The effectiveness of Urban Green Infrastructure for urban heat regulation

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Candidate's Declaration

This thesis is submitted as a Thesis by Compilation in accordance with the Australian National University policies[1].

I declare that the research presented in this thesis represents original work that I carried out during my candidature at the Australian National University. This thesis contains no material which has been previously published or accepted for the award of any other degree or diploma in any university. To the best of my knowledge, it contains no material written by another person, except for contributions to co-author papers incorporated in the thesis where my contributions are specified in this Statement of Contribution and where due reference is made in the text.

Prabhasri Herath
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Publication Declaration

Table 0-1: Attribution statement of the chapters compromising the thesis

Chapter	Attribution statement
1	Introduction (unpublished) This chapter is written by myself with academic guidance and extensive constructive feedback from the panel, Xuemei Bai, Marcus Thatcher and Huidong Jin.
2	**Paper title:** Benefits and co-benefits of Urban Green Infrastructure for sustainable cities: Six current and emerging themes **Authors:** Prabhasri Herath and Xuemei Bai **Status:** Revised and under review **Contribution:** Prabhasri Herath and Xuemei Bai conceptualised and designed the methodology for the paper. Prabhasri Herath performed the literature search and data analysis and then the original draft preparation with visualisations. Both authors did critical revision and editing, and the overall supervision is provided by Xuemei Bai.
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5	**Paper title:** Does the spatial configuration of urban parks matter in ameliorating extreme heat? **Authors:** Prabhasri Herath, Xuemei Bai, Huidong Jin and Marcus Thatcher **Status:** Accepted **Contribution:** Prabhasri Herath conceived the idea and Prabhasri Herath and Xuemei Bai contributed to the conceptualisation and designing of the methodology. Marcus Thatcher and Huidong Jin assisted with improvements in conceptualisation and methodology. Prabhasri Herath performed the simulations, formal analysis, investigation, first draft preparation and visualisation. Xuemei Bai, Huidong Jin and Marcus Thatcher provided editorial advice and overall supervision.
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Dedication

To all the taxpayers of

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Abstract

Excess urban heat imposes severe heat stresses in cities, negatively affecting all social, economic and environmental sectors. The heat from local-scale urban processes - urban heat and urban heat island (UHI) effect, exacerbated by synoptically driven, large-scale extreme heatwaves, generates cumulative excess urban heat. These extreme heat conditions decrease the quality of urban life and make cities intrinsically more vulnerable than rural areas. Diminishing human thermal comfort is a key concern of extreme heat while increasing the risks and vulnerabilities towards heat-related mortality and morbidity. In Australia, extreme heat has claimed more human lives than any other weather event. For example, 473 heat-related deaths were recorded from 2001–2018. Global warming and rapid urbanisation have aggravated the challenges of urban heat, necessitating the urgent development of adaptation and mitigation strategies to address current and anticipated excess urban heat. In this study, ‘mitigation’ refers to actions that reduce heat and its associated impacts, while the term ‘adaptation’ relates to the capacity of those actions to enhance a city's preparedness for current and future heat challenges. Over time, these adaptive measures contribute to broader climate change resilience.

Among several engineering and nature-based solutions, Urban Green Infrastructure (UGI) has recently gained prominence and increased attention as a mitigation solution for excess heat. UGI is defined as a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services (ESS) in a city. This thesis focuses on the ability of UGI to mitigate excess heat through evaporative cooling from evapotranspiration and shading from the canopy cover.

The evolving climate context has introduced a new, complex scale to urban climatology, making it increasingly challenging to investigate the causes and consequences of local urban heat separately from heatwaves. Furthermore, the interventions and mitigation strategies should also accommodate corrective measures for excess urban heat

driven on both local and larger scales. This obligatory concern is largely underexplored in Australian literature since most available studies are focused on preparing cities for extreme heat from either the UHI effect or heatwaves. Furthermore, urban areas possess unique microclimates influenced by geographical, geometric, and local climatic factors, and no 'one-size-fits-all planning solution' exists. Therefore, mitigation strategies should be context-specific and operationalisable, a critical requirement often overlooked in urban research. We identified that the existing assessments on the effectiveness of UGI strategies are based on a narrow definition of functional aspects, underexploring the operationalisability in practical urban contexts, particularly on regional and neighbourhood scales. Moreover, some aspects, including comprehensive evaluations of effectiveness, large-scale, context-specific and realistic assessments, and the impact of the spatial configuration of UGI on urban heat mitigation, require in-depth investigation as areas not extensively explored in the literature. A lack of comprehensive knowledge about the effective use of operationalisable heat mitigation planning impedes the ability of planners and policymakers to prepare for this challenge.

Therefore, this thesis evaluates the effectiveness of urban green infrastructural solutions as mitigation and adaptation strategies for local excess urban heat by producing empirical evidence using high-resolution climate modelling experiments to capture these descriptive microclimatic characteristics for Melbourne–an exemplary susceptible Australian city with a temperate-oceanic climate. This was assessed through four research questions, which investigated: (1) the role of green infrastructure for sustainable cities and the gaps in the current literature regarding UGI solutions; (2) the effectiveness of the different urban surface parameters in mitigating excess urban heat; (3) how different heat mitigation solutions can be combined into operationalisable strategies that deliver maximum effectiveness in real-world cities; and (4) the spatial configuration of UGI matter in reducing excess urban heat and improving human thermal comfort.

The findings are presented in six chapters: an introduction, a systematic literature review, three content chapters, and a conclusion. Each chapter addresses one research question. The thesis begins by reviewing the literature, identifying the role of UGI in a sustainable city and discussing ESS, including multi-functionality, interlinkages and co-benefits in Chapter 2. This chapter presents six current and emerging research themes regarding the benefits of UGI while identifying 15 research gaps in the existing literature. The subsequent three content chapters explore the objectives of evaluating the effectiveness of urban surface parameters (USPs) (Chapter 3), identifying the effectiveness of combined USPs to maximise the cooling potential and operationalisability in real-world cities (Chapter 4) and assessing whether the spatial configuration of UGI matters in mitigating excess urban heat at a neighbourhood scale (Chapter 5).

A modelling study in Chapter 3 quantifies the thermal behaviour of multiple USPs over average heat conditions. From the USPs evaluated in a scenario analysis, green roofs, cool roofs and ground-level vegetation ratios showed high correlations (strong, negative, near-linear relationships) with temperature reduction, proving every bit of enhanced green in city-wide matters in urban cooling. Moreover, city-scale implementations of mitigation strategies are essential to achieve maximum effectiveness. Green surfaces exhibit the maximum heat reduction during night-time, while reflective, cool roofs are more effective during the daytime. This diurnal variation supports the design of the next chapter – Chapter 4, to combine USPs to achieve a diurnal maximum cooling impact. Realistic ratios and albedos for three effective parameters were selected to ensure operationalisability, and 18 scenarios were simulated for a period of 10 years. The scenario with maximum combined surface parameters proved to be the most effective with realistic implementation with maximum functionality. Green surfaces excel in their maximum effectiveness to counteract nighttime heat where the strongest UHI magnitudes are pronounced, while cool surfaces are highly effective during daytime, targeting peak thermal stress conditions. Integrating mitigation strategies leads to more effective outcomes in combating local urban heat compared to their individual contributions in isolation. The outcome emphasises the necessity of evaluating the effectiveness of heat mitigation solutions considering both functional performance and operationalisability. The results in Chapter 5, suggest that the same amount of green spaces with different spatial configurations as big parks or pocket parks matter for a location, but there is no universally superior design. This effectiveness is highly context-specific and influenced by the local climate zone, which is driven by factors such as surface cover, built-up area and structural elements such as building height and configuration.

