Landscape and Urban Planning 134 (2015) 127–138

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes

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HIGHLIGHTS

- Review of cooling potential from green infrastructure in cities with hot, dry summers.
- Presents a hierarchical process to prioritise urban areas for green infrastructure.
- Framework to strategically select green infrastructure that is 'fit-for-place' and '-purpose'.
- Case study of framework applied to local government planning scale.

ARTICLE INFO

Article history:
Received 25 May 2014
Received in revised form 19 October 2014
Accepted 21 October 2014
Available online 11 November 2014

Keywords:
Urban greening
Climate change adaptation
Heat wave
Public health
Urban planning
Green roof

ABSTRACT

Warming associated with urban development will be exacerbated in future years by temperature increases due to climate change. The strategic implementation of urban green infrastructure (UGI) e.g. street trees, parks, green roofs and facades can help achieve temperature reductions in urban areas while delivering diverse additional benefits such as pollution reduction and biodiversity habitat. Although the greatest thermal benefits of UGI are achieved in climates with hot, dry summers, there is comparatively little information available for land managers to determine an appropriate strategy for UGI implementation under these climatic conditions. We present a framework for prioritisation and selection of UGI for cooling. The framework is supported by a review of the scientific literature examining the relationships between urban geometry, UGI and temperature mitigation which we used to develop guidelines for UGI implementation that maximises urban surface temperature cooling. We focus particularly on quantifying the cooling benefits of four types of UGI: green open spaces (primarily public parks), shade trees, green roofs, and vertical greening systems (green walls and facades) and demonstrate how the framework can be applied using a case study from Melbourne, Australia.

1. Introduction

Globally, extreme heat events (EHE) have led to particularly high rates of mortality and morbidity in cities as urban populations are pushed beyond their adaptive capacities. Recent EHE examples include: Chicago, USA (1995; 31% mortality increase) (Whitman et al., 1997), Paris, France (2003; 130% mortality increase) (Dhainaut, Claessens, Ginsburg, & Riou, 2003), Moscow, Russia (2010; 60% mortality increase) (Revich, 2011) and Melbourne, Australia (2009; 62% mortality increase) (Department of Human Services, 2009). Many cities expect catastrophic EHEs more often, as the frequency, intensity and duration of EHEs are projected to increase with climate change (Alexander & Arblaster, 2009).

There is evidence that increased mortality and morbidity from EHE are exacerbated in urban populations by the urban heat island (UHI) effect (e.g. Gabriel & Endlicher, 2011). Modified land surfaces from urbanisation lead to the formation of distinct urban climates (Coutts, Beringer, & Tapper, 2007). Natural surfaces and vegetation are replaced with a complex, three-dimensional impervious surface

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http://dx.doi.org/10.1016/j.landurbplan.2014.10.018
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Table 1
Existing grey and green infrastructure to be documented as part of the process of selecting and integrating new green infrastructure to mitigate high temperatures in high priority, vulnerable neighbourhoods.

Urban green infrastructure	Grey infrastructure
Irrigated and non-irrigated green space	Street orientation
Location of trees	Building heights (*H*)
Trees species mapping	Street widths (*W*)
Tree health mapping	Height to width ratio (*H*:*W*)
Green roofs	
Green walls	

that absorbs large amounts of solar radiation during the day and this energy is then slowly released at night, keeping urban areas warmer than the surrounding rural countryside and leading to the UHI (Oke, 1982). Rainfall is rapidly drained via stormwater pipes leaving little moisture in the urban landscape, which reduces evapotranspiration and increases sensible heating of the local atmosphere (Coutts et al., 2007). Several studies have shown that higher night time temperatures limit people's recovery from daytime heat stress (Clarke & Bach, 1971). Consequently, many urban populations must adapt to the compounding effects of the UHI, climate change and EHE (Bi et al., 2011).

Many governments are now strategically planning for EHE (O'Neill et al., 2009), often with a focus on short-term preparation and prevention, for example warning systems, promoting behavioural change and preparing emergency services (Kovats & Hajat, 2008; Queensland University of Technology, 2010). Increasing the amount of vegetation, or green infrastructure, in a city is one way to help address the root cause of the problem, by reducing urban air and surface temperature maxima and variation (Bowler, Buyung-Ali, Knight, & Pullin, 2010). However, to substantially reduce the UHI, widespread implementation of green infrastructure is required. For example, measurements during an EHE in Melbourne, Australia, suggested a 10% increase in vegetation cover could reduce daytime urban surface temperatures by approximately 1 °C (Coutts & Harris, 2013).

Urban green infrastructure (UGI) can be defined as the network of planned and unplanned green spaces, spanning both the public and private realms, and managed as an integrated system to provide a range of benefits (Lovell & Taylor, 2013; Tzoulas et al., 2007). UGI can include remnant native vegetation, parks, private gardens, golf courses, street trees and more engineered options such as green roofs, green walls, biofilters and raingardens (Table 1). This paper focuses on the integration of UGI into the public realm to mitigate high urban temperatures and considers the various UGI types and possible locations.

UGI research is not well integrated with urban design and planning, which contributes to the lack of guidance on how best to implement UGI (Bowler et al., 2010; Erell, 2008). UGI is a particularly good option for temperature mitigation in Mediterranean or warm temperate climates due to the greater relative cooling benefits in hot, dry climates (Ottelé, Perini, Fraaij, Haas, & Raiteri, 2011), particularly if water is available to maintain vegetation health and evapotranspiration. Yet, there is a dearth of empirical evidence regarding the benefits of UGI in cities experiencing a Mediterranean climate, nor information on successful and cost effective UGI implementation strategies (Williams, Rayner, & Raynor, 2010). Clearly a cross-disciplinary approach is required.

We present a framework, supported by relevant literature, for green space managers, planners and designers to most effectively integrate UGI into existing urban areas for the primary goal of improved urban climate. With the aid of thermal mapping, a decision framework was developed for local government authorities in Melbourne, Australia. A step by step case-study implementing the framework is provided, drawing on high resolution, airborne thermal mapping as a tool within this framework. Melbourne (37°49′ S; 144°58′ E), on the southern coast of south eastern Australia, has a warm Maritime Temperate climate (Peel, Finlayson, & McMahon, 2007), but has long periods of summer drought and extreme heat. This framework can be applied to cities with classic Mediterranean climates (e.g. Perth, San Francisco, Seville, Beirut and Athens) and those that experience extended summer periods of hot, dry conditions, such as Adelaide and Melbourne. Cities in colder or more humid climates may have different considerations, for example in humid areas there can be a greater emphasis on maximising air flow (Emmanuel, 2005).

2. A framework for using UGI to mitigate excess urban heat

We propose a hierarchical, five step framework to prioritise urban public open space for microclimate cooling (Steps 1–4) using the most appropriate 'fit for place' UGI (Step 5) (Fig. 1). The same principles will apply to privately-owned outdoor space, although this may be complicated by issues of multiple ownership (Pandit, Polyakov, Tapsuwan, & Moran, 2013).

The framework operates firstly at the 'neighbourhood' scale, then the 'street' scale and finally the 'microscale' (Fig. 1). While the actual area would be defined by organisation implementing the framework, a neighbourhood would encompass hundreds of houses and urban features such as a shopping precinct, a school, a railway station, parks and playing fields. The street scale is a smaller unit within a neighbourhood, for example some houses and a strip of shops. The microscale is an area within a street canyon, equivalent to one or more property frontages perhaps. Integrating these three scales is central to this framework, and is important to the strategic integration of UGI for microclimate cooling (Dütemeyer, Barlag, Kuttler, & Axt-Kittner, 2014). This framework is flexible and can be applied and adapted by green space mangers, planners and designers to meet their local circumstances. Local stakeholders can also be involved in the decision framework at any, or all, stages as determined by budget, time and engagement philosophy of the local government authority.

