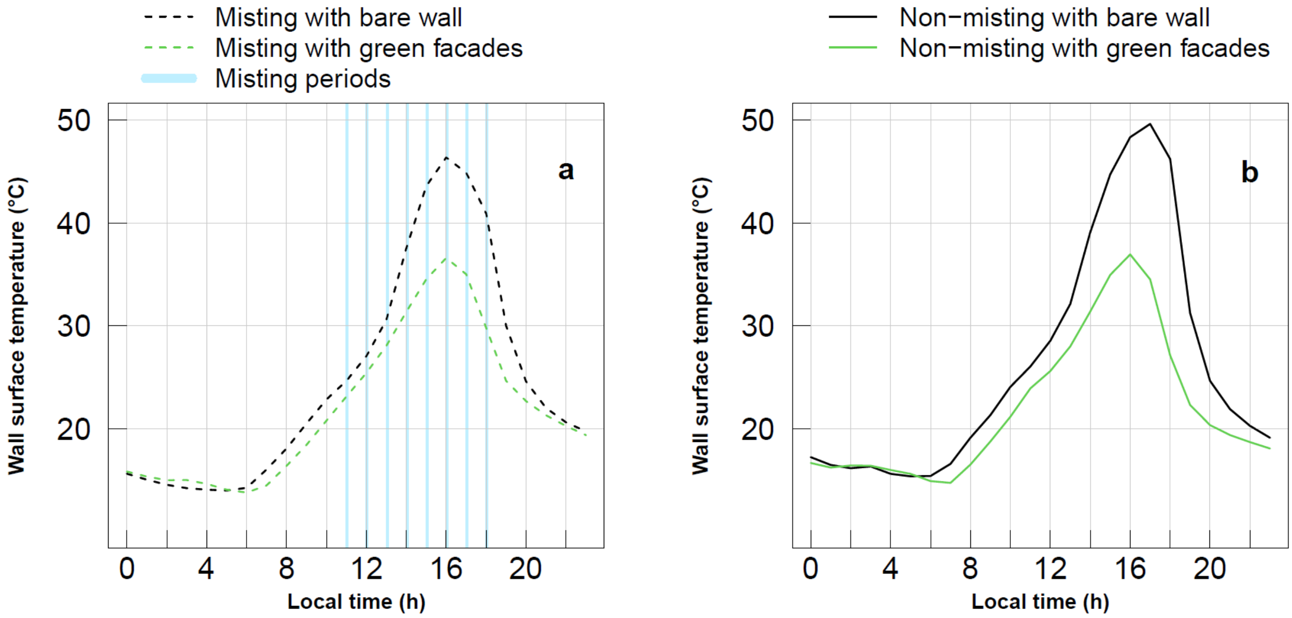


Figure. 4. The average hourly diurnal changes in wall surface temperature for bare wall and green façades on (a) misting days and (b) non-misting days that had hot and cloudless weather conditions (see Table 1).

The thermal images of the bare wall and green façades provided a snapshot of their difference in wall surface temperature at 17:00 when the background air temperature was 33.5 °C (Figure 5). The wall surface temperature of the bare wall (44.7 °C) was 7.9 °C higher than the green façades (36.8 °C).

Figure. 5. Thermal images that show the differences in wall surface temperature between the bare wall and the green façades without the influence of misting when the background air temperature was 33.5 °C.

The installation of a misting system and green façades in private homes is a long-term investment for many people. It is important to understand the cooling effectiveness of these measures to help people make informed decisions. The results of this study suggested that five minutes of misting (with bare wall or with green façades) is effective in reducing air temperature for approximately 30 minutes and human heat stress for approximately 15 minutes on sunny days in summer. Longer misting time will likely reduce air temperature by a greater amount. Continuous misting for 30 minutes was measured to reduce air temperature from 35.7 °C to 29.0 °C at 40 % relative humidity in sunny weather conditions (Huang et al., 2011). Their measured air temperature reduction was >10 times higher than ours. However, continuous misting for 30 minutes may cause discomfort as water droplets may start to wet people's skin and clothing if the misting rate exceeds the evaporation rate. The manufacturer of the misting system that we used in this study recommends misting for 15 seconds and pausing for 20 seconds to allow all mist to evaporate. More studies are needed to optimise the misting operation timetable for different climate and weather conditions.

The air temperature and heat stress reductions due to misting were not strengthened by adding green façades. This suggested that the evaporation that occurs on the surface of the green façades did not contribute to additional air temperature and heat stress reductions. The evaporation of water droplets that occurs on the skin of a person, which is approximated by the surface of the black globe thermometer, is the main mechanism through which misting reduces heat stress (Lehnert et al., 2021). The evaporation of water droplets on skin directly reduces skin temperatures and human heat stress as evaporation absorbs heat from the skin (Farnham et al., 2015; Oh et al., 2020).

The green façades were effective in reducing external wall surface temperature. This will substantially reduce heat gains of the building and indoor heat stress (Medl et al., 2017). However, green façades are unlikely to reduce outdoor heat stress because they do not provide shade, and they are ineffective in reducing outdoor air temperature (Wong et al., 2010). The outdoor thermal benefits of vertical greening can be improved if they are trained to grow with overhead structures such as arbor and pergola to provide shade (Pfautsch et al., 2025; Water Sensitive Cities Australia, 2023). These shading structures will also strengthen the cooling benefits of misting because misting is more effective in cooling in shade than in sun (Vanos et al., 2022).

Urban heat is expected to increase in many parts of the world due to climate change in urban densification. It is important to design and manage backyards to increase the amount of time that they are thermally comfortable to use. The results of this study suggested that misting is an effective measure to reduce human heat stress in backyards. Further studies are needed to identify the optimal misting timetable for different background climate and weather conditions. Installing green façades in backyards cannot increase the cooling benefits of misting. Misting with overhead vegetated shading structures such as arbor and pergola are recommended to optimise human thermal comfort through both evaporation and shading.

4. Water cycle benefits

Methodology (Work Package 4)

Retaining stormwater runoff onsite – infiltration trenches on the private lot

Sealing native soils with impervious surfaces changes the water balance. In pre-urban landscapes, very little rainfall becomes surface runoff. Most rainfall infiltrates the soil, recharging groundwater, or is lost to the atmosphere through evapotranspiration. With increasing urbanization, the water balance becomes dominated by surface runoff, commonly referred to as urban stormwater runoff (Walsh et al., 2009). Such changes to the water balance contribute to altered flow regimes (Figure 1), characterised by an increased frequency and magnitude of high flows, as well as reduced baseflows. These hydrologic changes are directly linked to the degradation of urban stream ecosystems (Walsh et al., 2005). In addition, the increase in high flows can lead to more frequency and severe nuisance flooding.

To address the issues caused by increased surface runoff in urban landscapes, alternative approaches towards urban stormwater management have emerged (Fletcher et al., 2014). These approaches aim to mitigate the hydrologic and ecological impacts of urbanisation by promoting infiltration, evapotranspiration, and retention of urban stormwater runoff. Collectively referred to as Water Sensitive Urban Design (WSUD) in Australia, these strategies seek to mimic natural hydrologic processes within the built environment.

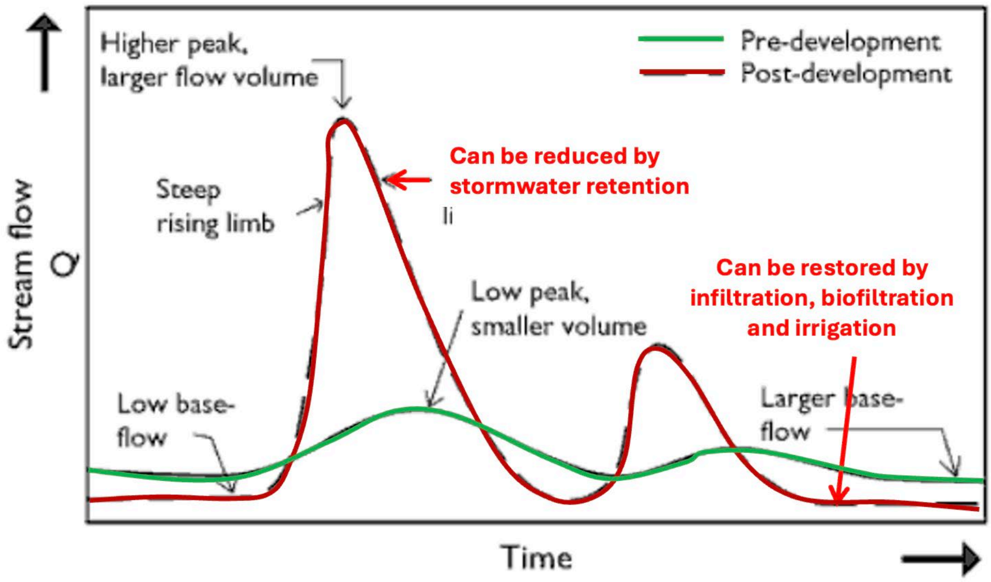


Figure 1. Changes to the flow regime caused by urban stormwater runoff. Retaining stormwater helps reduce peak flows, while promoting infiltration is essential for restoring diminished baseflows.

There is a suite of tools commonly used in WSUD to manage and treat urban stormwater effectively. At the private allotment scale, rainwater tanks and infiltration-based measures are particularly common. Rainwater tanks are designed to retain runoff by capturing and storing it for both internal (e.g. toilet flushing and clothes washing) and external household use (e.g. garden watering). They are most effective when water demand is consistent and regular, helping to maximise the reuse of harvested rainwater (Burns et al., 2015). Infiltration trenches also retain runoff, but unlike rainwater tanks, they primary promote infiltration by allowing water to exfiltrate slowly into the surrounding soils. This process helps to recharge groundwater and reduce surface runoff volumes. An important benefit of infiltration trenches is that they are passive systems, functioning continuously without requiring active management.

The aim of this component of the project was to evaluate the effectiveness of infiltration as a method for retaining urban stormwater runoff within private lots. To achieve this, an infiltration trench was constructed within the footprint of an existing residential property in Lyndhurst, Victoria—commonly referred to as the Aquarevo house. The hydrologic performance of the trench was monitored over a 3-month period, with monitoring still ongoing.

Study design

The demonstration house features a total roof area of 292 m2. Approximately 100 m2 of roof drains to a 2,400L rainwater tank located on the eastern side of the property. Water from this tank is used internally for hot water; however, usage is minimal as the house is currently unoccupied. Another rainwater tank, located on the western side of the property, receives roof runoff from a single downpipe. This tank supplies water for external garden use; however, usage is again minimal. Overflow from the rainwater tanks, along with runoff from roof areas not connected to the tanks, drains to the designated discharge point.