The research outcomes and implications are highly applicable to planning real-world cities. These results and insights will inform the city authorities, urban planners and practitioners, enabling them to plan and design incorporating combined USPs to achieve maximum effectiveness by assuring functional efficiency and operationalisability. Spatial configurations and diurnal functional variability should be key concerns for cooling effectiveness during planning. Therefore, it is essential to perform context-specific simulations that provide empirical evidence for the city context before planning and designing the best and most effective heat mitigation plan. Such strategies will empower heat mitigation and disaster preparedness planning to enhance urban liveability, sustainability, and resilience of cities while protecting against future climate challenges.

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List of Abbreviations

ACC	Average Cooling Capacity
ACE	Albedo Cooling Effectiveness
ACT	Australian Capital Territory
AGRTP	Australian Government Research Training Program
AOGCM	Atmospheric Ocean Global Climate Models
ATEB	Australian Town Energy Budget model
BGI	Blue–Green Infrastructure
BoM	Australian Bureau of Meteorology
BR	Brownfield Rehabilitation
BSL	Baseline Data
CBD	Central Business District
CCAM	Conformal Cubic Atmospheric Model
CESM	Community Earth System Model
Cfb	Temperate Oceanic Climate
CFD	Computational Fluid Dynamics
CLM	Community Land Model
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EbA	Ecosystem-based Adaptation
EDC DAAC	EROS Data Centre Distributed Active Archive Centre
EHF	Excess Heat Factor
EMM	Estimated Marginal Mean
EQ	Environmental Quality
EROS	Earth Resources Observation and Science
ESS	Ecosystem Services
ES	Ecosystem Services
ET	Evapotranspiration
GDP	Gross Domestic Production
GHG	Greenhouse Gas
H/W ratio	Height/Width ratio
HD	Hot Days
HN	Hot Nights
IUCN	International Union for Conservation of Nature
IWM	Integrated Water Management
LAI	Leaf Area Index
LCZ	Local Climate Zone
LGA	Local government area
LH	Latent Heat Flux
LMM	Linear Mixed Models
LST	Land Surface Temperature
LST_UHI	Urban Heat Island with land surface temperature
MAE	Mean Absolute Error
MEA	Millennium Ecosystem Assessment
MEMI	Munich Energy–balance Model for Individuals
MLCII	Maximum Local Cool Island Intensity
MRT	Mean Radiant Temperature

MUKLIMO_3	Microscale Urban Climate Model
NbS	Nature-based Solutions
NCAR	National Centre for Atmospheric Research
NDVI	Normalized Difference Vegetation Index
NR	Noise Reduction
NSW	New South Wales
OAT	One-at-a-time approach
OTC	Outdoor thermal comfort
OBS	Observed Data
PCUM	Princeton Urban Canopy Model
PET	Physiological Equivalent Temperature
PMV	Predicted Mean Vote
RH	Relative Humidity
RMR	Raw Materials and Resources
RMSE	Root Mean Square Error
SA	South Australia
SCI–E	Science Citation Index-Expanded
SDG	Sustainable Development Goal
SE	Social Equity
SH	Sensible Heat Flux
SHF	Storage Heat Flux
SIM	Simulated Data
SQ	Soil Quality Regulation
SR	Spiritual Rewards
SS	Social Sustainability
SSCI	Social Science Citation Index
SST	Sea–surface Temperatures
SUHI	Surface Urban Heat Island
SVF	Sky View Factor
TAPM	The Air Pollution Model
TAS	Tasmania
TC	Thermal Comfort
TCI	Thermal Comfort Indices
UBGI	Urban Blue-Green Infrastructure
UBL	Urban Boundary Layer
UCCRN	Urban climate change research network
UCLEM	Urban Climate and Energy Model
UCM	Urban Canopy Models
UES	Urban Ecosystem Services
UG	Generic Urban Area
UGI	Urban Green Infrastructure
UHI	Urban Heat Island
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USP	Urban Surface Parameter
UT&C	Urban Tethys-Chloris model
UTCI	Universal Thermal Climate Index
VCE	Vegetation Cooling Effectiveness

VHD	Very Hot Days
VHN	Very Hot Nights
VIC	Victoria
WB	Windbreaks
WHO	World Health Organisation
WOS	Web of Science
WRF	Weather Research and Forecasting
WSUD	Water Sensitive Urban Design
WTP	Willingness to Pay

Chapter 1

"If you have a natural disaster like a cyclone or an earthquake or a flood, the impacts are immediate. Things get washed away, people drown. But heat is a silent killer."

Sarah Perkins-Kirkpatrick
Climate change researcher, University of New South Wales

1. Introduction

1.1. Research Background

Urbanisation is one of the most important global change processes and one of the biggest social transformations of modern times. This social transformation is driving and driven by several social, economic and environmental processes (Bai et al., 2017; Haase et al., 2018). Cities are home to 4.2 billion people, which is over half of the world's population (56.61% in 2021) and are expected to grow to nearly 70% by 2050 (Dodman et al., 2022; UN DESA, 2018b). Cities continuously evolve and change to accommodate this urban population growth by changing land use and consuming natural resources. Despite covering a scarce share of the land surface (M. Zhao et al., 2022), cities substantially contribute to global gross domestic production (GDP) by 80% (World Bank, 2020). They consume around 78% of the world's energy (Grubler et al., 2012) while generating 75% of global CO_2 emissions (UNEP, 2022).

1.1.1. Urban climatology, local urban heat and urban heat island

Urbanisation is linked with a complex array of major environmental, economic and social challenges. These challenges include land-use changes, water–soil–air pollution, environmental and ecosystem disturbances, public health issues, significant infrastructure costs, urban sprawl, solid waste management, urban heat concerns, exacerbated impacts of extreme weather events and disasters, social inequalities and economic disparities (Bai et al., 2017; Brody, 2013; Elmqvist et al., 2018; Kuddus et al., 2020). Among these multifaceted challenges, excess urban heat stands out as a prominent and urgent global issue for cities. The cumulative heat generated due to multiple natural and anthropogenic causes and exceeds the average thresholds in a particular urban setting is referred to as 'excess urban heat' throughout this study. Excess urban heat poses significant threats on urban sustainability and liveability.

The extensive modifications of surface and atmospheric characteristics in cities at local scales, make cities able to influence the nearby atmospheric variables. Cities are significantly influencing the weather in local scale and modifying/ enhancing high-imapct weather hazards, which is referred to as urban climate (Masson et al., 2020). Each city inherently develops its unique microclimate, primarily shaped by urban characteristics, such as city design, networked infrastructure, urban materials, population and cultural assets (IPCC, 2007). Urban form modifies the radiation trapping, ventilation patterns and moisture balances. Due to the alterations of surface energy and radiation balances (Oke, 1982; Stewart & Oke, 2012), cities experience an elevated temperature as a distinct feature characterising urban climate (Masson et al., 2020) by giving rise to 'urban heat'. As a result, cities have intrinsically warmer air and land surface temperatures than surrounding rural neighbourhoods, leading to the 'urban heat island (UHI) effect' (Oke, 1973). Both urban heat and UHI occur as local, urban climatological impacts and are collectively introduced as the 'local urban heat' in this thesis.