2.1. Step 1—Identify priority urban neighbourhoods

Specific neighbourhoods are prioritised by identifying areas with the largest numbers of people that may be exposed and/or are vulnerable to excessive urban heat. A risk of mortality and morbidity from excessive urban heat is based on a combination of *heat exposure*, *vulnerability* to extreme heat (Dütemeyer et al., 2014), as well as the *behavioural exposure* occurring, in terms of the number of people using public open spaces (Fig. 2). When these three risk drivers intersect (C), a high priority neighbourhood has been identified. However, it is hard to predict the amount of *behavioural exposure* in public open spaces such as community health centres, so neighbourhoods where *heat exposure* and *vulnerability* intersect (B orange) can also be regarded as a priority (Fig. 2).

2.2. Heat exposure

Areas within cities that experience extreme heat are not evenly distributed spatially and 'hot-spots' occur where there is intense urban development with little vegetation and/or water. Consequently, air temperatures predicted from coarse resolution models (e.g.100–200 km) can frequently be exceeded in susceptible urban neighbourhoods or 'hot-spots' (McCarthy, Best, & Betts, 2010). To adequately assess how exposed a neighbourhood population may be to high temperatures, temperature information that is specific to that location is important (Kovats & Hajat, 2008). Satellite or airborne remotely sensed thermal data can provide a snapshot in time of land surface temperature across a large spatial area,

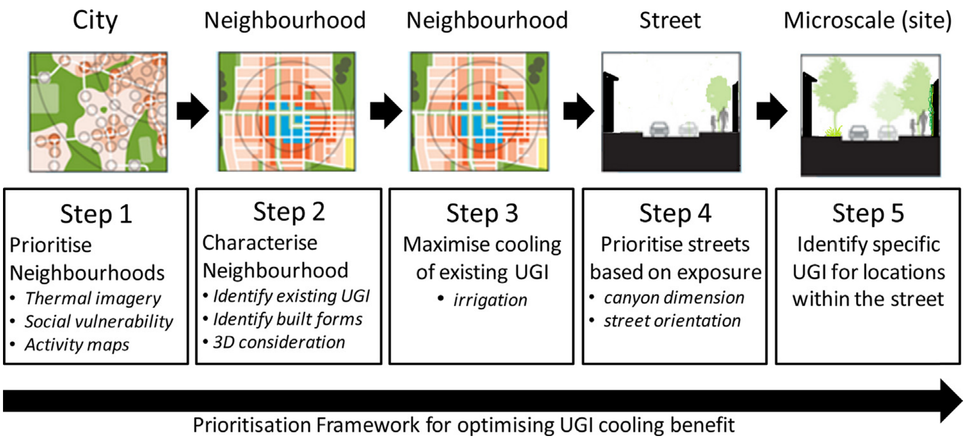


Fig. 1. The steps in the prioritisation operate at the neighbourhood scale (Steps 1–3), where the physical environment and people's vulnerability are characterised for the area; and the street (Step 4) and microscales (Step 5), at which scales UGI that is fit for place is selected and implemented. See text for details.

and can be used as a proxy for air temperature (Saaroni, Ben-Dor, Bitan, & Potchter, 2000) although the correlation may be poor under unstable (windy) conditions (Stoll & Brazel, 1992). While land surface temperature and air temperatures are clearly different, mitigating high surface temperatures in cities is an appropriate target, as these reflect locations where both air temperature and absorbance of solar radiation is high, which impacts directly on human thermal comfort (Matzarakis, Rutz, & Mayer, 2007). Satellite remotely sensed data are low-resolution but often freely available, whereas airborne remotely sensed data can provide higher resolution (1–5 m) but can be costly and time-consuming to process (Coutts & Harris, 2013; Tomlinson, Chapman, Thornes, & Baker, 2011).

2.3. Vulnerability

A wide range of factors influence the vulnerability of urban populations to extreme heat. Socially disadvantaged neighbourhoods (those with lower household income and lower quality parks, shops and transport) often experience greater negative health impacts from extreme heat. The elderly, those with pre-existing physical (i.e. heart disease, obesity) or mental illness, the very young and those living alone and in low socio-economic circumstances are particularly vulnerable (Bi et al., 2011). Prioritising neighbourhoods for high temperature mitigation is therefore a social justice issue, as well as a preventative health measure (Wolch, Byrne, & Newell, 2014). Assessing vulnerability of a population to high temperatures requires demographic information (e.g. Huang, Zhou, & Cadenasso, 2011; O'Neill et al., 2009). Loughnan, Tapper, Phan, Lynch, and McInnes (2013) have developed methods for assessing vulnerability in Australian cities primarily using Australian census information (Australian Bureau of Statistics, 2011c) collected every five years, including a vulnerability index for all Australian capital cities.

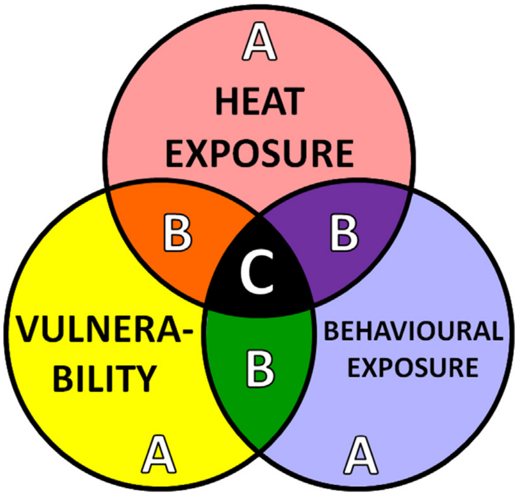


Fig. 2. Factors required to identify neighbourhoods of high (C), medium (B) and moderate (A) priority for UGI implementation for surface temperature heat mitigation. The key factors are high daytime surface temperatures (*Heat exposure*) intersecting with areas with more vulnerable sections of society (*Vulnerability*) and identifying the zones of high activity (*Behavioural exposure*) with this area.

2.4. Behavioural exposure

Areas in a city where large numbers of the public are active outdoors should rate highly for heat mitigation, such as public transport interchanges, recreational spaces, outdoor shopping strips, schools and pedestrian thoroughfares. These areas may be prioritised to modify the human thermal comfort of large proportions of the population. For instance, during an extreme heat event the public transport network can be interrupted, leaving commuters waiting in extreme heat for transport services. Furthermore, public areas of activity where vulnerable populations may be exposed should be identified, including outside aged care facilities, schools and community centres, health care centres, socio-economic support locations, and social housing complexes. Such information can be sourced from census data, local planning schemes, and other institutional resources.

Heat related stress, stroke or death do not occur spontaneously or rapidly, it is prolonged exposure to higher than normal temperatures, often over several days, that causes heat related illness (e.g. Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Luber & McGeehin, 2008; McGeehin & Mirabelli, 2001). Hence, people are exposed to thermal stress throughout the day and night, and respond negatively after different periods of time depending upon their vulnerability and the temperatures they experience. The aim of this framework to prioritise UGI implementation for heat mitigations is really an aim to reduce the overall outdoor exposure of vulnerable individuals (and all people) to high temperatures throughout the course of the day. Furthermore, this framework applies to public spaces where local governments can more easily intervene.