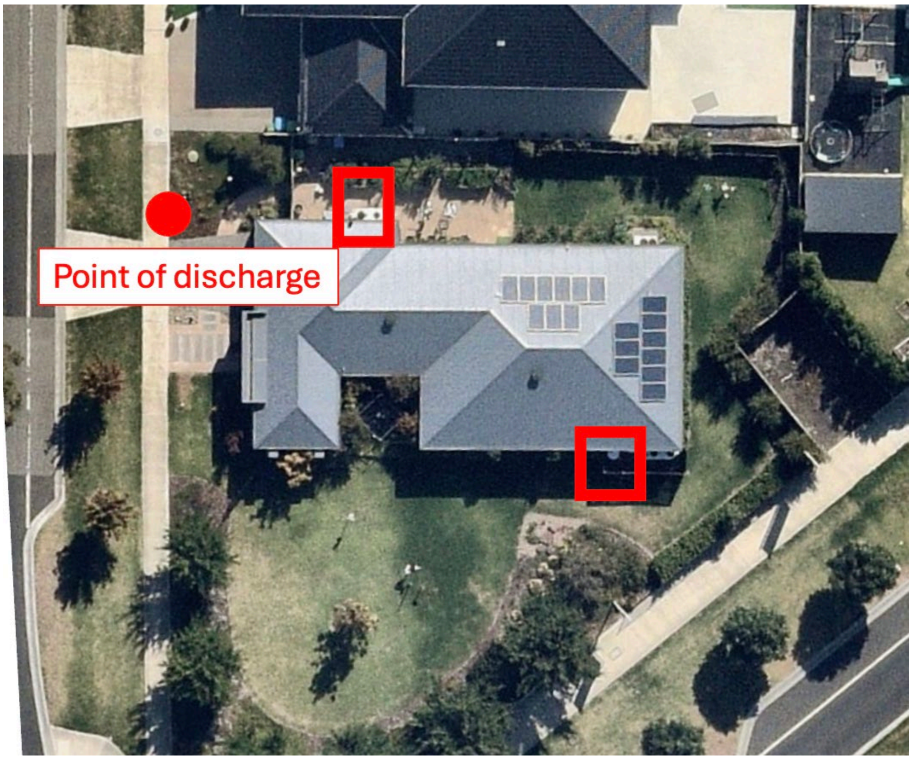


Figure 2. Aerial image of the Aquarevo house. The red circle indicates the drainage point where all stormwater runoff from the property is directed. The two red boxes highlight the locations of rainwater tanks on the property.

The infiltration trench was installed alongside to the footpath shown in Figure 3. Construction took approximately one week and involved two major components. The first component involved the installation of a diversion pit, which intercepted all stormwater runoff from the property by connecting into the existing legal point of discharge (Figure 2). The second component involved construction of the trench itself (Figure 3). A hole was excavated to a depth of 1 m, with dimensions of 10 m in length and 0.9 m in width. The exaction was filled with structural soil, and a slotted pipe was installed within the trench. Additional structural soil was then placed above the pipe to complete the backfilling process. The slotted pipe was connected to the diversion point.

Figure 3. Construction of the infiltration trench. The structural soil used in the trench is visible on the left-hand side of the image.

To measure the hydrologic performance of the infiltration trench, monitoring sensors and supporting infrastructure were installed (Figure 4). A V-notch weir and water level sensor were installed in the pit to monitor overflow from the property. In addition to its monitoring function, the weir also acted as the control mechanism for maintaining the water level in the trench. Standard weir equations were used to convert water level measurements into discharge. Another water level sensor was installed in the monitoring pipe, which had been placed within the infiltration trench during construction. This sensor enabled the calculation of water exfiltration from the trench. Both water level sensors were pressure transducers, custom-built by staff from the Waterway Ecosystem Research Gorup at The University of Melbourne.

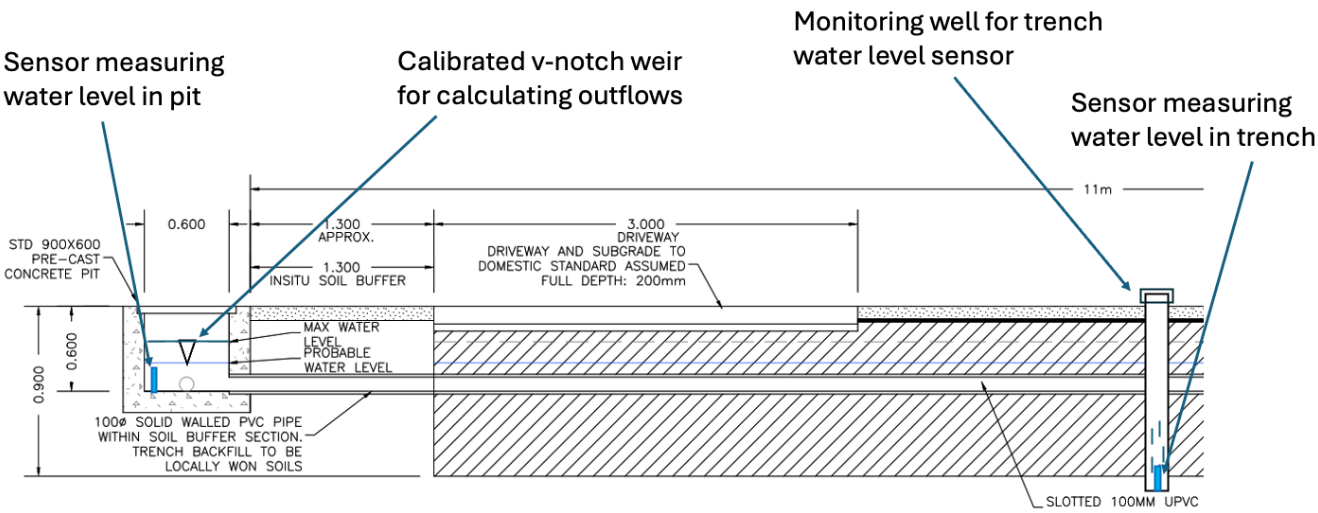


Figure 4. Monitoring setup of the infiltration trench. The configuration enabled calculation of both overflow leaving the property and exfiltration from the trench.

Results and Discussion (Work Package 4)

Hydrology Targets to Achieve "Zero" or Pre-Urban Runoff

During the monitoring period from February to May 2025, an estimated 27,000 litres of rainfall fell on the roof area of the Aquarevo property, generating approximately 26,000 litres of stormwater runoff. This runoff was conveyed to the infiltration trench via the diversion pit. Under pre-urban conditions, approximately 7,000 litres of runoff could have been generated from a parcel of land the same size as the roof over this three-month period. Therefore, for the trench to mimic natural hydrology over this period (i.e., achieve 'zero' runoff), the total overflow from the property should be less than 7,000 litres. In addition to managing surface runoff, it is necessary to address the reduction in baseflows caused by decreased infiltration. A possible infiltration target is derived by converting the annual pre-urban streamflow (in mm) of the nearest waterway (https://tools.thewerg.unimelb.edu.au/mwstr/) to a volume by multiplying it by the impervious catchment area (292 m²), then dividing by 365 to obtain a daily target. For the Aquarevo property, the daily infiltration target is around 100 L/day.

Hydrology performance

Over the three-month monitoring period, the infiltration trench retained the majority of runoff generated from impervious surfaces on the Aquarevo property. Total overflow from the property during the monitoring period was approximately 2,000 litres, well below the pre-urban runoff target of 7,000 litres (Figure 5). Although the monitoring period was relatively short, overflows generally occurred only in response to high-intensity rainfall events. At this stage, exfiltration from the trench into the surrounding soils could not be accurately quantified due to the lack of an estimate for the porosity of the structural soil used. Nevertheless, exfiltration did occur and will be estimated in future work using water level data collected during recession periods (Figure 6).

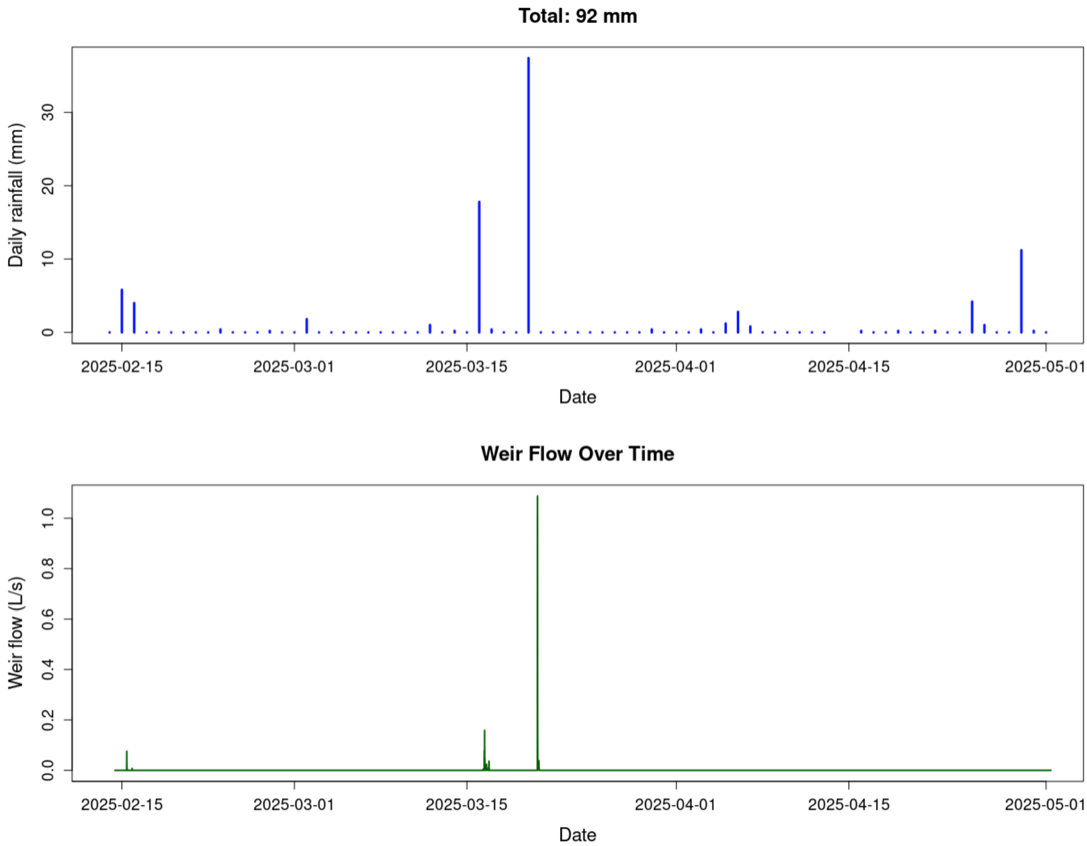


Figure 5. Daily rainfall recorded at the Aquarevo property (top panel) and corresponding sub-daily overflows discharged from the property (bottom panel).