The UHI as a source of extreme heat, the characteristics, causes and effects have been extensively studied in previous literature (Rizwan et al., 2008). UHI effect happens as a meteorological phenomenon due to intricate thermoradiative and energetic processes within complex urban systems. Natural surfaces in urban areas undergo extensive transformations into artificial, impermeable settings, while urban structures, urban forms and materials are converted into heat-absorbing and heat-storing configurations to facilitate infrastructure and various physical activities, both industrial and mobility. Urban materials enhance heat absorption, storage and delayed heat release, directly influencing alterations in the urban energy budget as the drivers of UHI effect (Masson et al., 2020; Rizwan et al., 2008). These altered surface impermeability, urban geometry and thermodynamics, combined with limited green spaces, cumulatively disrupt surface energy balance, particularly leading to increased sensible heat and reduced latent heat fluxes (Gu et al., 2020). Consequently, this results in elevated air and surface temperatures in cities compared to neighbouring rural areas (Akbari & Matthews, 2012; Arnfield, 2003; Coutts et al., 2007; Grimmond, 2007; Howard, 1833; D. Li et al., 2019; Seto et al., 2014). The magnitude of UHI intensity varies based on several factors, including synoptic weather conditions, urban materials, local morphology, geography and city structure, anthropogenic heat generation, and heat sinks (Haddad et al., 2020; Santamouris & Kolokotsa, 2016).

Urban areas generally exhibit different UHI intensities ranging from 0.4 to 11 °C (Mentaschi et al., 2022; Santamouris, 2015; Sharifi & Lehmann, 2014). The strongest UHI magnitudes are observed during the evening and nighttime (Martilli et al., 2020; Masson et al., 2020). The excessive heat from UHI directly influence on the city's energy demand, as urban buildings require a 13.1% increased cooling load compared to rural buildings (Santamouris, 2014). This leads to an additional 0.45-4.6% of peak electricity demand per degree Celsius rise (Santamouris et al., 2015).

1.1.2. Extreme heat from heatwaves

During the summer, excess heat poses a dual pressure on cities as heatwaves exacerbate already elevated urban temperatures. For instance, both Melbourne and Adelaide experience higher UHI intensities at night during heatwaves (Rogers et al., 2019). Heatwaves are extreme weather events that occur in the atmosphere and the ocean and are driven by large-scale climate variabilities, land surface temperatures, sea surface temperatures and atmospheric conditions (Perkins-Kirkpatrick et al., 2016). They are defined as a period of persistent excessive heat, leading to disastrous effects as natural hazards on different systems. Synoptically driven extreme heat is the concern of this thesis, as heatwaves generate extreme heat conditions, substantially impacting human health, the economy and the environment (Perkins-Kirkpatrick et al., 2016) while increasing the risk to urban communities with greater exposure and vulnerabilities (Herath et al., 2023; Tuholske et al., 2021).

With the observed long-term heating of the Earth's surface since the 1950s - the pre-industrial era, global warming caused increases in both maximum and minimum air temperatures (Stocker et al., 2013). During 1973-2012, cities worldwide experienced an increased number of heatwaves and extreme hot days (Mishra et al., 2015). For example, the occurrence of heatwaves in major cities across the United States is observed as increasing from two average heatwaves per year (during the 1960s) to six per year (during 2010–2020) (US-EPA, 2022). According to current statistics, 70% of cities worldwide are already contending with the consequences of climate change, leaving nearly all cities vulnerable to these risks (C40 Cities & UCCRN, 2018). Approximately 350 cities worldwide are experiencing extreme heat conditions, affecting over 200 million urban residents (C40 Cities & UCCRN, 2018). With the projected increasing global warming and climate change trends, extreme weather events, such as heatwaves, droughts, flash floods, heat stress, and storms, are anticipated to become more frequent and intense while occurring over an extended spatial extent and duration (Dodman et al., 2022; IPCC, 2022; Kirezci et al., 2020; Schiermeire, 2018). The frequency, severity and duration of extreme weather events will be exacerbated due to climate change in the context of the 2 °C global warming level in future (IPCC, 2022). Consequently, it is predicted that over the next 30 years, more than 1,000 cities, with a collective population exceeding 1.6 billion, will face regular and extreme heatwaves (C40 Cities & UCCRN, 2018; Schiermeier, 2019, 2021).

Several deadly heatwaves in cities worldwide serve as historical evidence of the severity of this issue. For instance, in the summer of 2003, the European region faced a record-breaking heatwave with temperatures exceeding the 1961−90 mean by ~3°C (Schär et al., 2004). According to Guinness World Records (2022), the 2010 Russian Federation heatwave stands as the deadliest in the past five centuries, resulting in 56,000 heat-related fatalities. This extreme event was marked by scorching temperatures (reaching 44°C), droughts, forest fires, and smog (Grumm, 2011). Notably, subsequent decades have witnessed even hotter heatwaves in 2010, including the 'mega heatwaves' of 2003 and 2020. From June to August 2022 (lasting 64 days), China endured its hottest-ever heatwave, with some areas recording a maximum temperature of 41.6 °C (CMA, 2022). Parts of Europe experienced the 2022 European heatwave in July, with Portugal reaching a high of 47 °C, followed by Spain at 45.7 °C (France, 2022; Kendon, 2022). In June (which lasted until August) 2022, Japan faced the hottest heatwave in 150 years, with temperatures reaching 40.2 °C (BBC News, 2022). The North American region, in June 2021, recorded the highest temperature at 49.6 °C in Lytton, a Canadian town, exceeding local temperature records by 4.6°C (Uguen-Csenge & Lindsay, 2021).

1.1.3. Impacts of extreme heat

Extreme heat from heatwaves has claimed more human lives than any other weather event (CCA, 2016). The acute gravity and dangerousness of heatwaves are often underestimated and overlooked, as the immediate destruction and death toll may not be readily apparent (WHO, 2022). As highlighted by Coates et al. (2014), pp 33, the 'definitional confusion and inconsistencies in defining' the heatwaves and extreme heat have impeded the accurate determination of their overall impact, including the absolute death toll.

Moreover, urbanisation exacerbates the risks and vulnerability of communities to extreme heat, especially as urban populations swell, with particularly pronounced impacts on vulnerable age groups. Romanello et al. (2021) in Lancet, reported increased exposure to extreme heat among these groups, with 626 million more infants (under 1 year) and 3.1 billion more older adults (over 65) exposed daily in 2020 compared to the 1986-2005 average. With a projected 1.6 billion people in over 970 cities likely to be affected by intensified extreme heat due to climate change by 2050, this issue deserves significant attention (C40 Cities & UCCRN, 2018).

As a whole, excess heat deprives the coping ability of all urban communities and ecosystems (Herath et al., 2021). The negative impacts burden the society, environment, and economy, diminishing the quality of urban life, residents' thermal comfort, health and well-being, and straining critical infrastructures, such as energy, transport, and water. Rising temperatures elevate energy demand for cooling and irrigation, as well as societal challenges such as food security, migration, and displacement (Ali et al., 2013; Hou et al., 2014; Matthews et al., 2017; Mora et al., 2017; Watts et al., 2020; Q. Zhao et al., 2021).

The impact on human health is diverse, encompassing heat stress, a surge in heat-related illnesses and fatalities, shifts in both mental and physical behaviour, and the transmission of diseases. During heatwave events, there is a notable increase in heat-related mortalities, hospitalisations, and cardiorespiratory diseases (Martinez et al., 2018). The risks and vulnerability depend on several factors, including age, gender, socioeconomic status, remoteness, and geographical location (Xiao et al., 2017). The economic implications of extreme heat are significant, including reduced workforce productivity, increased costs for reinstalling damaged infrastructure and assisting affected communities. Cities unprepared for extreme urban heat may face future expenditures of 5.6% of their GDP (Matthews et al., 2017). Moreover, heatwaves create long-term and short-term environmental impacts such as wildfires, droughts, air quality changes and sea-level rise (WHO, 2018).