2.5. Step 2—Characterise UGI and grey infrastructure

Once priority neighbourhoods have been identified, it is important to characterise the built form (grey infrastructure) in a three-dimensional sense, and to identify existing UGI. Step 2 helps identify opportunities for micro-climate improvements, and documents the landscape for later steps. The aim is to identify the location of existing, healthy vegetation, and where UGI is lacking, i.e. which parts of the current built environment could be retrofitted with UGI (Table 1). If thermal mapping data (Step 1) are unavailable, this step increases in importance. Characterising street width and building height will determine street openness to solar radiation, and self-shading by buildings. This information can be gathered from a combination of visual surveys, aerial imagery, LiDAR data, GIS databases, etc.

2.6. *Step 3—Maximise the cooling benefit from existing UGI*

Many cities already have well-established urban forests and other green infrastructure networks. Their cooling benefit is most important during very hot, dry periods, however this is when urban vegetation can be most water stressed. Stress from low water availability during hot weather can lead to defoliation and possibly death. The impacts of this are most serious when large trees die due to the large reduction in cooling they provide and high replacement cost (Gill, Handley, Ennos, & Pauleit, 2007). Vegetation that is water stressed has higher surface temperatures than irrigated vegetation (Coutts & Harris, 2013). Inadequate water availability will also lead to reduced plant transpiration when it is most desired (Leuzinger, Vogt, & Körner, 2010; Shashua-Bar, Pearlmutter, & Erell, 2011). Consequently, supplementary irrigation of UGI in cities that experience hot, dry summers is a wise investment to ensure long-term temperature mitigation, as well as other ecosystem services (May, Livesley, & Shears, 2013). However, some cities (e.g. Melbourne), introduce water use restrictions in response to extended drought, even though this approach immediately reduces and threatens the long-term temperature mitigation benefits from UGI (Coutts, Tapper, Beringer, Loughnan, & Demuzere, 2013; May et al., 2013). Some supplementary water can also be supplied through water sensitive urban design that utilises stormwater runoff rather than potable water (Coutts et al., 2013), but this will require increased investment in stormwater capture and storage within the urban landscape.

2.7. *Step 4—Develop a hierarchy of streets for new UGI integration*

After selecting priority neighbourhoods for temperature mitigation, particular streets that are most vulnerable to high temperatures can be targeted. Urban streets can be viewed as canyons, with a floor (the road, walkway, verge and front yards) and two walls (the building frontages up to the top of the roof). Our five-step hierarchy focuses on street canyons because: (1) they occupy a large proportion of the public domain in cities; (2) a lot of urban climate research is based around street canyons; (3) street features relevant to assessing the thermal environment are relatively easy to measure and often already available to local government agencies; (4) street geometry and orientation are important determinants of surface and air temperatures in urban areas (Bourbia & Awbi, 2004a, 2004b); and (5) the principles for cooling based on canyon geometry can be usefully applied to other urban open spaces, e.g. car parks (Onishi, Cao, Ito, Shi, & Imura, 2010) and intersections (Chudnovsky, Ben-Dor, & Saaroni, 2004; Saaroni et al., 2000).

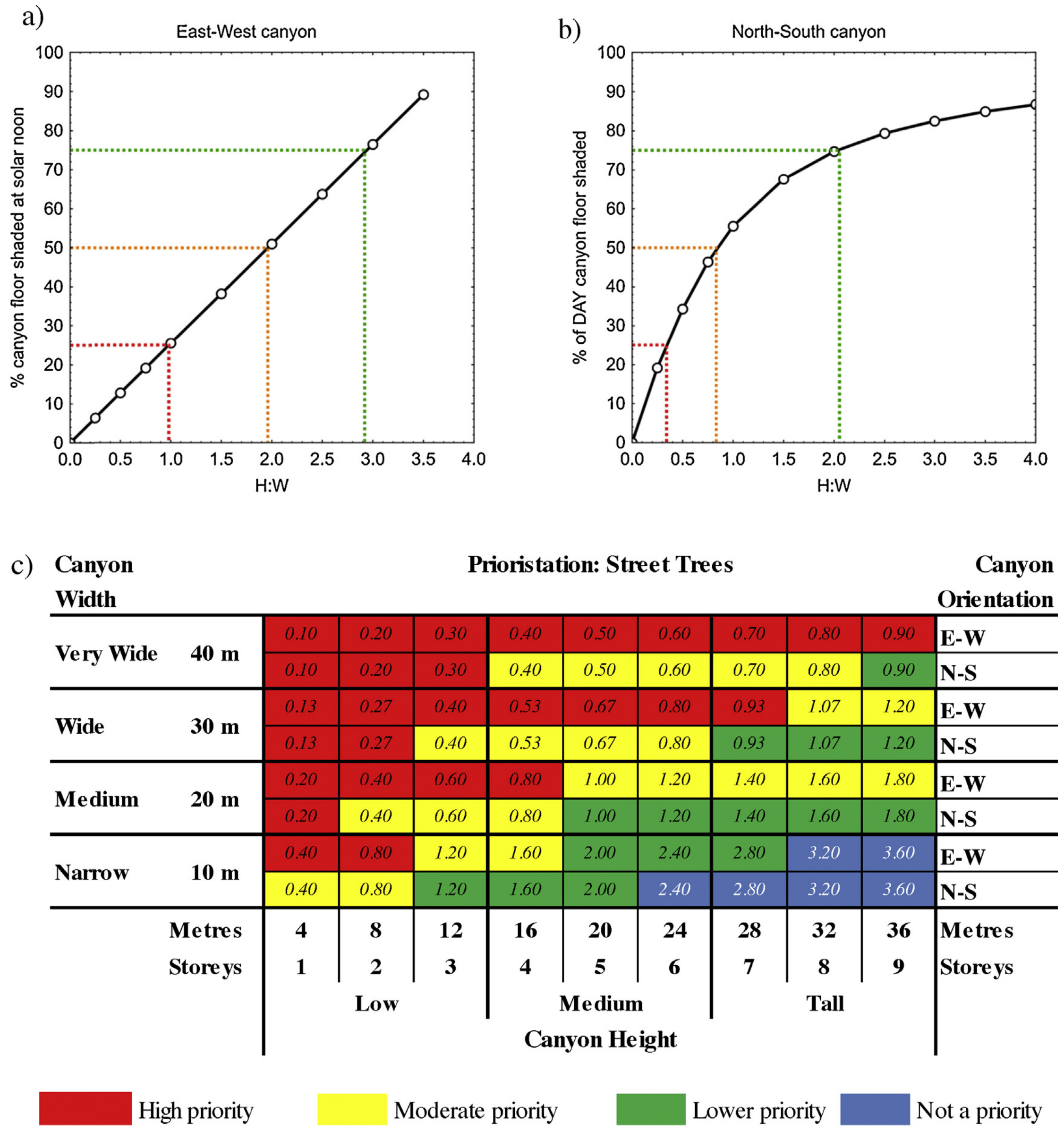
An important goal in using UGI to reduce surface temperature is to replace or shade impervious surfaces with vegetation (Oke, Crowther, McNaughton, Monteith, & Gardiner, 1989). Selection of UGI should therefore focus on the properties of the street canyon that determine level of solar exposure. These are building height (H), street width (W), height to width ratio (H:W), and orientation, but providing sufficient capacity for ventilation at night is also important. The street canyon H:W ratio determines the amount of shade cast by the buildings themselves across the canyon floor. Wide, open canyons (low H:W ratios) experience higher daytime temperatures due to high solar exposure, as compared to deep, narrow canyons (high H:W ratios) where buildings self-shade the canyon (Johansson, 2006). Canyon orientation influences the level of solar exposure, as east-west canyons receive more hours of direct solar radiation than north-south orientated canyons (Ali-Toudert & Mayer, 2006). If street H:W ratio is low (e.g. 0.5), an east-west oriented street will receive direct solar radiation while the sun is up, whereas north-south streets are solar exposed only in the middle hours of the day (Bourbia & Awbi, 2004a). The number of solar exposed hours is also related to a street canyon's H:W ratio and solar zenith angle, which changes predictably throughout the year. For Melbourne's latitude (37.8° S), a street canyon H:W ratio of between 0.5 and 1.0 would provide some self-shading during the day, but be able to dissipate heat at night (Bourbia & Awbi, 2004b; Mills, 1997; Oke, 1988).