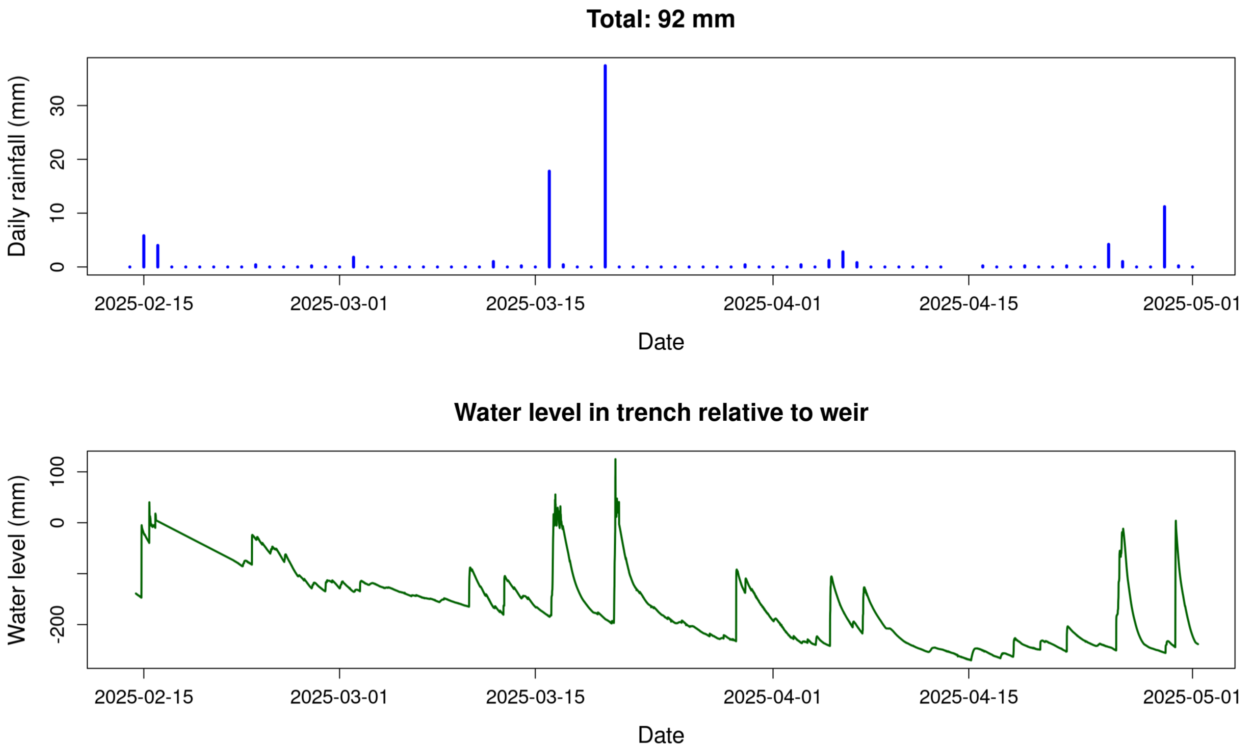


Figure 6. Daily rainfall recorded at the Aquarevo property (top panel) and corresponding sub-daily water level in the infiltration trench (bottom panel).

Implications

Although the monitoring period spanned only three months, the results demonstrate that zero or 'natural' runoff from private lots is achievable through the use of infiltration trenches. This finding is encouraging given that the trench installed at the Aquarevo property was installed in soils with low hydraulic conductivity. Had the trench been situated in more permeable soils, its performance would likely have been even greater. These findings should provide urban planners and stormwater managers confidence that such technologies can play an important role in managing urban stormwater runoff at the source. As passive systems, infiltration trenches require minimal operational input, offering a low-maintenance solution to the stormwater problem. And they also help compensate for the loss of baseflows in urban areas by enhancing groundwater recharge.

Protection or restoration of flow regimes at the catchment scale requires interventions at a range of scales, including within private lots. By maximising stormwater retention within private lots, managing runoff from roads and other areas becomes more feasible and effective. This work further highlights that new housing can be designed to minimize runoff through the implementation of effective stormwater solutions, such as rainwater tanks and infiltration trenches.

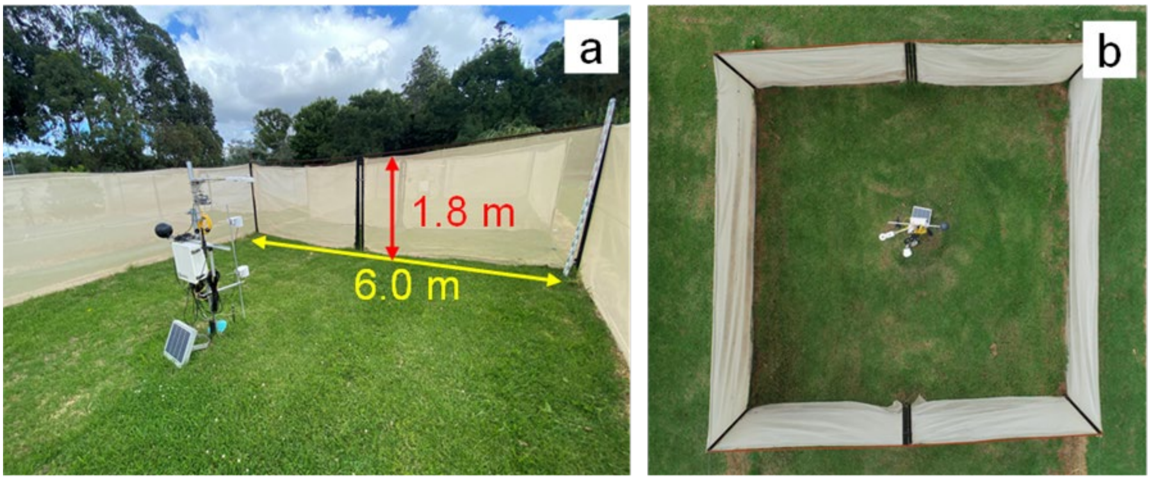
Outputs

Table 1. Output summary for GC21000

Output	Description	Detail
Journal article: Cheung, P. K., & Livesley, S. J., 2025. The microclimate, surface energy flux and human skin burn risks of artificial turf as compared to natural turf. Building and Environment, 112679. https://doi.org/10.1016/j.buildenv.2025.112679	This output reported the surface temperatures, and the associated risk of skin burns for artificial turf as compared to natural turf (results of Work Package 3.1). The intended audience includes researchers, policy makers, landscape designers, and the public.	This output was published in an international peer-review Journal and is available at: https://www.sciencedirect.com/science/article/pii/S0360132325001611
Popular science article: Cheung, P. K., & Livesley, S. J., 2025. Here's how to make your backyard safer and cooler next summer. The Conversation.	This output summarised the findings of Work Packages 3.1 and 3.2, and made recommendations to keep backyards safe and cool in summer. The intended audience includes policy makers, landscape designers, and the public.	This output was published by the Conversation and is freely available here: https://theconversation.com/heres-how-to-make-your-backyard-safer-and-cooler-next-summer-254928 This output has attracted >8,000 views
Conference presentation: Cheung, P. K., & Livesley, S. J., 2025. Designing private residential gardens that are climate resilient and temperature safe. In the Australasian Housing Researchers Conference (AHRC) 2025: Housing at a crossroad: wealth, inequality and housing futures. The University of Sydney 19-21 February 2025.	This output reported the findings of Work Package 3.2. The intended audience includes researchers, policy makers, landscape designers, and the public.	This output is an in-person presentation at the Australasian Housing Researchers Conference 2025.
Conference presentation: Macaulay, R., Lavau, S., Williams, N.S.G., & Hahs, A.K, 2025. Resident preferences and role of green spaces in Australian greenfield estates. In the Australasian Housing Researchers Conference (AHRC) 2025: Housing at a crossroad: wealth, inequality and housing futures. The University of Sydney 19-21 February 2025.	This output reported the findings of Work Package 1.1. The intended audience includes researchers, policy makers, landscape designers, and the public.	This output is an in-person presentation at the Australasian Housing Researchers Conference 2025.
Industry article: Cheung, P. K., & Livesley, S. J., 2025. Burn Risk: New Research Demonstrates Alarming Synthetic Turf Findings. TurfConnect Magazine, Winter edition, p 8-9.	This output reported the results of Work Package 3.1 in laymen terms. The intended audience includes practitioners, policy makers, landscape designers, and the public.	This output was published in the TurfConnect Magazine of Turf Australia. https://www.turfaustralia.com.au/wp-content/uploads/2025/07/TurfMagazine_Issue44_Winte

		r2025_36pp_Final.pdf
Industry article: Cheung, P. K., & Livesley, S. J., 2025. Surface temperatures and burn risks: artificial vs. natural grass. Irrigation Australia Journal, winter edition, p 52-53.	This output reported the results of Work Package 3.1 in laymen terms. The intended audience includes practitioners, policy makers, landscape designers, and the public.	This output was published in the winter 2025 edition of the Irrigation Australia Journal. https://issuu.com/irrigationaustralia/docs/irrigation_australia_journal_winter_2025
Industry & government workshop: Online and in person workshop held at the Burnley campus, University of Melbourne. Final workshop to communicate project findings and to elicit comment and feedback	The audience was made up of 30 participants from Landscape Architecture, Landscapers, State government planning, local government urban greening, Nursery and Garden Industry Victoria and other Universities.	Four videos will be released through University of Melbourne website to provide a resource for other stakeholders to view the presentations and discussion.
Macaulay, R., Lavau, S., Williams, N.S.G., & Hahs, A.K., in review. Resident values shape green infrastructure interactions in new greenfield developments. Urban Forestry & Urban Greening (Under Review)	This output reported the findings of work Package 1.1 The intended audience is practitioners, policy makers, landscape designers, and the public.	This output is currently under review and will hopefully be published and available in 2025.
Macaulay, R., Lavau, S., Williams, N.S.G., & Hahs, A.K., in review. Social and psychological values for private and public green spaces in a new greenfield estate: A qualitative study. Urban Forestry & Urban Greening (Under Review)	This output reported the findings of work Package 1.2 The intended audience is practitioners, policy makers, landscape designers, and the public.	This output is currently under review and will hopefully be published and available in 2025.
Technical CAD drawing: Burns, Szota, Livesley, Poelsma and Tainton (2025) created an engineer's technical drawing for the construction of an infiltration trench at the front of a private lot.	This output reported the findings of work Package 4 The intended audience is road engineers, environmental engineers, construction industry and developers, landscape designers.	This output will be made freely available from the website: bluegreenstreets.org.au