Although the mechanisms are entirely different for the synoptically driven extreme heat (during heatwaves) and UHI as local urban climatological impact, the drivers often interact synergistically (D. Li & Bou-Zeid, 2013; Nazarian et al., 2022). The heat from local-scale urban processes- UHI and urban heat, that is exacerbated by synoptically driven, large-scale extreme heatwaves (also intensified due to climate change), contributes to the overheating in cities (Chapman et al., 2017; Santamouris & Kolokotsa, 2015). Nazarian et al. (2022) introduced this as 'urban overheating', the exceedance of locally defined thermal thresholds that correspond to negative impacts on people (e.g., health, comfort, and productivity) and associated urban systems. While these phenomena operate at two different scales, their consequences, exacerbated excess urban heat, have similar impacts on human health, ecosystems, infrastructure and the economy. Consequently, investigating the causes, consequences, and mitigation-adaptation interventions for the cumulative excess heat (from both local-scale and larger-scale phenomena in tandem) is meaningful, but needs extra caution around complexities due to scale disparities. This obligatory concern - identifying mitigation strategies to accommodate corrective measures for this cumulative heat, is particularly underexplored in Australian literature.

With the concerns of future extreme heat threats, cities must take proactive measures to cope with current and anticipated extreme climate and urban climate shocks. Thus, developing preparedness and resilience through urgent adaptation and mitigation strategies is imperative. Such strategies should serve as integral components of urban planning and decision-making.

1.2. Mitigation and adaptation to excess urban heat

Heat mitigation is ‘modifications to urban characteristics and behaviours made with the objective to reduce urban temperatures where they pose a negative impact’ (Masson et al., 2020). In the context of this thesis, the definitions of mitigation and adaptation do not adhere to the textbook definitions related to greenhouse gas emissions by the IPCC (2001). Instead, in this study, ‘mitigation’ pertains to actions aimed at reducing heat and its associated impacts, while 'adaptation' relates to the capacity of these actions to enhance a city's preparedness for present and future heat-related challenges, in the long run, towards climate change.

Reducing or mitigating urban heat and UHI magnitudes while adapting to extreme heat impacts from climate change would be the appropriate approach to face the multifaceted challenges created by urban heat hazards. As Martilli et al. (2020) suggested, mitigating UHI intensity should not necessarily be relevant to heat mitigation. Hence, mitigation strategies for UHI or urban heat may or may not address extreme heatwave temperatures. Martilli et al. (2020) presented evidence to emphasise the necessity of differentiating the mitigation strategies. Urban heat, which arises due to its urban climatology, claims the highest building energy consumption for cooling and creates the worst thermal stress during daytime. This differs from UHI as the strongest UHI is observed during the evenings and nights (Martilli et al., 2020). Moreover, the cities surrounded by deserts (e.g., Phoenix) and those with semi-arid land cover (e.g., Madrid) do not experience UHI during daytime; however, they confront heat-related issues such as poor thermal comfort and high cooling energy consumption. Therefore, mitigating urban heat and UHI are different approaches with both similarities and disparities, while adaptation is needed to face extreme heatwave temperatures. Hence, it is essential to identify where and which mitigation is required.

There are several infrastructure-based approaches for extreme heat mitigation and adaptation. Infrastructure-based approaches involve modifying building envelope and surface characteristics, optimising urban geometry and Nature-based Solutions (NbS). The building envelope and surface characteristics can be modified by altering the building orientation and changing the surfaces of roofs, walls, roads and paving to highly reflective and permeable materials (e.g., cool roofs, cool pavements, permeable and water-retaining pavements). Optimising urban geometry is practised at different urban scales by modifying the building orientations, public and outdoor spaces, sky-view factor, height-to-width ratio and street canyon orientation (Han et al., 2022). Increasing surface greenery, adding water bodies, tree configuration and landscape design are successful NbS techniques (Hayes et al., 2022). Nature-based solutions are defined as solutions to societal challenges that are inspired and supported by nature, which are cost-effective, while simultaneously providing environmental, social and economic benefits to help build resilience (Cohen-Shacham et al., 2016; Pauleit et al., 2017; Raymond et al., 2017). Urban parks, green areas, street trees, green walks, green walls and green roofs are several examples of NbS that integrate nature components into cities, thus, increasing the urban green coverage.

Urban green infrastructure, a popular concept under NbS, is a successful heat mitigation and adaptation strategy in cities (Herath et al., 2021, 2023; Herath & Bai, 2023). Introducing green components into cities is referred to in the literature using various terms, such as Urban Green Infrastructure (UGI), NbS, Ecosystem-based Adaptation (EbA) and Ecosystem Services (ESS) (Pauleit et al., 2017). These terms have similarities and differences in their definitions. NbS are the broadest concept and considered an umbrella to other subset concepts. Green infrastructure is the most popular concept under NbS. It is defined as a “strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ESS" in the city (European Commission, 2013). Green infrastructure contains,

- entirely natural areas (e.g., woodland, wildflower meadows and ponds),
- semi-natural spaces (e.g., parks, private gardens, agricultural fields and hedges), and
- artificial and built features (e.g., green roofs, green walls and eco-bridges) (European Commission, 2013).

Urban green interventions increase the canopy and vegetation cover in cities to provide several ESS categorised as regulating, provisioning, supporting and cultural (MEA, 2005). The functions, including microclimate regulation, air quality regulation and carbon sequestration, are categorised as regulating ESS and attract the most attention in the existing literature (Haase et al., 2014; Herath & Bai, 2023). Urban vegetation provides evaporative cooling through evapotranspiration and shading (Taha, 1997; Tran et al., 2006) and supports heat mitigation. Therefore, this thesis focuses on microclimatic cooling as an urban heat mitigation solution from UGI.

All the approaches mentioned above have different effectivenesses in heat mitigation, which should be considered during implementation. Integrating UGI into urban heat mitigation and adaptation systems necessitates careful consideration of specific requirements and limitations. Adequate spatial planning is essential to maximise the distribution of UGI within the city, ensuring their accessibility, safety, equity and efficacy. Strategic placement of UGI is another key consideration to achieve the highest cooling effectiveness during extreme heat events. Moreover, the associated limitations also need to be considered, including costs and design standards for installation, maintenance, space and resources, concerns regarding ownership of the property, and socioeconomic considerations, such as public perception, policy constraints, administrative restrictions, technology and innovation (Herath et al., 2023).

1.3. Urban heat in the Australian context

In Australia, heatwaves have claimed more human lives (473 heat-related deaths were recorded from 2001–2018) than any other natural hazard, including floods, cyclones and bushfires (DEA, 2020). Due to Australia's past experiences with extreme heat and associated events, such as heatwaves, droughts, and wildfires, it is expected that their severity and frequency will continue to escalate (Perkins-Kirkpatrick et al., 2016; Perkins-Kirkpatrick & Lewis, 2020).

One of the most severe heatwaves occurred in 2009 (south-eastern Australian heatwave), affecting the southern and south-eastern regions, including Victoria (VIC), parts of South Australia (SA), New South Wales (NSW), Tasmania (TAS) and the Australian Capital Territory (ACT) from 27 January to 9 February. This heatwave was exceptionally severe, breaking several temperature records in Australian history (NCC, 2009). The highest-ever recorded temperatures were reported as 48.8 °C in Hopetoun (VIC), 45.7 °C in Adelaide (SA), and 46.4 °C in Melbourne (VIC) (Karoly, 2009; NCC, 2009). These extreme temperatures led to the tragic Black Saturday bushfires, which started on 7th February, in Kilmore East, VIC, and spread through pine plantations into VIC, SA and ACT (Karoly, 2009). The fire caused significant casualties and destruction, making it the worst Australian disaster. The heatwave and bushfires together killed 374 people, significantly displaced many- people and livestock, and damaged infrastructure (properties and electricity) (McEvoy et al., 2012; National Museum of Australia, 2022a).