Implementing UGI is one of the easiest ways to modify street canyon microclimates, other than façade awnings and overhangs to shade footpaths (Ali-Toudert & Mayer, 2007). Ranking canyon geometry and orientation can help prioritise streets for tree planting or other UGI interventions. Using the RayMan model (Matzarakis, Rutz, & Mayer, 2010), we hierarchically prioritised streets of different geometry, based on self-shading by buildings at the summer solstice (Fig. 3). For east-west oriented canyons the proportion of the street canyon floor exposed to the sun is calculated at solar noon (Fig. 3a), and for north-south oriented canyons the proportion of the day that the canyon floor is shaded is calculated (Fig. 3b). The amount of shading was then equally divided into four priority classes (Fig. 3a and b). It should be noted that these priorities are specific to Melbourne and will vary with geographic location. This hierarchical approach demonstrates that wide/very wide, east-west orientated streets should be prioritised for street trees because of high solar exposure (Fig. 3c). Street trees would provide less benefit in narrow street canyons with a high degree of self-shading. In an analysis of daytime thermal imagery, Coutts and Harris (2013) found that street trees in Melbourne were particularly effective at reducing surface temperatures in canyons with a H:$W < 0.8$, whilst above this H:W the effects of trees on surface temperature were reduced, which is consistent with our findings.

In narrow canyons, where there is adequate light, green walls and façades as well as ground level vegetation should be prioritised over trees due to reduced space, and because they allow better ventilation and long wave cooling at night. Appropriate plant selection is very important in these situations. As H:W increases, light levels drop and wind turbulence may increase, and few plant species are likely to tolerate these conditions. There is a paucity of empirical data on the performance of plants suitable for green walls and facades in deep, narrow urban canyons (Hunter et al., 2014; Rayner, Raynor, & Williams, 2010).

2.8. *Step 5—Select new UGI based on site characteristics and cooling potential*

The final step selects and implements new UGI that is 'fit-for-place'. The order of UGI elements presented in this section reflects their priority given the goal of surface temperature reduction. The primary goal for new UGI implementation should be to maximise 'overhead' vegetation canopy cover, to reduce canyon surface temperatures as well as provide shading of pedestrian space and transpirative cooling. The secondary goal should be to implement either ground or wall 'surface' vegetation cover, also to reduce surface temperatures and provide transpirative cooling, but no (or little) shading. Surface vegetation cover includes vertical greening systems, green roofs and grassed ground surfaces. Table 2 presents a



Prioristation: Street Trees

Canyon Width											Canyon Orientation
Very Wide	40 m	🟥 0.10	🟥 0.20	🟥 0.30	🟥 0.40	🟥 0.50	🟥 0.60	🟥 0.70	🟥 0.80	🟥 0.90	E-W
		🟥 0.10	🟥 0.20	🟥 0.30	🟨 0.40	🟨 0.50	🟨 0.60	🟨 0.70	🟨 0.80	🟩 0.90	N-S
Wide	30 m	🟥 0.13	🟥 0.27	🟥 0.40	🟥 0.53	🟥 0.67	🟥 0.80	🟥 0.93	🟨 1.07	🟨 1.20	E-W
		🟥 0.13	🟥 0.27	🟨 0.40	🟨 0.53	🟨 0.67	🟨 0.80	🟩 0.93	🟩 1.07	🟩 1.20	N-S
Medium	20 m	🟥 0.20	🟥 0.40	🟥 0.60	🟥 0.80	🟨 1.00	🟨 1.20	🟨 1.40	🟨 1.60	🟨 1.80	E-W
		🟥 0.20	🟨 0.40	🟨 0.60	🟨 0.80	🟩 1.00	🟩 1.20	🟩 1.40	🟩 1.60	🟩 1.80	N-S
Narrow	10 m	🟥 0.40	🟥 0.80	🟨 1.20	🟨 1.60	🟩 2.00	🟩 2.40	🟩 2.80	🟦 3.20	🟦 3.60	E-W
		🟨 0.40	🟨 0.80	🟩 1.20	🟩 1.60	🟩 2.00	🟦 2.40	🟦 2.80	🟦 3.20	🟦 3.60	N-S
	Metres	4	8	12	16	20	24	28	32	36	Metres
	Storeys	1	2	3	4	5	6	7	8	9	Storeys
			Low			Medium			Tall		
						Canyon Height					

🟥 High priority 🟨 Moderate priority 🟩 Lower priority 🟦 Not a priority

Fig. 3. Classification of streets for the implementation of street trees to mitigate daytime surface temperatures at the summer solstice in Melbourne, Australia (37.8136°S, 144.9631°E) based on the extent of self-shading by buildings. Figs. (a) and (b) show the percent of the street canyon floor shaded at solar noon for streets of different *H*:*W* ratios. Calculations use the RayMan model. Fig. (c) demonstrates how this can be used to prioritise street tree installation for cooling assuming no existing UGI, where sites with high solar exposure and resulting high temperatures are high priority targets for mitigation. Numbers inside the boxes are *H*:*W* ratios.

simple guide to how different UGI elements provide surface cooling benefits.