Photos/images/other audio-visual material



Four videos from presentation of the Final workshop can be made available with Talent Release Form

Outcomes

Table 1. Outcome summary for GC21000

Outcome	Alignment to fund outcome, strategy, KPI	Description	Evidence
Knowledge and evidence of the unrealized demand for smaller footprint homes, and greater outdoor green infrastructure, in build options for new greenfield residential developments.	Outcome 1: Demand creation - supports the Australian nursery industry to develop existing and future domestic markets. 1. Increase domestic consumer demand for quality Australian greenlife products through improving knowledge, attitudes and purchase intent KPI - Positive influence on consumer preference	Very relevant to the SIP 2022-26 in Demand creation, or in this case demand realization, if the nursery industry can work with developer and construction industry to provide smaller footprint housing options.	Survey >1000 homeowners in new residential developments in Sydney, Melbourne and Adeliade. 49% preference to have the option to have purchased a smaller footprint house and larger outdoor space (WP1).
Knowledge of the social, economic and cultural issues that drive unique perspectives on the value of green infrastructure in public and private green spaces in new greenfield residential communities.	Outcome 4: The Australian nursery industry is more profitable through informed decision-making using consumer knowledge and tracking, production statistics, forecasting, benchmarking and independent reviews. 1. Increase industry alignment with quality and brand-positioning opportunities driven by consumer insights* KPI - Delivery of consumer insights strategy KPI - Evidence that consumer insights inform strategic market engagement (case studies)	Understand the role of private and public urban greening on the well-being, sense of community and nature-connection of new greenfield residential communities.	Interview one-on-one providing insight "in their own words" and survey of >1000 homeowners in Sydney, Melbourne and Adelaide (WP1)
Quantify and demonstrate how private green infrastructure can make new residential development more climate resilient.	Outcome 1: Demand creation supports the Australian nursery industry to develop existing and future domestic markets. 2. Promote the nursery industry's sustainability credentials to enhance the industry's reputation KPI - Positive influence on consumer preference	Improved climate resilience of outer suburb communities through reduced flood risk, reduced local summer heat stress, and improved waterway environmental ecology.	Quantified the runoff reduction of blue-green infrastructure infiltration trench on a private lot (WP4). Quantified the reduced air temperatures and human thermal stress from replacing artificial turf with natural turf, and from the use of misting in private backyards (WP3).

Understand the cost-benefit drivers and economic business case for the developed industry to make space for green-blue infrastructure on private properties.	Outcome 1: Demand creation supports the Australian nursery industry to develop existing and future domestic markets 1. Increase domestic consumer demand for quality Australian greenlife products through improving knowledge, attitudes and purchase intent KPI - Positive influence on consumer preference	The Developer and Construction industry will hopefully realise there is a market demand for smaller footprint homes and therefore greater outdoor space which will required greening and therefore an ongoing market opportunity for residential market to turf and nursery growers.	Hedonic price modeling and cost-benefit analysis shows the high sales value ($120k) premium of including green space and quality green infrastructure (WP2).
Understand cost-benefit for homeowners, and the greater housing market, to select and maintain green infrastructure on their private properties.	Outcome 1: Demand creation supports the Australian nursery industry to develop existing and future domestic markets 1. Increase domestic consumer demand for quality Australian greenlife products through improving knowledge, attitudes and purchase intent KPI - Positive influence on consumer preference	Purchasers of homes in these new residential developments will learn of the sales value premium for properties with greater green space when maintained with high quality green infrastructure.	Hedonic price modeling and cost-benefit analysis shows the high sales value ($120k) premium of possessing a property with larger outdoor green space with quality green infrastructure (WP2).

Monitoring and evaluation

Table 1. Key Evaluation Questions for project GC21000

Key Evaluation Question	Project performance	Continuous improvement opportunities
1. To what extent does the project demonstrate, promote and communicate the benefits of incorporating blue-green infrastructure in new private residential estates?	The project has performed to a very high standard in demonstrating the benefits of green infrastructure in new private residential estates. Presentation of work packages 1 and 3 at national conferences, and publication of media articles, industry articles and scientific publications for work package 3. Promotion and communication of work packages 2 and 4 will now start to perform highly as research has been completed. The industry workshop was the first opportunity for all four work packages to promote and communicate blue-green infrastructure and the response was very positive.	Media articles and industry articles will continue to be published to coincide with scientific publications throughout 2025 and into early 2026. The 'Guide to the benefits of private green infrastructure in new residential developments' will be published later in 2025 – again bringing together all work packages. Work package 4, on water cycle benefits will continue to promote and demonstrate blue-green infrastructure benefits to the urban planning and stormwater management communities in 2025.
2. How relevant was the project to the needs of growers, urban planners and developers?	Project work packages 1 and 2 provide strong social and economic evidence as to the market opportunity to growers, urban planners and developers to increase space for green in private lots. This evidence is unique and very valuable. The project work package 3.1 and 3.2 was very relevant to turf growers by demonstrating the benefits of natural turf over artificial turf. Work package 4 is less relevant to growers, but very valuable to urban planners and developers seeking OR being required legislatively to increase sustainability and lower environmental impact from a runoff perspective.	The work packages (especially 2, 3 and 4) will continue to promote the project findings and evidence base to the horticulture community, industry and developers/urban planners through a workshop online to NSW state government in late 2025, and through future conference presentations and scientific publications as well as industry articles.
3. How well have intended beneficiaries been engaged in the project?	The intended beneficiaries of the development and construction industry have not been well engaged as their economic circumstances changed drastically in the first year of the project. As such the most	Engagement with all stakeholders will increase and continue through 2025 – especially for work packages 2 and 4. Articles in the Conversation are planned, as are industry articles, workshop presentations and scientific

	engaged beneficiaries have been state and local government planners and the water utilities industries. The growers have also been little engaged as yet, but that is increasing as evidenced through the industry workshop and invitation to contribute to the Vic state government lobby event organized by NGIV.	publications.
4. Were engagement processes appropriate to different target audiences?	We are targeting Horticulture magazine and industry journals for growers. For urban planners and developers, we targeted conferences and the final workshop, which was well attended (both). For the development industry we have struggled to regain their interest as economic conditions continue to challenge their fundamentals.	We will continue to improve and diversify our engagement strategies to the urban planning and horticulture grower communities.
5. What efforts did the project make to improve efficiency of communication and promotion?	In the last 6 months of the project (since Jan 2025) we have greatly increased the communication and promotion through the use of industry articles and media releases. These will continue through the rest of 2025.	We will continue to improve industry and general public communication of the project findings though 2025 and into 2026. The online workshop for NSW state government planning will increase the project profile in other parts of Australia than Victoria alone.

Summary of project monitoring and evaluation in Project Reference Group meetings

Project Reference Group (PRG) meeting #2 at 6 months (15 December 2023) the chair reminded all participants that the Monitoring and Evaluation Plant – provided the framework to evaluate progress during a PRG meeting. The #2 PRG stepped through the M&E plan but without full project commencement due to contract variation and absence of collaborative agreement this was deemed premature. However, in the Risk Management Plan two lines of concern were added. The first regarding the risk and impact of Mirvac being unable to construct the Olivine Future Home not constructed before Jan 2025. This was regarded as a “likley’ with “moderate” risk impactions to the project – essentially an inability to install stormwater runoff trench, courtyard misting system, smart water irrigation and tanks. It was suggested that alternative sites for stormwater runoff research elements were investigated, with South East Water (David Bergmann) with lead responsibility with the rest of the project team. The second issue of concern raised in PRG#2 was the inability to sign off on a Collaborative Research Agreement – regarded as a “possible” risk with “moderate” impacts to the project.

PRG meeting #3 on 10 July 2024 at 12 months the three milestone variations to 104, 105 and 190 which pushed project completion back to 05 May 2025 were discussed. The “Likely” risk that Mirvac could not construct the Future Home came to pass, with Mirvac withdrawing this inkind contribution to the project in May 2024. As such, PRG #3 disussed the need to relocate the stormwater runoff research and courtyard cooling research to the Aquarevo Demonstration House managed by South East Water and Villawood Properties. The Project Research Team had already met on site – including David Bergmann, Ninad Dharhadhikari, Matt Burns, Steve Livesley, Chris Szota and Peter Poelsma to talk through the ability to set up the stormwater research package rapidly. The PRG was shown the site through Google maps and a streetview screenshot. PRG #3 was happy to proceed with this as the alternative site and a target date of November 2024 was agreed for instrumentation completed and data collection commenced.

PRG meeting #4 on 12 December 2024 stepped through M&E plan in detail to draw attention to Table 2 and the Intermediate and 'End or Project' Outcomes in the plan and the need for greater promotion of project findings, the conference presentations, the articles, and the project overall to achieve these outcomes. The need to influence urban planners and developers was highlighted for the workshop to be held in 2025.

Recommendations

- Practical application of the project findings
    1. Provide smaller footprint home options in all new residential builder portfolios. Include with these the benefits that can be gained from greening the greater outdoor space provided from a sales value, social, cooling and environmental impact perspective.
    2. Work with developers in other parts of Australia to demonstrate and trial the infiltration trench on private property frontage. This can transform the stormwater runoff reduction of all future residential developments. This will also require involvement and encouragement from the state planning authorities.

- Possibilities of future RD&E that directly flow from the work undertaken and its results
    1. There is an urgent need to follow up with nature positive benefits of greater greening of the private realm in new residential developments – habitat and fauna diversity for nature connection but for conservation in its own right. Greenfield residential developments often adjacent to protected conservation areas, so providing greater habitat resources makes sense to reduce environmental impact and to provide a sense of place and community pride with regards to the local natural values.
    2. The hedonic analysis is very persuasive and will be the greatest aspect to gain interest from developers and builders. This type of analysis should be repeated in Queensland, Victoria and Western Australia to provide context and local evidence base.

- Development and adoption activities that would ensure full value from the project's findings for industry.
    1. Need for nursery industry to engage with Developers and Builders so that they adopt smaller footprint home offerings in their construction portfolio.

Refereed scientific publications

Journal articles

Cheung, P. K., & Livesley, S. J., (2025). The microclimate, surface energy flux and human skin burn risks of artificial turf as compared to natural turf. *Building and Environment*, 112679.

Macaulay, R., Lavau, S., Williams, N.S.G., & Hahs, A.K., (in review). Resident values shape green infrastructure interactions in new greenfield developments. *Urban Forestry & Urban Greening (under review)*

Macaulay, R., Lavau, S., Williams, N.S.G., & Hahs, A.K., (in review). Social and psychological values for private and public green spaces in a new greenfield estate: A qualitative study. *Urban Forestry & Urban Greening (under review)*

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Introduction

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Intellectual property

No project IP or commercialisation to report.