Subsequent heatwaves in 2014, Adelaide and Melbourne experienced maximum temperatures of 46 °C (average 43.6 °C) and 41 °C (43.1 °C average), respectively. In response to the extreme heat of the 'angry summer' in 2013, the Australian Bureau of Meteorology (BoM) added a new colour contour to the existing temperature scale to represent temperatures up to 54 °C (National Museum of Australia, 2022b), signifying the potential severity of the heat stress. When global warming escalates from 1.5 to 2 °C, heatwaves will become 85% more frequent in Australia. Furthermore, a temperature rise from 1.5 to 3 °C could lead to these events persisting for up to a month (Trancoso et al., 2020).

Local urban heat in Australia, often measured in terms of Urban Heat Island (UHI) effect, has been widely documented in the literature. Recent data reveals significant UHI intensities ranging from 1 to 13 °C in Australian cities (Yenneti et al., 2020). For example, in NSW, the western suburbs of Greater Sydney, like Paramatta, experience temperatures ~10 °C higher than eastern Sydney suburbs during extreme heatwave days (Pfautsch & Rouillard, 2019). According to Rogers et al. (2019), Melbourne and Adelaide both experience 1.2 °C higher UHI intensities at night during heatwaves. Different UHI values have been reported for Melbourne, and the mean UHI of 20 years average was 1.13 °C (summer: 1.29 °C, spring: 1.25 °C, autumn: 1.02 °C and winter: 0.98 °C) in 2000 (Morris et al., 2001). Coutts et al. (2008) reported summer maximum UHI as 3–4 °C (at 2 am, modelling values). All these records are older than a decade, and recently reported UHI values could be changed with the impacts of current urban growth. The typical raw UHI magnitude reported in 2019 by Rogers et al. was up to 3.3 °C (2.7 °C) on the first nights of the heatwave and 2.2 °C (2.6 °C) during the middle nights.

According to the Australian Bureau of Statistics (ABS), the urban population rate in Australia grew from 60% to 90% during 1911–2016. With 86% of the population living in urban areas, Australia has become one of the most urbanised countries in the world (ABS, 2019; UN DESA, 2018a). Consequently, Australian cities have high exposure, risks and vulnerabilities associated with urbanisation and excess urban heat. Each Australian city faces unique challenges, risks and vulnerabilities related to heat hazards. Australia's vast size and geographical diversity result in a wide range of climate classifications for its cities, which is described with climate classification of cities (Peel et al., 2007; Wasko et al., 2018). Among these major cities, Sydney and Brisbane experience hot, humid summers and mild winters, classifying them as subtropical cities. The high humidity conditions in those cities create thermally uncomfortable conditions during the summer months (Johansson & Emmanuel, 2006; Yang et al., 2013). Darwin, a city with tropical climate features, is generally experiencing warm ambient temperatures (e.g., 1,764 hours above 30 °C during a study period of 2017–2018 by Haddad et al. (2020). Combining high air temperatures with high relative humidity increases the risk of thermal discomfort and heat-related illnesses (Oppermann et al., 2017). Perth has a Mediterranean climate characterised by hot, dry summers and mild, wet winters. The risk of extreme heat events is higher during the summer, with elevated temperatures often leading to wildfires (Steffen et al., 2015). Melbourne has a temperate oceanic climate featuring mild, damp winters and warm to hot summers. Considering the observed and predicted extreme heat risks and heatwave frequencies in Melbourne (Steffen et al., 2015), it is evident that a combination of factors beyond climate classification influences current vulnerability to heat hazards. Most major Australian cities, including Melbourne, are located in coastal areas. The geographical location of a city is a critical factor, as proximity to coastal regions provides some relief in the form of sea breezes. This proximity can also lead to increased heat and humidity due to a medium UHI effect (Masson et al., 2020). Additionally, local climate impacts due to urban climatology, local climate zones, and population density play a significant role in determining a city's vulnerability to heat hazards (Gilabert et al., 2021; Masson et al., 2020).

Australian cities have undergone significant urbanisation, and their urbanisation characteristics, such as high concentration of built-up areas, infrastructure, and population density, have contributed to the heat challenges and vulnerability to heat hazards (X. Li et al., 2021; Q. C. Sun et al., 2022). This rapid urban development leads to UHI and urban overheating (Nazarian et al., 2022; Tapper, 2012). The conversion of natural vegetative surfaces into built-up areas has resulted in increased surface temperatures. Highly urbanised Australian cities are susceptible to the health impacts of climate change, including increased morbidity and mortality from thermal stress (Bambrick et al., 2011). Urban expansion due to current urban development has increased Melbourne's nighttime near-surface (2 m) UHI value by 0.75 °C – 2.8 °C (Imran et al., 2019a). Brisbane is expected to be 2.44 °C – 2.54 °C hotter than surrounding rural areas in 2023 (Deilami & Kamruzzaman, 2017). Adelaide has reported a maximum urban−rural temperature difference of 5.9 °C during some days at midnight in July and August 2013 (Soltani & Sharifi, 2017). The most recent record for surface UHI (LST UHI) in Melbourne is from Sun et al. (2019), which used land surface temperature (LST) values from Landsat 8 remote sensing images, ranging from −7.16°C – 10.75 °C across different local government areas (LGAs). According to Imran et al. (2019a), the skin-surface UHI value for Melbourne was 1.9 °C – 5.4 °C.

Considering the severity of extreme heat events, Australia needs to plan ahead, invest effort and capital in corrective measures against extreme heat impacts and implement successful heat mitigation and adaptation strategies. Recovering is always costly; hence, the cost of preparedness is an investment. For instance, Melbourne has spent approximately $1.8 billion for the recovery processes of the affected community due to hot weather conditions, and $300 million − one-third of the total cost, is allocated explicitly to mitigating the effects of heatwaves on the community (AECOM, 2012). At the jurisdictional level, the Australian government has introduced the National Climate Resilience and Adaptation Strategy through the Department of Agriculture, Water and the Environment to ensure the health and well-being of cities, communities and the environment (DAWE, 2021). In addition, different state and territory governments are performing local strategic planning to emphasise the country's vision towards more rigorous climate actions. For example, the ACT government has initiated a plan to enhance living infrastructure to adapt to climate change impacts (ACT Government, 2019). Further, Melbourne is performing a long-term metropolitan planning strategy, Plan Melbourne 2017–2050, to define the future shape of Melbourne in the next 35 years by increasing the urban green cover to 40% (City of Melbourne, 2012, 2017).

Urban climatology aids in identifying the microclimate system of a city, its climate drivers and contributors, and provides insight into the impacts, risks, vulnerabilities and potential pathways for mitigation and adaptation. When transferring theoretical and scientific knowledge into operation, the identified gap in the existing literature needs to be addressed through more realistic urban climate studies. Several modelling studies were identified in the literature that were conducted in academia to support national and state-wise jurisdictional heat mitigation planning on different spatial and temporal scales. For example, different vegetation cover and urban expansion scenarios were studied for Brisbane (Australia) using the Conformal Cubic Atmospheric Model (CCAM), which showed that nighttime temperatures are higher in a zero-vegetation area than in a high urban density area (Chapman et al., 2018). The Weather Research and Forecasting (WRF) model was used to simulate Melbourne (Australia) to demonstrate that green roofs and cool roofs could have mitigated the higher temperatures experienced during the 2009 heatwave (Imran et al., 2018). The same authors also assessed the efficacy of vegetative patches to minimise extreme heat impacts experienced during the most extreme heatwave in Melbourne that occurred in January 2009. The simulation results revealed that mixed vegetation patches with forests, grasslands and shrublands could reduce the near-surface UHI (Imran et al., 2019a). Moreover, Jacobs et al. (2018) used the WRF model to simulate the Melbourne climate during several heatwaves and observed that vegetation patches have an effective nighttime cooling potential, while cool roofs provide a more effective daytime cooling potential. While providing essential insights into heat mitigation possibilities, the abovementioned mesoscale modelling studies tend to focus only on one or two urban surface parameters as mitigation options and have concentrated solely on UHI or historical heatwaves.