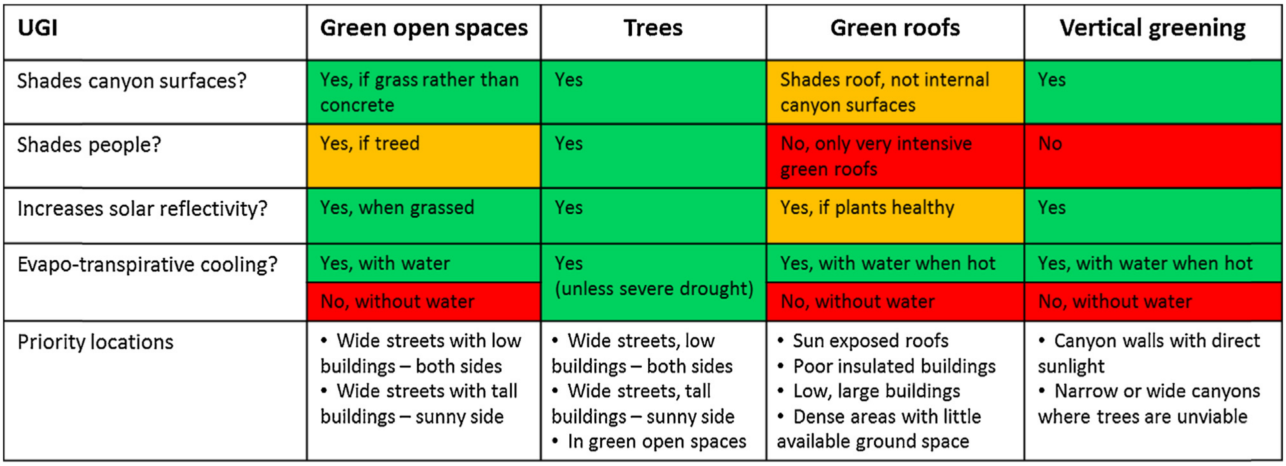
2.8.1. *Trees*

In most cases, tree canopies are the optimal solution for shading both canyon surfaces and the pedestrian space, and they also provide evapotranspirative cooling (Rosenzweig et al., 2006; Spronken-Smith & Oke, 1999) (Table 2). The amount of shade trees provide depends on their architectural form and canopy density (Pataki, Carreiro, et al., 2011; Shashua-Bar, Potchter, Bitan, Boltansky, & Yaakov, 2010). Thick or dense canopy trees provide particularly good shade, meaning that broadleaf trees are generally more effective than needle-leaf trees (Leuzinger et al., 2010; Lin & Lin, 2010). However, trees that provide the greatest shade during hot summer days can also trap heat under their canopy at night (Spronken-Smith & Oke, 1999). To minimise heat trapping, street trees should not form a continuous canopy, thereby allowing ventilation and long-wave radiation to escape (Dimoudi & Nikolopoulou, 2003; Spronken-Smith & Oke, 1999). A mix of tree species, with different canopy architectures, could be considered for the same reason (Pauleit, 2003).

2.9. *Urban green open spaces*

Urban green open spaces are primarily grassed areas with a relatively sparse (or absent) tree canopy, such as ornamental parks, sporting fields and golf courses. Depending on their design and irrigation regimes, urban green open spaces can potentially provide 'islands' of cool in hot urban areas, so it is important they be easily accessible to people (Giles-Corti et al., 2005). Depending on their size and the wind direction, they can also cool urban areas downwind (Dimoudi & Nikolopoulou, 2003; Spronken-Smith &

Table 2
Modes of cooling provided by different urban green infrastructure options during summer and priority locations to optimise those cooling benefits.



UGI	Green open spaces	Trees	Green roofs	Vertical greening
Shades canyon surfaces?	Yes, if grass rather than concrete	Yes	Shades roof, not internal canyon surfaces	Yes
Shades people?	Yes, if treed	Yes	No, only very intensive green roofs	No
Increases solar reflectivity?	Yes, when grassed	Yes	Yes, if plants healthy	Yes
Evapo-transpirative cooling?	Yes, with water No, without water	Yes (unless severe drought)	Yes, with water when hot No, without water	Yes, with water when hot No, without water
Priority locations	• Wide streets with low buildings – both sides • Wide streets with tall buildings – sunny side	• Wide streets, low buildings – both sides • Wide streets, tall buildings – sunny side • In green open spaces	• Sun exposed roofs • Poor insulated buildings • Low, large buildings • Dense areas with little available ground space	• Canyon walls with direct sunlight • Narrow or wide canyons where trees are unviable

Oke, 1998). Urban green open spaces cool more effectively if they contain scattered trees and receive irrigation (Spronken-Smith & Oke, 1998, 1999), and their spatial layout and vegetation structure will be important in determining their cooling potential (Lehmann, Mathey, Rößler, Bräuer, & Goldberg, 2014).

Greatly increasing the total area of green open space within a city may significantly reduce temperatures at the city scale (Bowler et al., 2010) but this is unlikely to be an option in most cities. Providing many small, distributed green open spaces could benefit a larger number of neighbourhoods (Coutts et al., 2013; Shashua-Bar & Hoffman, 2000), and the spatial prioritisation of green open space for urban cooling is an area of ongoing research (Chang, Li, & Chang, 2007; Connors, Galletti, & Chow, 2013). As cooling benefits are focussed downwind of any urban green open spaces, they would be best placed upwind of particularly hot areas or vulnerable populations.

2.10. *Green façades*

Green façades are climbing plants grown up a wall directly or on a trellis or similar structure set away from the wall (Hunter et al., 2014). Green façades can be planted in the ground or in planter boxes at any height up the walls of a building. As well as preventing heat gain to building walls, green façades can provide cooling through evapotranspiration (Köhler, 2008). Unlike green walls, green façades are a realistic option for wide spread UGI implementation because of lower installation and maintenance costs (Ottelé et al., 2011).

Green façades are particularly beneficial on walls with high solar exposure and where space at ground-level is limited (Wong & Chen, 2010), or where aerial obstructions limit tree growth. Dark coloured walls should be prioritised for green façade covering over light coloured walls, which do not become as hot (Kontoleon & Eumorfopoulou, 2010). To benefit pedestrians, green façades should be installed adjacent to walkways (Table 2).

2.11. *Green roofs*

During the day, roofs are some of the hottest surfaces in urban areas (Chudnovsky et al., 2004). Greening those roofs can greatly mitigate urban surface temperatures, as well as reducing air-space cooling requirement inside those buildings. Green roofs may be extensive, with thin substrates (2–20 cm) and a limited range of plants, or, where building structure is sufficiently strong, intensive, with a thicker substrate layer that can support a wider range of plants (Oberndorfer et al., 2007; Wilkinson & Reed, 2009).

Modelling suggests that green roofs can cool at a neighbourhood-scale if they cover a large area (Gill et al., 2007; Rosenzweig et al., 2006). To be effective, green roofs need to be irrigated and maintain a high leaf area index before they become comparable to the cooling provided by roofs painted with high albedo paint (Santamouris, 2014) but their influence on cooling at street level will be low (Ng, Chen, Wang, & Yuan, 2012). Green roofs reduce surface temperatures best when they are covered in taller vegetation (Lundholm, MacIvor, MacDougall, & Ranalli, 2010; Wong & Chen, 2010) and irrigated (Liu & Bass, 2005). Achieving a balance between maximising cooling performance during hot summer conditions, whilst keeping plants alive in shallow soils with minimal irrigation is an ongoing research challenge (Williams et al., 2010). Green roofs have multiple benefits but for urban surface cooling that has human health benefits, we recommended adding green roofs to large, low buildings, or in areas with little ground level green open space (Table 2).

3. Case study—city of Port Phillip, Melbourne, Australia

The City of Port Phillip comprises 20.62 km^2 of predominantly pre-1900 suburbs on the north shore of Port Phillip Bay in inner city Melbourne, Australia (City of Port Phillip, 2014) and is home to over 91,000 people (Australian Bureau of Statistics, 2011b). The City of Port Philip was a key partner in this research and keenly aware of the impacts of heat on communities especially from the 2009 extreme heat event in Melbourne which contributed to 374 excess deaths (Department of Human Services, 2009). In the summer of 2011–12 the City of Port Phillip undertook airborne thermal remote sensing of their municipality, a primary input to the prioritisation framework, to help understand where areas of heat occurred in the municipality in order to inform planning decisions. The City of Port Phillip is an affluent, high density suburb populated by many city professionals, yet pockets of disadvantage remain as it has the second highest amount of community and social housing in Victoria. The elderly in the City of Port Phillip make up 6.8% of the population which is slightly lower than the average for Greater Melbourne of 8.2% (City of Port Phillip, 2014). The interest and positive collaboration with the City of Port Phillip including the provision of thermal data made this local government area an excellent case study. In the 2011 census, the City of Port Phillip contained 228 statistical areas (Statistical Area Level 1) which have an average population of around 400 people (Australian Bureau of Statistics, 2011a). We averaged the thermal data over the statistical areas to correspond with demographic data. Steps 1–3 were undertaken with the support of the City of Port Phillip (Coutts & Harris, 2013) and a trial of Steps 4 and 5 was undertaken with local council representatives from across Melbourne.