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Appendices list

Appendix 1 – *Online Panel Survey Questions*

Appendix 2 – *CoreLogic data and house attributes*

Appendix 3 – Cross section of the artificial turf plot

Appendix 4 – CAD technical drawing of the infiltration trench

Appendix 1

Online Panel Survey (>1000 respondents)

A. Screening questions

A1.

Are you 18 years or older?

Yes
No

A2. What state or territory do you currently live in?

Victoria
New South Wales
South Australia
Western Australia
Northern Territory
Australian Capital Territory

A3.

What is your postcode at your current residential address?

My postcode is not in this list
List of eligible postcodes from state (depending on answer to above question)

A4.

Which of the following options best describes the area where you currently live?

Recently developed housing estate, < 5 years since development
Established housing estate, 5-15 years since development
Well-established housing estate, > 15 years since development
Other – e.g., rural area outside suburban housing estate

A5.

Is your current residence:

Owned outright (by you or family member)
Owned with a mortgage (by you or family member)
Rented
Occupied rent free
Other, please describe: *text entry*

A6.

What language/s do you primarily speak at home?

English
Other, please specify: *text entry*

B. Interactions with public GI

We are interested in the way you think about and interact with the public green space in your neighbourhood. By *green space*, we are referring to all the public natural features around where you live, including public parks, street trees, verge gardens or nature strips, and waterways.

B1. How often do you visit green space in your neighbourhood? *By green space, we are referring to all the public natural places around where you live, including public reserves or parks, waterways, community gardens, golf courses.*

Never
Rarely (a few times a year, or less)
Occasionally (monthly to fortnightly)
Frequently (weekly)
Very frequently (daily or multiple times a week)

B2. When you spend time visiting local green space, what do you <u>usually</u> do there? *(Please indicate your usual activities at your local green space. Choose as many as apply).*

	Never	Sometimes	Often	Most of the time
Rest and recover				
Engage in social activities				
Accompany children to an activity				
Engage in any form of physical activities				
Enjoy a sense of peace, tranquillity and awe				
Engage in cultural activities				
Enjoy and connect with nature				
Have a picnic or BBQ				
Walk your dog				
Gardening				
Pass through to reach my destination				
Act to protect the natural environment				

B3.

Do any of the following factors prevent you from visiting local green space?

	Statements	Never	Sometimes	Often	Most of the time
1	I prefer to do other indoor activities				
2	The local green space is too far away				
3	A lack of time				
4	I dislike some of the wildlife, such as birds or insects				
5	Weather				
6	Not safe				
7	No appropriate facilities				
8	Facilities are too far away or inaccessible				
9	A lack of transport				
10	Poor health or physical ability				
11	Nothing special to see or do				
12	Other (please specify)______________				

B4.

How long would it take you to walk to your local green space? *Please answer in minutes. If the walk would take 10 minutes please write 10. If the walk would take 1 hour, please write 60.*

____ Minutes

B5. NAVS. Please indicate the extent to which you agree with the following statements about natural areas. *5-point Likert scale from strongly disagree to strongly agree.*

I value natural areas mainly because they give me a sense of awe and peace
I value natural areas primarily for their beauty
The beautiful atmosphere of natural environments is what I value about them
Nature is of value because it gives me a sense of peace, quiet and tranquillity
It is better to test new drugs on animals than on humans
All plants' and animals' lives are precious and worth preserving, but human needs are more important than all other beings
To say that natural areas have value just for themselves is a nice idea, but we just cannot afford to think that way: the welfare of people has to come first
I don't like industries such as mining destroying parts of nature, but it is necessary for human survival
The only value that a natural place has is what humans can make from it
The value of an ecosystem only depends on what it does for humans
Only humans have intrinsic value, that is, value for their own sake
Natural areas are valuable to keep for future generations of humans
I'm seeing natural areas the next generation of children may not see, and that concerns me
I need to know that natural places exist
We have to protect the environment for humans in the future, even if it means reducing our standard of living today

B6. VALS. Please indicate how important to you each of the following things are about public green space in your neighbourhood? *7-point Likert scale.*

Rare or threatened plants and animals
Native plants and animals
Having many kinds of plants and animals
Healthy land and waterways in which natural processes can continue
Large trees
Learning about nature
Experiencing nature through activities such as sight-seeing or bird watching
Being accessible for people
Spaces for people to interact and socialise
A place that is safe for people to visit
Spaces for people to exercise, e.g., jogging, walking
Beautiful scenery
A sense of peace, tranquillity and awe
Rest and recovery from the stresses of daily life
Uniqueness, being different to other places
Learning about cultural traditions
Experiencing human history and stories
Naturalness and fresh air
Water (e.g., pond, lake, creek)
Well-maintained
Open space
Seating / sitting areas
Children’s playgrounds
Community garden

C. Private green infrastructure

We are interested in the way you think about and interact with the private green space in your home. By *private green space*, we are referring to all the outdoor natural features in your home, including your private backyard and front yard garden, green walls, and facades.

C1. Which of the following describes the private green space in your home? *Select all that apply.*

Large backyard and/or front yard (i.e., size of a tennis court or larger)
Medium backyard and/or front yard (i.e., between the size of a carport and tennis court)
Small backyard and/or front yard (i.e., size of a carport or smaller)
Courtyard with greenery
Courtyard with no greenery
Balcony with greenery
Balcony with no greenery
Vegetable garden and/or fruit trees
Large/established trees in front or backyard
Significant lawned area
Gardened area with trees, shrubs and/or flowering plants
Entertainment area (e.g., includes decking)
Pool

C2.

How often do you spend more than 10mins a day in your garden or backyard?

Never
Rarely (a few times a year, or less)
Occasionally (monthly to fortnightly)
Frequently (weekly)
Very frequently (daily or multiple times a week)

C3.

When you spend time in your garden or backyard, what do you do there?

Statements		Never	Sometimes	Often	Most of the time
1	Gardening				
2	Watching or playing with the children				
3	Relaxing				
4	Working				
5	Playing with pet				
6	Exercising				
7	Eating meals				
8	Spending time with friends/family				
9	Food production – e.g., growing vegetables				
10	Spending time with nature				
11	Other, please specify:				

C4

Do any of the following factors prevent you from spending time in your garden or backyard?

Statements		Never	Sometimes	Often	Most of the time
1	I prefer to do other indoor activities				
2	A lack of time				
3	I dislike some of the wildlife, such as birds or insects				
4	Weather – too hot				
5	Poor health or physical ability				

6	Nothing special to see or do				
7	Other (please specify)_____________				

C5. VALS. Please indicate how important to you each of the following things are about private green space in your home? *7-point Likert scale*

Rare or threatened plants and animals
Native plants and animals
Having many kinds of plants and animals
Healthy land and waterways in which natural processes can continue
Large trees
Learning about nature
Experiencing nature through bird watching, seeing animals or wildflowers
Being accessible for people
Spaces for people to interact and socialise
A safe place for people to be
Space for gardening
Space for playing or other activities
Beautiful scenery
A sense of peace, tranquillity and awe
Rest and recovery from the stresses of daily life
Uniqueness, being different to other places
Learning about and/or practising cultural traditions
Experiencing human history and stories
Naturalness and fresh air
Water (e.g., pond, water feature)
Well-maintained
Open space
Seating / sitting areas
Children's playground
Garden, including vegetable/food garden

D. Outcomes

D1.

Nature connection

Connectedness to nature scale:

Items
1 I often feel a sense of oneness with the natural world around me.
2 I think of the natural world as a community to which I belong.
3 I recognize and appreciate the intelligence of other living organisms.
4 I often feel disconnected from nature.
5 When I think of my life, I imagine myself to be part of a larger cyclical process of living.
6 I often feel a kinship with animals and plants.
7 I feel as though I belong to the Earth as equally as it belongs to me.
8 I have a deep understanding of how my actions affect the natural world.
9 I often feel part of the web of life.
10 I feel that all inhabitants of Earth, human, and nonhuman, share a common 'life force'.
11 Like a tree can be part of a forest, I feel embedded within the broader natural world.
12 When I think of my place on Earth, I consider myself to be a top member of a hierarchy that exists in nature.
13 I often feel like I am only a small part of the natural world around me, and that I am no more important than the grass on the ground or the birds in the trees.
14 My personal welfare is independent of the welfare of the natural world.

D2.
Personal wellbeing – life satisfaction
Personal wellbeing index (Cummins et al., 2003).
The following questions ask about people's satisfaction with different aspects of their life. Please select a response between 0 and 10 for each of the following questions. (Scale 0 to 10)

1	Thinking about your own life and personal circumstances, how satisfied are you with your life as a whole?
2	How satisfied are you with your standard of living?
3	How satisfied are you with your health?
4	How satisfied are you with what you are currently achieving in life?
5	How satisfied are you with your personal relationships?
6	How satisfied are you with how safe you feel?
7	How satisfied are you with feeling part of your community?
8	How satisfied are you with your future security?

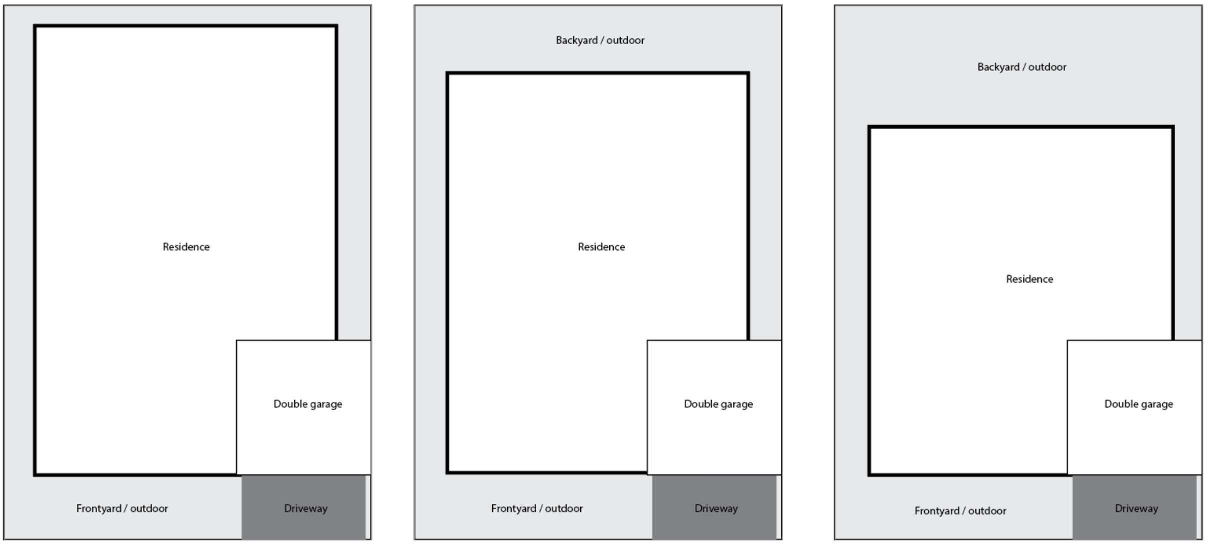
D4.
GI-related housing choices
D4A: We're interested in the types of factors that motivated you to select the home you currently live in. How important were the following factors in motivating you to select your current home? Please answer *Not Applicable* if this question does not apply to you (e.g., you were not involved in the decision to live in your current residence). *From not at all important to extremely important.*