1.4. Research questions, framework and methods

1.4.1. The thesis problem statement

This thesis spotlights Australia because it is one of the most urbanised countries globally, with predictions of increasing urban populations in future (ABS, 2019). Given the urban population growth, urbanisation rate, heightened UHI intensities and predictions for severe, frequent and persistent heatwaves with intensifying climate change impacts, Australian cities are at high risk regarding heat stress (Coates et al., 2014; Sachindra et al., 2016). Melbourne is particularly vulnerable to extreme heat in future with the predicted rising UHI intensities and heatwave frequencies with climate change (Sachindra et al., 2016). Regardless of being a significant public health risk, the focus and attention from researchers, policymakers and emergency management agencies on extreme heatwaves seem limited and unequal compared to other natural hazards (Coates et al., 2014; Xiao et al., 2017). Although extreme heat events emphasise the relative significance associated with high vulnerability and mortality to humans, researchers believe Australia's attention and study level towards extreme heat disasters are insufficient for implications for emergency management and policy change (Coates et al., 2014; Perkins-Kirkpatrick et al., 2016; Perkins-Kirkpatrick & Lewis, 2020).

Cities need to prioritise heat mitigation and adaptation planning. Urban studies for excess urban heat should be conceptualised to investigate the combined effects considering the cumulative heat from local urban heat and extreme heat from heatwaves. According to Hatvani-Kovacs & Boland (2015), neither the causes nor consequences of UHI should be investigated separately from heatwaves. In contrast, according to (Martilli et al., 2020), heat mitigation strategies should focus on reducing the 'absolute' impact on temperature, not the impacts on UHI magnitude. These debates and concerns remain unclear and underexplored in Australian literature since most available studies are focused on preparing cities for extreme heat from either the UHI effect or heatwaves (e.g., Chapman et al., 2018; Jacobs et al., 2018). This thesis investigated heat mitigation strategies associated with urban microclimate adjustments. Thus, this thesis focused on excess urban heat, cumulatively generated with urban heat and UHI effect, and exacerbated due to extreme heat conditions during heatwaves, to investigate mitigation and adaptation approaches using urban green infrastructural solutions.

Assessing the effectiveness of mitigation and adaptation approaches in real-world cities is essential, as these cities serve as the frontlines of climate change impacts. Current research literature often assesses the effectiveness of mitigation strategies with a narrow framework defined on the effect and success in terms of functional aspects. This approach, however, leaves a significant gap in our understanding of how these strategies can be practically and operationally implemented in urban settings. To bridge this gap and enhance the real-world applicability of urban heat mitigation and adaptation strategies, it is imperative that research focus on operationalisable approaches, which are feasible solutions readily implementable within urban landscapes. One pressing avenue for research is the exploration of the spatial configuration of urban green for urban heat mitigation. The importance of green spaces in mitigating extreme urban heat is widely acknowledged; however, the spatial arrangement and distribution of these green elements remain underexplored, particularly in heat mitigation planning. Moreover, a shift in focus beyond the traditional urban–rural temperature difference to the temperature difference between different urban areas, as suggested by Martilli et al. (2020), opens up a new avenue of research exploration. This shift can be introduced by examining the diverse Local Climate Zones (LCZs) within the same urban area, which are characterised by their unique surface cover, materials, structural attributes, and human activities, encompass a range of scales from hundreds of meters to kilometres (Stewart & Oke, 2012). The classifications are based on urban morphology, built-up area, and pervious and impervious surface cover. Given the significance of the surface characteristics, it is imperative to investigate the influence of urban green surfaces in different spatial configuration settings. Due to the high urban area percentage and urbanisation rate in Australia, the incorporation of LCZs into heat mitigation and adaptation strategies is a critical consideration that has yet to be comprehensively investigated.

Urban planners and decision-makers rely on research for science and evidence-based, operationalisable and realistic empirical evidence in urban planning and policies for future cities (Bai et al., 2018). After the identification of the abovementioned gaps in the literature, this thesis conducted a comprehensive scientific research project focused on the effectiveness of UGI-related mitigation strategies to identify the best suitable heat mitigation and adaptation approach with maximum operationalisability. The urban case studies were conducted for Melbourne, by applying urban climatology approaches via climate modelling techniques focusing on neighbourhood and regional climate interrelations considering both urban–rural and urban–urban gradients or LCZs.

1.4.2. Aims and objectives

1.4.2.1. Overall aim

This thesis aims to evaluate the effectiveness of urban green infrastructural solutions as heat mitigation and adaptation strategies during extreme and average urban heat conditions in Melbourne, a temperate-oceanic Australian city. This aim includes using simulation case studies by conducting climate modelling to identify the best heat reduction strategy for maximum functionality, operationalisability and spatial configurational impacts.

1.4.2.2. Objectives and research questions

This overall aim is achieved through four main research objectives as follows:

1. Review the literature on the role of green infrastructure in sustainable cities.
2. Assess the effectiveness of different urban surface parameters in mitigating excess urban heat.
3. Evaluate the combinations of different heat mitigation solutions to maximise the effectiveness as operationalisable strategies in real-world cities.
4. Assess the impact of the spatial configuration of UGI for reducing excess urban heat.

These objectives are addressed through these four research questions:

1. What is the role of green infrastructure for sustainable cities, and what are the gaps in the current literature regarding UGI solutions?
2. How effective are the different urban surface parameters in mitigating excess urban heat?
3. How different heat mitigation solutions can be combined to deliver operationalisable strategies with maximum effectiveness in real-world cities?

4. Does the spatial configuration of UGI matter in reducing excess urban heat and improving human thermal comfort?

1.4.3. Research scope

To achieve the objectives mentioned above, this thesis investigates the city of Melbourne. By concentrating on a single city, this thesis was able to apply multiple modelling approaches, leverage high-quality observations, and make a significant impact on a city with a population of approximately 5 million people. Melbourne has a notable history of experiencing extreme heat conditions, with significant heatwaves occurring in 2009, 2013, 2014, and 2019. The study period for this thesis is designed to encompass these years, capturing a range of conditions from average summer heat to extreme heat (Chapter 3: 90 days in December to February in 2018–2019 summer period, Chapter 4: 90 days of summer for ten years from 2011 to 2020 – to represent average heat and UHI, and from 28 to 30 January in 2009 – to represent extreme heat conditions, and Chapter 5: 30 January in 2009). Furthermore, Melbourne has the potential to take advantage of natural vegetation for mitigation of urban excess heat due to its climate (oceanic temperate climate conditions - Cfb). The modelling studies in each chapter represent two different scales, microscale (10 m) and mesoscale (1 km), which enabled examining both large city-wide responses to green infrastructure and local climate changes within specific city sections. Both of these scales are important for the comprehensive understanding of the effectiveness of green infrastructure for excess urban heat mitigation. However, the modelling approaches did not address economic aspects or non-green infrastructure approaches towards excess urban heat mitigation. Consequently, this thesis is limited in scope to research related to the climate implications of green infrastructure in the context of a highly populated city within a temperate climate.