3.1. Step 1—Identifying priority neighbourhoods

Heat exposure was assessed using high resolution (0.5 m) airborne thermal remote sensing data for solar noon and midnight on the 25 February 2012, during an EHE (daytime max. 37.1 °C; overnight minimum 24.7 °C) (Coutts & Harris, 2013). The data were corrected for emissivity effects and then averaged for each statistical area to identify hot spots (Fig. 4a and b). The coolest location in the City of Port Phillip both during the day and night is Albert Park, a large park with a lake in the north east of the study area (see Fig. 4f). More information on the use of thermal imagery, data processing, and prioritising areas of high heat exposure can be found in Coutts and Harris (2013).

To assess *vulnerability* in the City of Port Phillip, several common indicators were used:

- elderly population (>65 years) (Fig. 4c)
- population of the very young (<5 years) (Fig. 4d) and
- the Index of Relative Socio-Economic Disadvantage (IRSD) (Fig. 4e).

These commonly identified contributors to vulnerability draw on information that is readily available and easily accessible at an appropriate resolution. Local knowledge of communities and what influences vulnerability in a neighbourhood can assist decisions regarding what contributors to include.

Finally, to determine zones of *behavioural exposure*, local knowledge can be supplemented with information on planning zones. In the City of Port Phillip we identified several planning zones (Fig. 4f) that are likely to experience high population activity;

- Park and Public Recreation Zone;
- public use zone (education, health and community, transport);
- mixed use zone (neighbourhood centres with residential and non-residential development around train stations); and
- commercial zones.

Using GIS software, we overlayed the data for all three components of the prioritisation framework: heat exposure (daytime and night time heat), vulnerability (elderly, very young and socially disadvantaged) and behavioural exposure (Public Use Zones, etc.). This produced a priority neighbourhood map for UGI implementation in the City of Port Phillip whereby the highest risk neighbourhoods intersected the highest levels of heat exposure, vulnerability and behavioural exposure (Fig. 5). Framework Steps 2–5 were applied to the priority neighbourhood highlighted in the inset of Fig. 5. This neighbourhood comprises a large number of services that may increase behavioural exposure including the South Melbourne Market and nearby shopping strips, the Port Phillip Community Rehabilitation Centre, and a light rail corridor including South Melbourne Station. The neighbourhood includes the Crawford Court Flats which house elderly citizens, and the area houses over 50 residents of >65 years. The South Melbourne Market and light rail station are located within a zone of relatively high heat exposure. As such, this area comprises vulnerable populations who live and engage in an area that has high heat exposure.

3.2. Step 2—Characterising UGI and grey infrastructure

To classify existing UGI and grey infrastructure, we created a detailed land cover map using a combination of aerial imagery and multispectral data and LiDAR data. Using a supervised classification in GIS software that was trained using these data sources, a map was produced comprising seven land cover classes: vegetation (trees), irrigated and non-irrigated green space, rooftops, concrete, asphalt (roads) and water (Fig. 6). We documented building heights based on height information from the LiDAR data in GIS software and manually measured street widths, also in GIS. If such data are not available, mapping of grey infrastructure can also be completed using visual surveys or products such as Google Earth, while local governments may also have tree inventories that can be drawn on. The characterisation information in Fig. 3 provides a guide for identifying the types of streets in our City of Port Phillip priority neighbourhood that are likely to experience poorer thermal comfort, with little shading and high levels of imperviousness leading to high land surface temperatures during the day.

3.3. Step 3—Maximising the cooling value of existing UGI

Vegetation health information, obtained from remotely sensed data (Step 2) or on-ground surveys, can be used to identify where water sensitive urban design can be used most efficiently to enhance existing UGI (Fig. 6). In the City of Port Phillip, annual stormwater runoff into Port Phillip Bay is estimated to be 4764 ML, while a further 11,460 ML flows through the municipality and into to the bay from neighbouring areas (City of Port Phillip, 2010). Not all of this large water resource can be captured and stored but if suitable technologies and distributed storage can be implemented this can greatly assist in optimising existing and new UGI performance. Water sensitive urban design and stormwater harvesting help capture and retain stormwater in the urban landscape for irrigation (Coutts et al., 2013). Modes of capture and storage that were considered were (1) bioretention pits, (2) curb cut-outs that direct water to tree root zones, and (3) roof runoff harvesting and storage in rainwater tanks for irrigation. Urban green open spaces in the priority neighbourhood are mostly unirrigated, and during the day can experience surface temperatures greater than roads and concrete. A 2009 streetscape assessment (City of Port Phillip, unpublished data) found that 40% of streets were rated fair for stocking, health and vigour of trees. Providing water to the other 60% of street trees can help improve health and vigour, increasing transpiration, leaf density and hence shading capacity.

3.4. Steps 4 and 5—Selecting and integrating new UGI

Steps 4 and 5 of the decision framework were applied in a field workshop with local council representatives from across Melbourne. Using the high resolution (0.5 m) thermal imagery, two City of Port Phillip streets were identified that illustrated the role of canyon geometry in high solar exposure and the potential role of UGI in public space cooling. Both were east-west facing: Street A was wide (approximately 30 m) and low (two storeys high, 6 m, $H{:}W = 0.2$), whereas Street B was narrow (5 m wide) and low (two storeys high, 6 m, $H{:}W = 1.2$) (Fig. 7). Street A had scattered, small trees that would never develop a large canopy, and Street B had no existing UGI. Based on the decision framework and discussions on-site, it was recommended to install a green wall or narrow hedge on the north-facing wall of Street B (Fig. 7). In contrast, the workshop group recommended that Street A would benefit from street trees that would produce wider, denser canopies, planted at a higher frequency, especially on the southern side of the street which is more solar exposed (Fig. 7). The footpaths are wide so additional UGI planting is possible. Although the road was also wide enough