1	Price/affordability
2	Large house/residence size
3	Large land size / outdoor area
4	Proximity to schools, work, or shop
5	Proximity to local green space (e.g., parks)
6	House layout/design (e.g., types of rooms available)
7	Outdoor entertainment area or area for pool
8	Outdoor space for plants/trees
9	Presence of established trees (on own property or within view of home)

D4B: How important would the following factors be if you were buying a <u>new house</u> in the area where you currently live, on a 450m^2 block of land? *5-point scale from not at all important to extremely important.*

1	Price/affordability
2	Large house/residence size
3	Large land size / outdoor area
4	Proximity to schools, work, or shops
5	Proximity to local green space (e.g., parks)
6	House layout/design (e.g., types of rooms available)
7	Outdoor entertainment area or area for pool
8	Outdoor space for plants/trees
9	Presence of established trees (on own property or within view of home)

D4C: Imagine you are buying a new house to move in to in the area where you currently live, on a 450m^2 block of land. Which of the following site plans would be most preferable to you?



D4D: To what extent did the following factors motivate your response?

	Statements	Not at all		Moderately		Very much
1	Cost (financial, time, or other) of maintaining outdoor space					
2	Cost (financial, time, or other) of maintaining residence/dwelling					
3	Desire for more plants/trees in outdoor space					
4	Desire for fewer plants/trees in outdoor space					
5	Space for outdoor activities (e.g., play, exercise, entertainment)					
6	Similarity to layout of current residence					

E. Demographic questions

E1.

Please indicate your gender

Male
Female
Non-binary
Other

E2.

Please indicate your age

18-20
21-29
30-39
40-49
50-59
60-69
70 or older

E3.

What is your total of all wages/salaries, government benefits, pensions and allowances, or other income for your household? *Income before tax, superannuation contributions, or other deductions.*

$3,000 or more per week $156,000 or more per year
$2,000 - $2,999 per week $104,000 - $155,999 per year
$1,750 - $1,999 per week $91,000 - $103,999 per year
$1,500 - $1,749 per week $78,000 - $90,999 per year
$1,250 - $1,499 per week $65,000 - $77,999 per year
$1,000 - $1,249 per week $52,000 - $64,999 per year
$800 - $999 per week $41,600 - $51,999 per year
$650 - $799 per week $33,800 - $41,599 per year
$500 - $649 per week $26,000 - $33,799 per year
$400 - $499 per week $20,800 - $25,999 per year
$300 - $399 per week $15,600 - $20,799 per year
$150 - $299 per week $7,800 - $15,599 per year
$1 - $149 per week $1 - $7,799 per year
Nil or negative income

E4.

What is the highest degree or level of school you have completed?

Less than Year 12 or equivalent
Year 12 or equivalent
Vocational qualification
Undergraduate degree
Postgraduate degree

E5.

What is your country of birth?

Drop down list of countries

E6.

What is your mother's country of birth?

Drop down list of countries

E7.

What is your father's country of birth?

Drop down list of countries

E8. Select the below option that best describes the composition of your residential dwelling (where you live currently)

One family household: Couple family with no children
One family household: Couple family with children all older than 15 years
One family household: Couple family with children younger than 15 years
One family household: One parent family
One family household: Other family
Multiple family household: with children
Multiple family household: with no children
Lone person household (live alone)
Group household (e.g., share house)
Other non-classifiable household, please describe: *text entry*

E9.

How long have you been residing in your current residence? (Years)

Please write the number of years. *If you have been residing at your current residence for 6 months, please write 0.5 years. If you have been residing at your current residence for 6 years, please write 6 years.*

Text entry _ Years

E10. What is your current residence like? *Please select an option from the list that best describes the dwelling.*

Detached house (i.e., no shared walls with other houses).
Townhouse/ Semi-detached house/ Terrace house (i.e., shared walls with other houses)
Apartment/ Flat/ Unit
Other, please specify: *text entry*

E11.

Where do you live currently?

Your responses are confidential and will only be used to assess location characteristics such as proximity to local community centres and public green space.

Map

Appendix 2

CoreLogic data and house attributes

App 2, Table 1. Summary statistics for house attributes across the Core Logic data set (n=4341 house sales).

Attribute	Unit	Percentile		
		25th	50th	75th
Contract price	$AUD	620,000	875,000	1,150,000
Land size	m2	278	326	411
Floor area	m2	153	184	225
Bedrooms	#	4	4	5
Bathrooms	#	2	2	3
House-to-block ratio	%	0.45	0.57	0.69

Greenspace quality

For this current study we have used a greenspace quality classification schema based on three key attributes identified by Sun et al. (2021) as being important for greenspace planning. The first two attributes - greenspace configuration (location on a private home block, on an adjacent private block, on the nearby streetscape, within a 200m radius, or within a 500m radius) and greenspace accessibility (public or private) – are presented in App 2, Table 2. Data relating to each of these attributes was collated using NSW Government's 'Six Maps' data service (NSW Government Land and Property Information, 2025). We downloaded a shapefile for each cadastral lot within the focus LGAs – alongside its ownership information and then designated each lot as either private (any lot with ownership listed as 'Freehold') or public (any lot with ownership listed as 'Crown', 'NSW Government' or 'Local Government'). Land areas that were not associated with a specific cadastral lot were designated as 'streetscape'. Diagrams showing additional details of the 'accessibility' and 'configuration' attributes are provided in App 2, Figure 1.

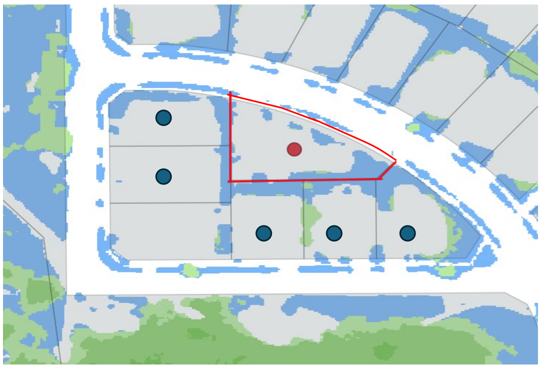
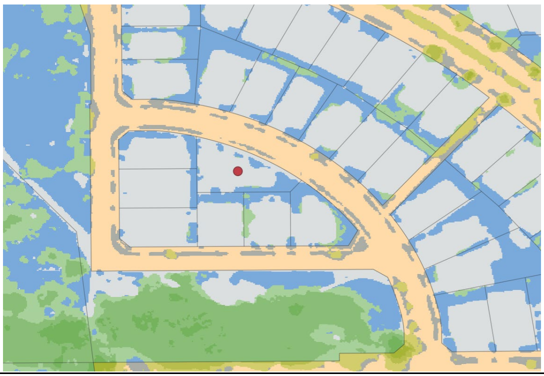
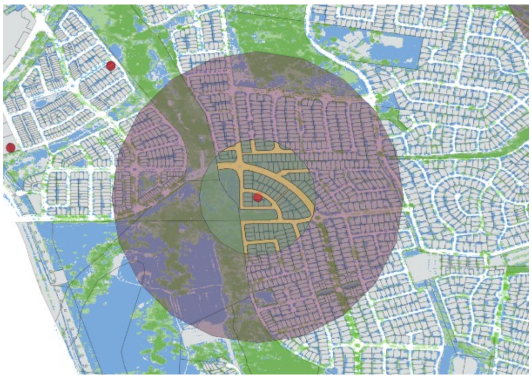
App 2, Table 2. Greenspace quality attributes as classified with reference to accessibility and configuration.

Accessibility	Configuration	Rationale
Private	On home lot	Vegetation on the home lot is typically for the sole use by home owner offers and offers greater privacy with respect to greenspace recreation. It may also offer ecosystem services relevant to housing costs or comfort. For example, trees may provide cooling and reduce the need for air-conditioning.
Private	Adjacent lot	Vegetation on an adjacent private lot may provide visual amenity to neighbouring properties. Shrubs or trees may provide additional benefits like privacy screening and shade.
Public	Streetscape	Vegetation on a streetscape can provide visual amenity and shade and may enhance wellbeing by increasing opportunities for outdoor activity in a social neighbourhood setting. Vegetation on the street frontage may improve drainage, depending on design specification and type of vegetation used.
Public	200m buffer	Access in public greenspace provide opportunity for recreational use – including for exercise, social or personal /experiential purposes. We selected a buffer with a 200m radius for 2 reasons: - It is relevant to a home buyer in that it represents greenspace areas

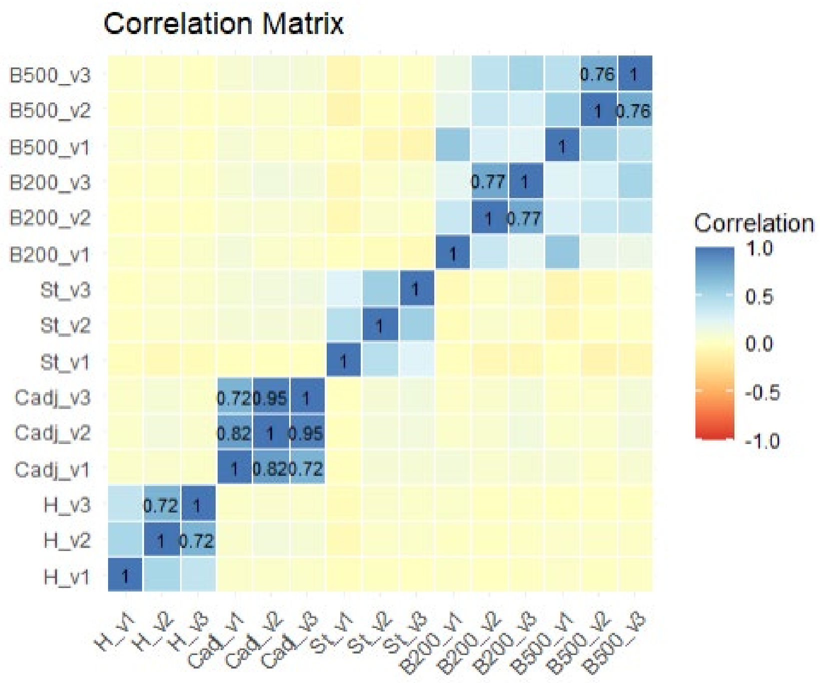
		of 'near walking distance' and hence available for frequent use - It is relevant to developers because it covers an area of ~12ha, which is the size of a 'small' housing development estate.
Public	500 m buffer	We selected a second public space buffer with a 500m radius for 2 reasons: - It is relevant to a home buyer in that it represents greenspace areas of 'intermediate walking distance' or 'short driving distance' and hence available for semi-frequent use - It is relevant to developers because it covers an area of ~28ha, which is the size of a 'large' housing development estate.