1.4.4. Research methods

This section will summarise the overarching research design and methods for addressing these four objectives as the building blocks of this thesis. The thesis uses Melbourne as the case study to assess the selected objectives. The heatwave occurrence in Melbourne has been frequent during the last two decades (Perkins-Kirkpatrick et al., 2016). Melbourne experienced several deadly heatwaves in its summers and a few were highlighted as record-breaking heatwaves, such as 2009, 2014 and 2019 (Bureau of Meteorology (BoM), 2020). The potential risks and vulnerabilities due to cumulative heat from these two extreme events: heatwave and UHI, make Melbourne an interesting case study for heat and mitigation analyses.

This thesis uses meso and microscale climate models as required in the case studies. Chapters 3 and 4 use The Air Pollution Model (TAPM) mesoscale climate model, while Chapter 5 uses the ENVI-met V5 microscale modelling platform. The subsections below provide essential model configuration information to justify the selection and usage of those two models for the case studies in this thesis.

1.4.4.1. Mesoscale climate modelling using TAPM

To evaluate the objectives that needed an urban or regional scale focus, this thesis used TAPM, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia. TAPM incorporates an incompressible, non-hydrostatic, primitive equation model in its meteorological component, which supports the three-dimensional mesoscale simulations with terrain-following vertical coordinates. The model can dynamically downscale the three-dimensional meteorology and air pollution concentration to high spatial and temporal resolution over a small area (Hurley, 2008a, 2008b). A series of equations (momentum, incompressible continuity and scalar equations with turbulence kinetic energy and eddy dissipation rate) simulate different meteorological components, including horizontal and vertical wind flow and velocity, potential virtual temperature and specific humidity (Hurley, 2008a). The model has also been coupled with the Urban Climate and Energy Model (UCLEM), which is based on an urban canopy model (Thatcher & Hurley, 2012) and a building interior energy model (Lipson et al., 2018), to integrate the urban characteristics into TAPM and intended to support multi-decade urban climate simulations in a computationally efficient way. The UCLEM is explicitly designed to represent the interactions between energy use and the urban environment in Australian cities over long periods. This model accommodates adjustments by the user for the parameters, including canyon and roof vegetation ratios, building height, density and the thermal and radiative characteristics of the building materials (Lipson et al., 2018; Thatcher & Hurley, 2012). As a result, it secures the mesoscale characterisations of urban surface parameters in large city-scale simulations. In addition, Chapters 3 and 4 discuss the details further on model configuration.

1.4.4.2. Microscale climate modelling using ENVI-met

To observe the spatial-level impacts of green infrastructural solutions in urban microclimate, evidence should be on more finer-scales. Therefore, this thesis used the ENVI-met microscale model, representing the downscaled neighbourhood-level interactions. ENVI-met V5 is based on a holistic, three-dimensional, non-hydrostatic microclimate model that follows computational fluid dynamics (CFD) and thermodynamics to recreate the urban conditions as simulations. As a multitude of tools, ENVI-met permits modelling simulations of the interactions among surfaces, soils, vegetation, air and buildings in different sizes and forms in the urban environment (Bruse & Fleer, 1998; ENVI-met GmbH, 2022). In addition, the software provides a 3D prognostic meteorological model to calculate air temperature, wind flow, humidity and turbulence for different grid resolutions (ENVI-met GmbH, 2022). These climate calculations are based on shortwave and longwave radiation fluxes determined by shading, reflection and re-radiation from built and natural environments. ENVI-met has been proven to be a successful model in several climate conditions with multiple case studies (ENVI-met GmbH, 2022) and has shown reliability in urban microclimates with the inclusion of rare urban canopy characteristics in most models, such as shading and drag. Further information on the models, configuration and experimental designs is available in Chapter 5.

1.5. Overview of the chapters

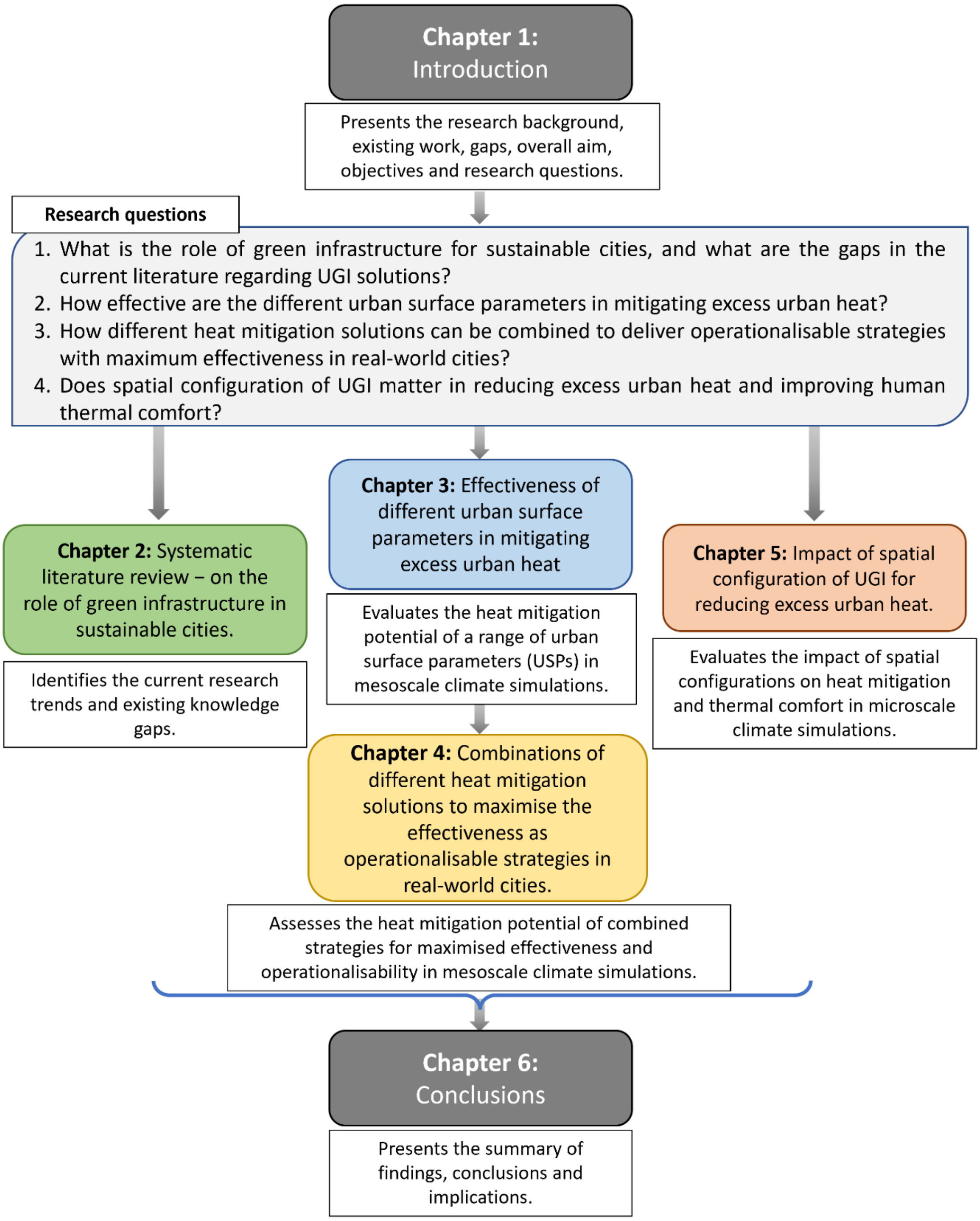

Figure 1.1: Structure of the thesis. Chapters 2 to 5 are dedicated to each objective to address the identified research questions.