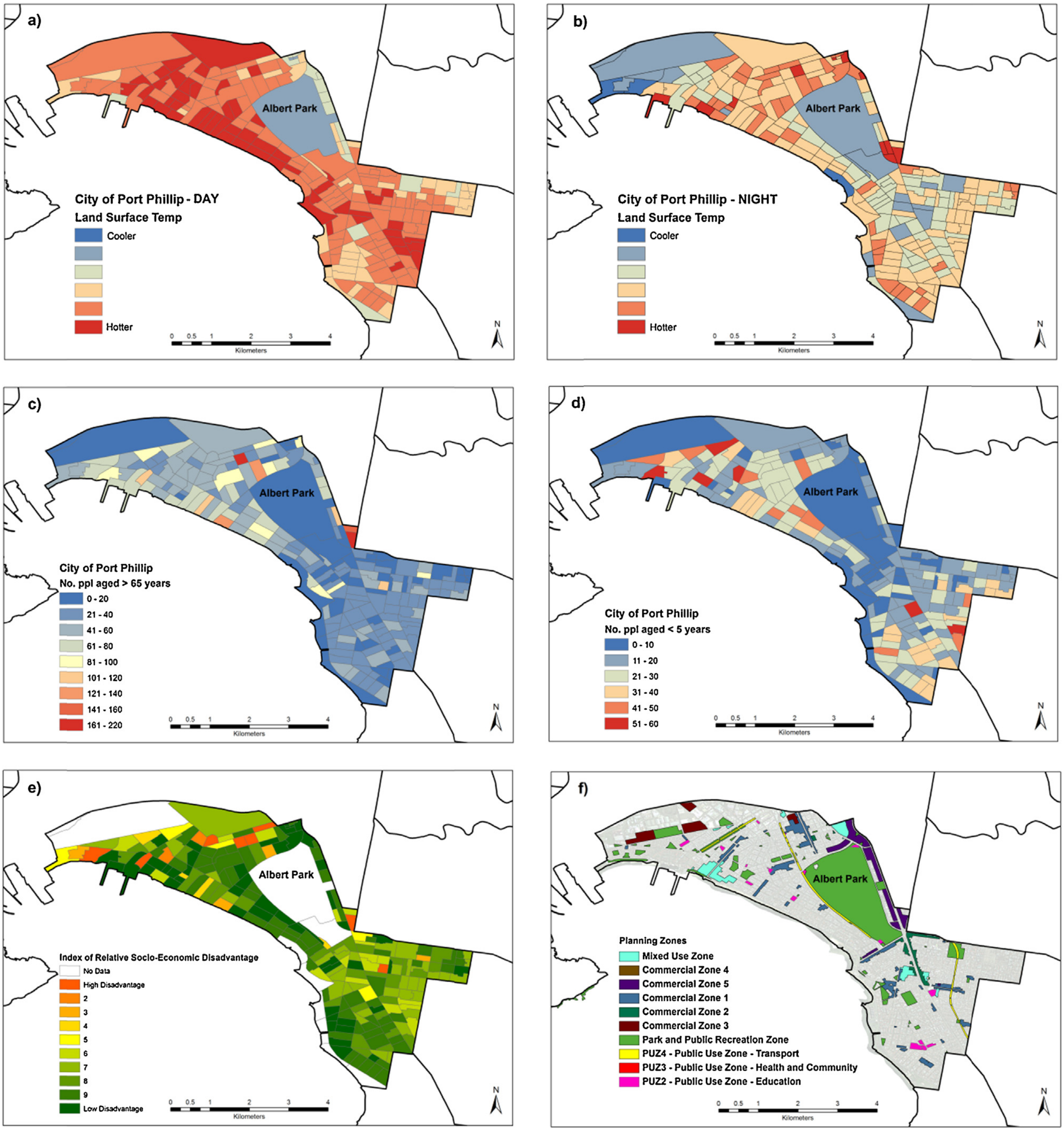


Fig. 4. Identifying priority neighbourhoods across the City of Port Phillip. Panels a and b present daytime and night time exposure respectively; panels c and d present population aged over 65 and below 5 respectively; panel e presents the Index of Relative Socio-economic Disadvantage; panel f presents areas of population behavioural exposure.

to accommodate central reservation tree planting, the proximity to a busy market makes this impractical from a car parking and access perspective.

The City of Port Phillip had already identified opportunities for street tree planting, and highlighted the need for water sensitive urban design elements such as bio-retention tree pits and rain gardens to improve water management (TreeLogic, 2010). The benefit of applying this case study framework, however, is that the City of Port Phillip can now prioritise their investment and implementation into neighbourhoods and streets that are 'high priority' and can deliver a greater temperature reduction benefit for this investment.

4. Discussion

We have reviewed the potential of urban green infrastructure to mitigate high temperatures and integrated this information with census data and remotely sensed thermal data to provide a decision framework that prioritises effective implementation of UGI. Although we make recommendations on what types of UGI will be most suitable in different circumstances, the selection of appropriate UGI will always depend on the local climate, soils, water availability as well as community norms and cultural values (Bowler et al., 2010; Pataki, Carreiro et al., 2011).

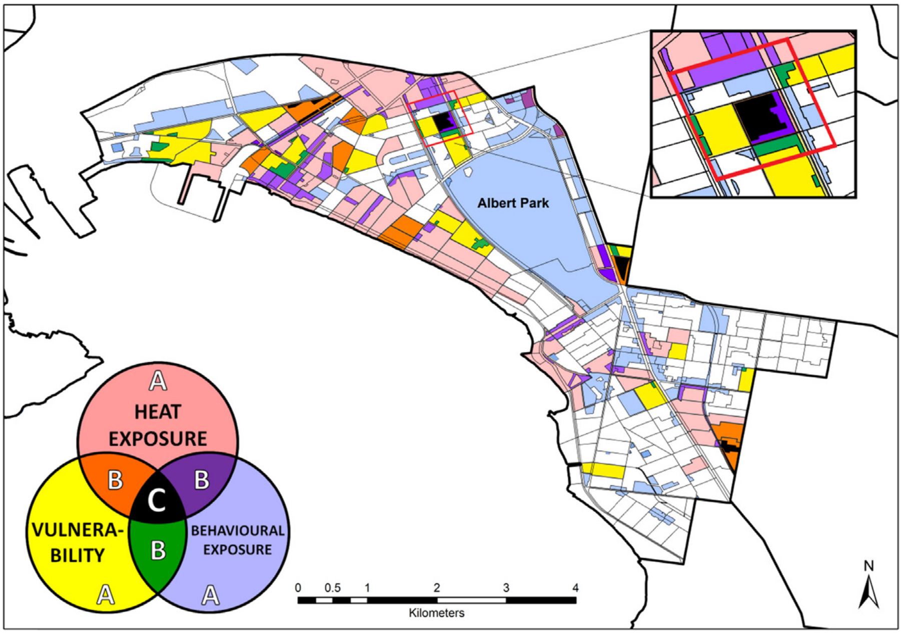


Fig. 5. Priority neighbourhoods for mitigation of high urban temperature using green infrastructure in the City of Port Phillip. Darker colours (purple, orange and green) represent higher priority locations, and black represents the highest priority locations for heat mitigation and UGI implementation. The inset is an identified priority neighbourhood surrounded by the red box. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This framework enables prioritisation of placement and UGI type at the neighbourhood scale. Most existing studies have measured cooling effects from UGI at the micro-scale, or modelled them at the city scale. More research is needed to understand the interactions between street canyon geometries, UGI placement and plant species selection to establish firm connections between UGI spatial arrangement and street-scale cooling. Increasingly, modelling tools are available to do this, and there are concerted efforts to improve the representation and simulation of vegetation in urban climate models (Grimmond et al., 2011). This is a complex problem and ultimately a combination of field measurements and modelling are likely required (Oke et al., 1989). Once a greater understanding is achieved, it might be possible to develop spatially explicit planning support tools similar to those used in conservation planning (e.g. Carsjens & Ligtenberg, 2007).