Greenspace parameter selection

Combining the three attributes of greenspace quantity and greenspace quality described above yielded 15 variables relating to different types / quality of greenspace. Data exploration identified a high degree of correlation in the area of tress 3-10m high and the area of trees >10m high for each of our greenspace configurations (on a private home block, on an adjacent private block, on the nearby streetscape, within a 200m radius, or within a 500m radius; App 2, Figure 2). Correlations amongst input variables are problematic for many modelling techniques, including generalised additive modelling (GAM) – the technique we have used for our hedonic model. Accordingly, we have summed the variables relating to different tree strata (3-10m, >10m) to give a single measure for trees >3m. We also observed a high degree of correlation between vegetation types with the 200m buffer and those within the 500m buffer areas around each sales lot (App 2, Figure 2) so we used greenspace area within the 500m buffer as a proxy for public greenspace in our hedonic model. The final set of eight greenspace parameters included in hedonic modelling is presented in the main report.

Greenspace accessibility and configuration	Data and methodology
Private greenspace; home and adjacent lots 	Shape files from Six Maps were used to map cadastral lot boundaries for sale properties included in the Core Logic data set (red dot) and any adjacent properties that were designated as having private ownership. A raster layer of height stratified vegetation cover was overlaid on the cadastral lot boundary maps to identify the extent of hard substrate (grey), grasses and low shrubs <3m (blue), trees 3-10m (light green) and trees >10m (dark green). Area measurements of each vegetation type on sale properties and adjacent lots were made using QGIS software and expressed as a percentage of the overall lot size.
Public greenspace; streetscape 	Any area from the Six Maps cadastral lot boundary shapefile that was not associated with a specific cadastral lot was designated as 'streetscape' as shown in the light orange shaded area. For each of the sale properties included in the Core Logic data set (red dot) we mapped the streetscape within a 200m buffer around the property, overlaid the raster layer of height stratified vegetation cover, and made area measurements of each vegetation type as described in the box above. These were expressed as a percentage of the overall streetscape area.
Public greenspace; 200m and 500m buffers 	We constructed a 200m buffer and 500m buffer around each of the sale properties included in the Core Logic data set (red dot). We overlaid the Six Maps cadastral lot boundary shapefile to identify any lots that were designated as having public ownership. We overlaid the raster layer of height stratified vegetation cover and made area measurements of each vegetation type as described in the box above.

App 2, Figure 1: Greenspace accessibility and configuration attribute classification schema and measurement



App 2, Figure 2. Correlation matrix showing degree of correlation amongst our initial set of greenspace variables. Correlation coefficients >0.7 are displayed. Variable labels - H = home lot; Cadj = adjacent lot, St = Streetscape, B200 = 200m buffer, B500 – 500m buffer; v1 = grasses and shrubs <3m, v2 = trees 3-10m, v3 = trees >10m.

Hedonic Modelling

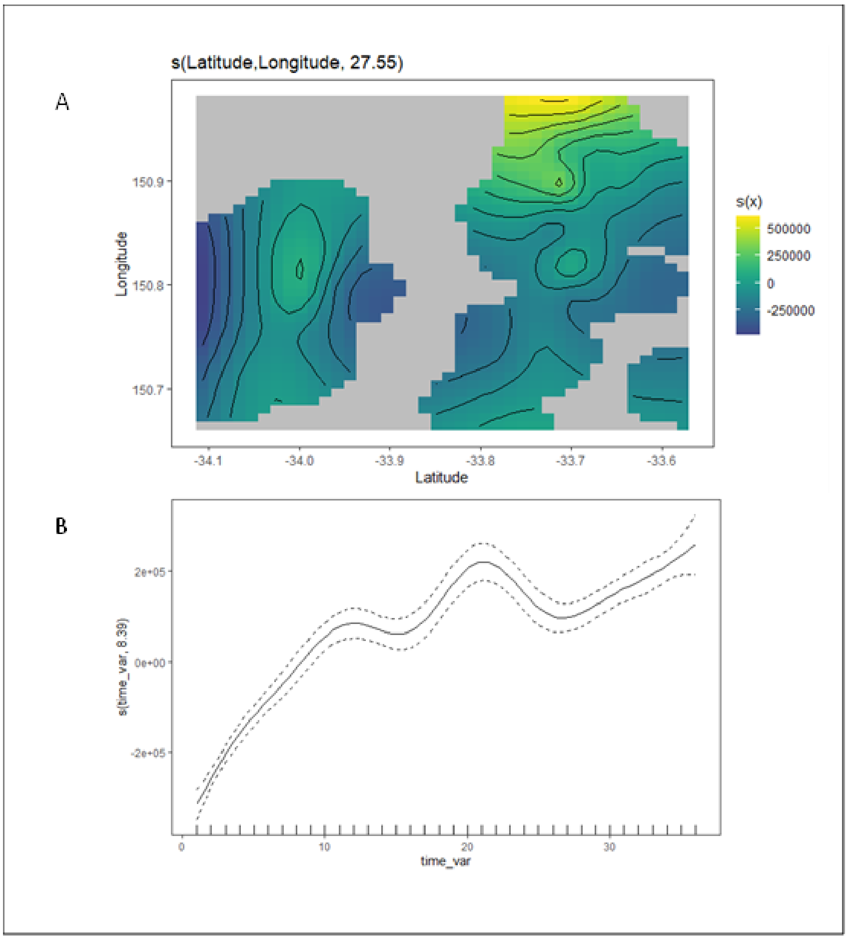
Our GAM included the variables relating to house attributes and the surrounding greenspace characteristics described in previous sections. Hedonic models typically also include a number of locational variables to account for the effect of proximity to beaches, transport, schools, shops, and other neighbourhood characteristics on house prices (Chau & Chin 2003). A very wide range of locational factors may be relevant to property purchasers, and accordingly, a very large number of locational variables have been examined through hedonic modelling – sometimes even within a single study. For example, Des Rosiers et al. (2000) identified 49 potential input variables for their hedonic model of neighbourhood effect on house price in Quebec, Canada; Czembrowski & Kronenberg (2016) include 48 parameters in their model of house prices in in Lodz, Poland.

Having a large number of locational variables as inputs to hedonic modelling can be problematic for two reasons. First many of the locational variables considered relevant to property purchasers are likely to be correlated in some way. For example, schools, shops and other neighbourhood facilities are often built close to one another and close to major transport hubs to maximise their accessibility. This issue of many correlated input variables is sometimes addressed by using dimension reduction techniques like Principal Components Analysis (PCA) or Factor Analysis, as implemented by Des Rosiers (2000), or by using stepwise regression or other model-led parameter selection techniques, as implemented by Czembrowski & Kronenberg (2016). Second, a model can only ever include a finite subset of all possible locational variables. These will be selected by the researcher and may or may not capture the full suite of considerations that are relevant to property purchasers. Where specific locational factors that affect house prices are unknown or unable to be quantified, this may lead to omitted variable bias and erroneous model coefficients. This issue is more difficult to address and is a problem common to modelling studies across disciplines.

In this current study, we seek to address potential for spatial autocorrelation and omitted variable bias by including a spatial term directly into our GAM. Our non-linear spatial term ‘s(latitude, longitude)’ had an unrestricted number of knots. In effect, this term constructs a map of smoothed house price gradients across the study region as the baseline of underlying spatial trends in house prices – which may arise in response to any number of unobserved neighbourhood attributes (App 2, Figure 3). The GAM then assesses the effect of the remaining model terms relating house and greenspace attributes based on whether these are associated with house prices that are above- or below- the price expectation in a given location. Similar approaches have been applied by Veie & Panduro (2013), Von Graevenitz & Panduro (2015) and Valtiala et al. (2019). The approach also builds on a range of previous studies that have sought to address the problem of spatial autocorrelation and/or omitted variable bias in hedonic modelling. For example, Law (2017) accounts for price effects associated with variation in neighbourhood character using a multi-level regression model that includes 'street local area' as a categorical grouping factor; Bax et al. (2021) use GAMs with a random term from each suburb in their large dataset of house sales in South Africa.

We also included a temporal term in our GAM model to account for price effects associated with changing property market conditions through time. In this case we included a non-linear term 's(month)', which represented a sequential count of months from the start of the study period and had an unrestricted number of knots. This method of generating temporal house price indices has been used by Mason & Quigley (1996) and Waltl (2016) and was recommended in a review by Hill & Rambaldi (2022).

GAMs are susceptible to the influence of outliers (Templ 2024). Accordingly, we have removed outliers (any point more than 3 standard deviations from the mean) prior to analysis. All input variables in our GAM (with the exception of spatial and temporal autocorrelation terms) were limited to a maximum of three knots (inflection points) to prevent overfitting and enable interpretation of key non-linear trends like threshold or parabolic (maxima or minima) effects. GAMs were implemented using *mgcv* package in R (Wood 2011).



App 2, Figure 3. Spatial and temporal terms used to account for autocorrelation effects in house prices. A shows a map of underlying house price trends generated from the non-linear term 's(latitude, longitude)'; B shows the background temporal trend in house prices over the study period 2021-2023 as generated from the non-linear term 's(month'.