UGI should be part of any urban heat mitigation strategy, and the strengths and flexibility of the other components to this strategy, such as alternative surface materials and street design, should be similarly well understood to enable an informed and optimised response (Emmanuel, 2005). These need to run in conjunction with adaptation measures in the public health service and attempts to invoke behavioural change in the urban population to better cope with higher temperatures (Bi et al., 2011; O'Neill et al., 2009). Furthermore, UGI will rarely be installed exclusively to mitigate high

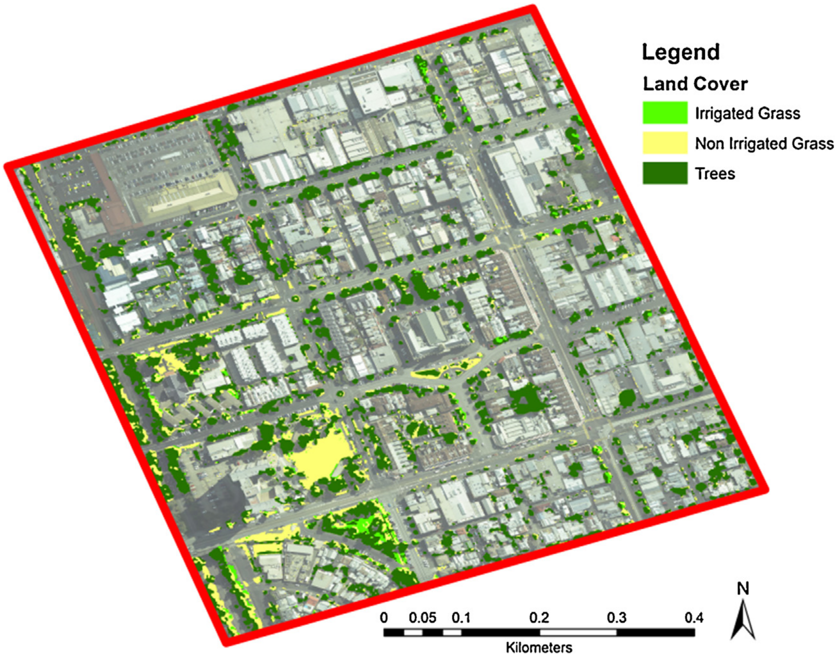


Fig. 6. Characterisation of urban green infrastructure using a combination of aerial imagery, multi-spectral data and LiDAR.

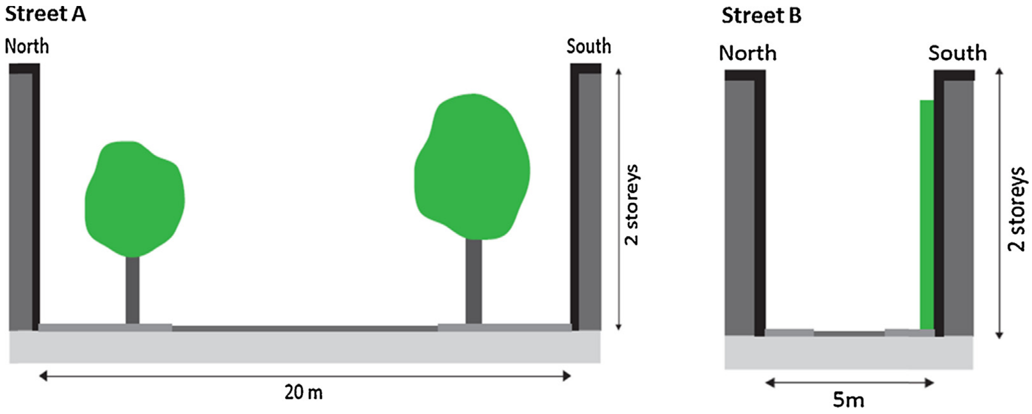


Fig. 7. Diagram of the street canyon of Streets A (left) and B (right) in the City of Port Phillip case study. Both streets are east-west oriented and the view is from the west. The diagrams show suggested UGI placement based on the context. See text for details.

temperatures, so there will likely be trade-offs and compromises when selecting the type of UGI and the plant species used.

There are two other major knowledge gaps that hinder successful implementation of UGI in hot or warm climates. The first is the horticultural limitations of UGI, which highlight a disconnect between some architectural and urban design 'visions' and what is biologically or physically possible (Hunter et al., 2014). There is an urgent need for species-specific (or functional type) data on plant ecophysiology, thermoregulation, water use and microclimate cooling benefits in urban settings to inform UGI plant selection, substrate selection, placement and subsequent irrigation. Related to this is the other major knowledge gap; a quantitative understanding of the water requirements of different UGI systems and plant species. Trees have received greatest research attention, yet there is still little information regarding the water requirements of urban trees (May et al., 2013; McCarthy & Pataki, 2010; Pataki, Carreiro, et al., 2011; Pataki, McCarthy, Litvak, & Pincetl, 2011). Water use and transpiration by street trees varies greatly among species (McCarthy & Pataki, 2010; Pataki, McCarthy, et al., 2011) but providing supplementary irrigation can increase cooling benefits (Gober et al., 2009). Until more detailed information on plant water requirements is available, strategies to maintain and maximise water availability to UGI elements during drought periods would be prudent. Especially so for street trees because of the direct and profound cooling benefits they provide to pedestrians and because of the many years 'invested' in their establishment and growth that can be lost if they die in one year of poor water management.

The case study application of the framework to the City of Port Phillip was very well received by the workshop group, challenging their thinking on prioritisation and implementation of UGI, especially in the objective of mitigating excess heat. Workshop participants highlighted the multi-functionality of UGI and that implementation would not consider urban heat alone. While they found the framework useful in prioritising neighbourhoods, the realities of implementation on the ground were complex with many competing factors such as surrounding infrastructure (e.g. above and below ground electrical and water services) and interactions between public and private space. Some local governments also do not have the resources to acquire thermal remote sensing data. High resolution thermal data are not necessary for this prioritisation purpose, and lower resolution satellite data would suffice (e.g. Landsat 8 provides 30 m resolution). The selection of key vulnerability risk factors could also be informed by local government staff knowledge and consultation with local social service and health professionals with a deep knowledge of local demographics. Applying the framework as we have in the case study requires suitable GIS software skills and products that may not be available to all local government authorities. Nevertheless, the framework can still be broadly followed without the detailed mapping applied in this study, and practitioners can adapt the framework to suit their local capacity and circumstance. This framework has already been taken up by the City of Geelong, Victoria, Australia, where a consultant has been engaged to apply the framework in prioritising neighbourhoods for heat mitigation within the municipality.

5. Conclusions

Mitigating extreme heat in urban climates will become increasingly important as climate change progresses and urban populations expand. UGI should be an important component of any urban climate change adaptation strategy because of the multiple benefits it provides to the community and local ecosystems. However, any UGI initiative should determine what the key objective(s) is at the outset. This study assumes the key objective is temperature mitigation. As such, in a situation where a decision may negatively impact other ecosystem service benefits provided by UGI, the trade-off would always be in favour of greatest temperature mitigation. If a UGI initiative has multiple objectives this becomes more difficult and priorities will have to be ranked, or trade-offs individually discussed with or without local community stakeholder engagement.

Despite the increasing amount of research on how UGI can prevent climatic extremes in urban areas, our understanding remains fragmented and the level of 'take up' by urban planners is low. We have presented, justified and applied a hierarchical decision framework that prioritises high risk neighbourhoods and then selects the most appropriate UGI elements for various contexts. Much work remains to be done, especially in determining the optimal arrangement of UGI in a street canyon or the wider urban landscape but there is sufficient information available for local governing bodies to take positive, preventive action and start mitigating high urban temperatures using UGI.

Acknowledgements

This paper arose from a project funded by the Victorian Centre for Climate Change Adaptation Research (VCCCAR). Sincere thanks to the City of Port Phillip for making available the thermal imagery data and supporting GIS layers. The manuscript has benefited from input during the project from Brod Street, all workshop participants, and Karyn Bosomworth and Alexei Trundle from RMIT University as well as from two anonymous reviewers. Andrew M. Coutts is funded by the Cooperative Research Centre for Water Sensitive Cities. Monash University provides research into the CRC for

Water Sensitive Cities through the Monash Water for Liveability Centre.

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