App 2, Table 3. Costs and other parameters used for cost-benefit analysis of greenspace features in our study area

Parameter	Description	Estimate	Source
House build cost	Cost of housing provision; estimated on a per square metre basis averaged across the full house size; mean for 4-bedroom weatherboard and 4-bedroom brick veneer	\$2,800/m^2	BMT (2025)
House sales price	Median contract price for dwellings included in the Core Logic dataset used in this current study	\$875,000	CoreLogic data
Developer's margin	Mean profit margin retained by developers in association with new build projects	18%	The CIE (2024)
Non-house hard substrate cost	Cost of non-house hard substrate landscaping features like driveways, patios; includes costs of material and labour	\$90/m^2	Average from 3 local commercial suppliers
Low vegetation cost	Cost of low vegetation (grasses and shrubs <3m); includes costs of material and labour	\$100/m^2	
Trees cost	Cost of trees (>3m); includes costs of material (mature trees), transport and labour	\$150/m^2	
House block size	Median block size for dwellings included in the Core Logic dataset used in this current study	350m^2	Spatial analysis of CoreLogic data using Six Maps and ArborCarbon (2025) remote sensing data layers
Number of adjacent private lots	Count of private lots with boundary adjoining boundary; average for all house lots in the CoreLogic data set	4	
Area of 'streetscape' within 200m radius	Median area within 200m radius that is not associated with a specific cadastral lot as reported in Six Maps; average for all house lots in the CoreLogic data set	30,000m^2 (3ha)	
Percent low vegetation in 500m radius	Median percentage of landcover within 500m radius with vegetation <3m as estimated from ArborCarbon (2025) canopy height layer; average for all house lots in the CoreLogic data set.	1.07	
Percent trees in 500m radius	Median percentage of the above area with vegetation canopy height >3m as estimated from ArborCarbon (2025) canopy height layer; average for all house lots in the CoreLogic data set.	0.15	
Number of private lots in 200m radius	Count of private lots within 200m radius; average for all house lots in the CoreLogic data set	225	
Number of private lots in 500m radius	Count of private lots within 500m radius; average for all house lots in the CoreLogic data set	1,900	

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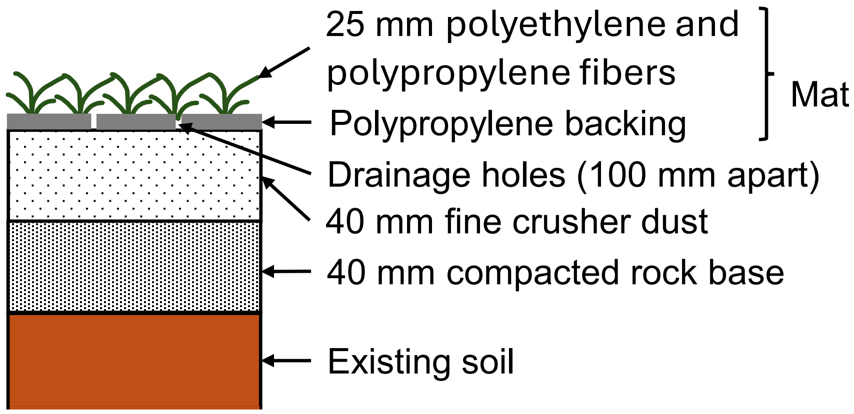
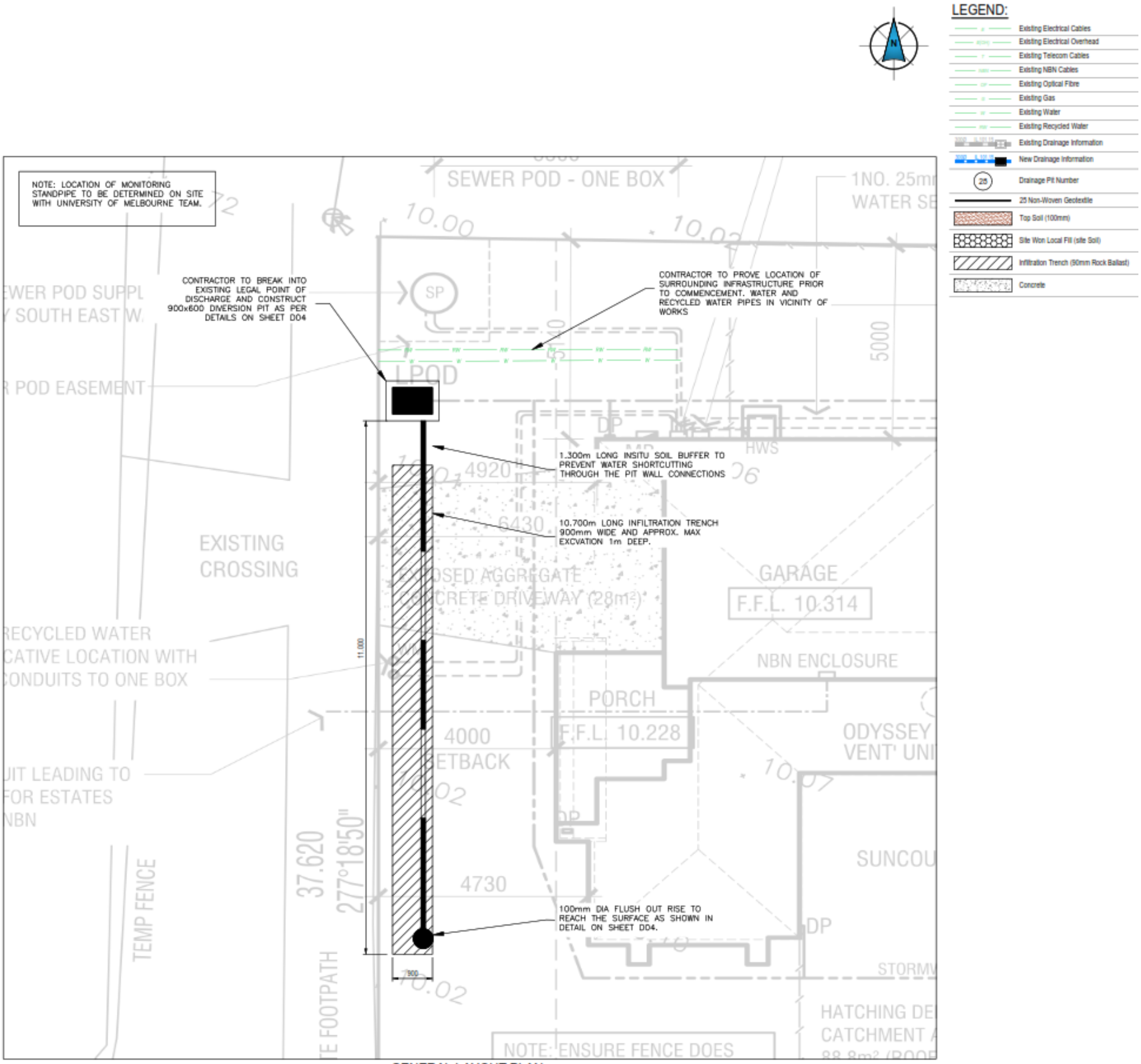
Appendix 3



App 3, Figure 1. The cross section of the artificial turf plot. The artificial turf surface was constructed by removing 80 mm of the topsoil, laying and compacting 40 mm of crushed rock, laying 40 mm of fine crusher dust, and fastening the artificial turf mats on top.

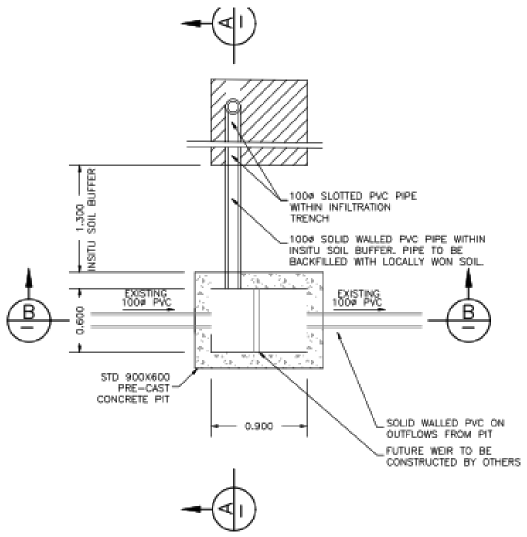
Appendix 4

CAD technical drawings of infiltration trench



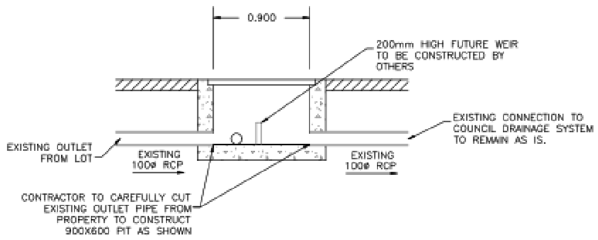
GENERAL LAYOUT PLAN

SCALE 1:50



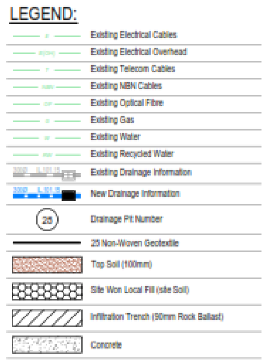
DIVERSION PIT - PLAN VIEW

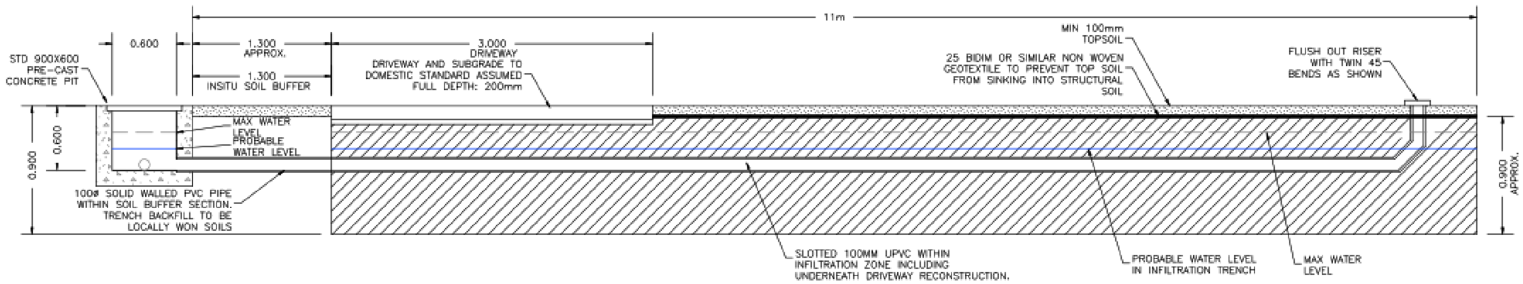
SCALE 1:25



DIVERSION PIT - SECTION VIEW BB

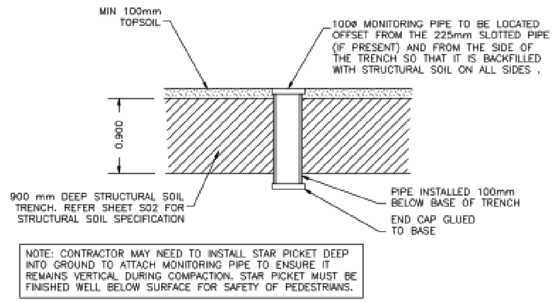
SCALE 1:25





DIVERSION PIT AND INFILTRATION TRENCH - SECTION VIEW AA

SCALE 1:25



TYPICAL MONITORING STANDPIPE

SCALE 1:25