This thesis, by compilation, is presented in six chapters (see Figure 1.1). Chapter 1 is an introductory chapter that provides introductory concepts, associating technical details and methods. The remaining chapters are focused on each research objective as research questions to answer through published or ready-to-publish journal articles.

Chapter 2 addresses objective 1 and presents a systematic review to understand the role of UGI for sustainable cities while presenting the current and emerging themes and existing knowledge gaps by reviewing the literature. The chapter synthesises the evidence of benefits and co-benefits of UGI from the literature to identify the types and benefits of ESS through categorisation, clustering and mapping. An extensive recognition of the climate benefits of UGI has been identified during the literature review. By observing the frequency of appearance in the keywords network, six themes of current trends were identified and discussed: benefits of UGI as UES, mitigating climate and urban climate impacts by UGI, UGI contribution to sustainable development goals, reconceptualising greenspaces as 'safe havens', public acknowledgement and supportive governance for UGI, and rethinking the operationalisability of UGI. Through a narrative review, 15 research gaps were identified in this chapter and have been used to create research objectives for the thesis. This chapter is under review for publication, titled as 'Benefits and co-benefits of Urban Green Infrastructure for sustainable cities: Six current and emerging themes'.

Chapter 3 is dedicated to objective 2, which evaluates the effectiveness of different urban surface parameters in mitigating excess urban heat. This chapter presents a case study in Melbourne using climate model simulations on an urban or regional spatial scale. The urban surface parameters, such as ground vegetation cover, built-up area cover, average building height, building height to canopy width ratio, roof surface albedo and green roof ratio, were tested individually for their influence on summer urban heat as a preliminary pilot to identify adaptable characteristics for heat adaptation strategies. The case study used a one-at-a-time (OAT) approach with mesoscale climate modelling and sensitivity analysis for the summer of 2009. Cool roofs, green roofs and the vegetation ratio were observed to be highly correlated with urban heat, and the reduction amounts differed according to the time of the day. This chapter is published under the title, 'Effectiveness of urban surface characteristics as mitigation strategies for the excessive summer heat in cities' (Herath et al., 2021).

Chapter 4 represents objective 3 to evaluate the combinations of different heat mitigation solutions to maximise the effectiveness as operationalisable strategies in real-world cities. Vegetative cover, green roof and cool roof ratios, which proved successful in the Chapter 3 pilot study, were used as combined mitigation strategies with realistic and practical ratios to select the most effective and operationalisable option through mesoscale climate modelling. Effectiveness and operationalisability of each mitigation strategy with UGI and urban surface parameters are explored against extreme and average summer heat events in different LCZs in the city. The simulations were performed for extreme and average summer heat events in Melbourne. Combined strategies have delivered the best diurnal thermal performance with practicality and cost. This chapter assures the necessity of UGI effectiveness to be defined with functional performance and operational factors. This chapter is published under the title, 'Comparing the effectiveness of operationalisable urban surface combination scenarios for summer heat mitigation' (Herath et al., 2023).

Chapter 5 addresses objective 4, to assess the impact of the spatial configuration of UGI for reducing excess urban heat, as a case study in Melbourne. The results provide empirical evidence to understand how different spatial arrangements of the same amount of urban green in an urban block in a finer-scale level modelling effort. Microscale climate simulations were used during the worst heatwave event in 2009 to signify the worst-case scenario. The observations emphasise that spatial configuration matters in microclimate amelioration. For a specific location, there is an effective way to include green spaces as big parks or pocket parks; however, that particular effective method is not universally superior for planning in the same city or different cities. The effectiveness depends on the surface cover characteristics and building configurations of the model location. The findings underscore the necessity of conducting site-specific simulations when introducing green infrastructure for heat mitigation. This chapter entitled ‘Does the spatial configuration of urban parks matter in ameliorating extreme heat?’ is accepted for publication.

Chapter 6 synthesises the overall conclusions from all the above chapters and presents the main findings of the thesis, conclusions, implications, limitations encountered and possible future research pathways.

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Chapter 2

A Chinese Proverb

Australian National University

Statement of Contribution

This thesis is submitted as a Thesis by Compilation in accordance with https://policies.anu.edu.au/ppl/document/ANUP_003405

I declare that the research presented in this chapter represents original work that I carried out during my candidature at the Australian National University, except for contributions to multi-author papers incorporated in the thesis where my contributions are specified in this Statement of Contribution.

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Senior author or collaborating authors endorsement: Xuemei Bai

Prabhasri Herath **Candidate**	**Signature**	6 November 2023 **Date**

Endorsed

Primary Supervisor – Xuemei Bai	**Signature**	**Date**: 7 November 2023
Delegated Authority - ~~Philip Gibbons~~ Joseph Guillaume	**Signature**	**Date**: 7 November 2023

2. Systematic Literature Review

Benefits and co-benefits of Urban Green Infrastructure for sustainable cities: Six current and emerging themes

Abstract

Integrating urban green infrastructure (UGI) into cities receives increasing attention owing to its potential to provide various urban ecosystem services (UES). This review assesses the multifaceted services of UGI as benefits and co-benefits. By combining systematic and narrative review processes, we aim to synthesise existing knowledge along six current themes and identify research gaps. A total of 690 peer-reviewed articles published during 2000-2020 from Web of Science were selected, followed by bibliometric and full-text analysis. Based on the frequency of appearance in the network visualisation of keywords, six themes of current trends were identified, namely: 1) benefits of UGI as UES; 2) mitigating climate and urban climate impacts by UGI; 3) UGI contribution to sustainable development goals; 4) reconceptualising greenspaces as 'safe havens'; 5) public acknowledgement and supportive governance for UGI, and 6) rethinking the operationalisability of UGI. The first two themes represent existing focus on categories of ecosystem services, the next two encompass broader emerging co-benefits and the last two focus on how to operationalise UGI and support widespread adoption and implementation. Within Theme 2, the most frequently discussed service with the largest number of research, we conducted a detailed analysis of the methods and content focus in the existing literature. Through a narrative review, we identified 15 research gaps throughout these six themes. This review provides a comprehensive overview for urban researchers and practitioners to inform the integration of urban green infrastructure into urban planning and management.

2.1. Introduction

Over half of the world's population lives in cities, and this number is estimated to increase to 68% by 2050 (UN DESA, 2018). Rapid urbanisation has been linked with various environmental, social, and economic impacts on a local and global scale (Bai et al., 2017; Grimm et al., 2008). For example, urbanisation-induced land-use change, mainly through replacing vegetated land with impervious and heat-absorbing surfaces, alters the urban energy system and water balance (ADB, 2015; Jiang et al., 2018). Such alterations lead to unique conditions in urban climates, such as the urban heat island (UHI) effect, while intensifying the impact of extreme heat events (Patricola & Wehner, 2018; P. Shi et al., 2017; W. Zhang et al., 2018), decreasing thermal comfort in urban areas, driving energy demand for cooling and heating (X. Li et al., 2019; Lundgren & Kjellstrom, 2013; Waite et al., 2017), and contributing to increased health issues and mortality due to heat stress (Lam et al., 2018; Lemonsu et al., 2015).

Cities are actively searching for climate mitigation and adaptation interventions using concepts, such as climate-proofing, low- and zero-carbon urban development, and other sustainable city initiatives (Albers et al., 2015; Bai et al., 2018; DTI, 2003; Kamal-chaoui & Robert, 2009; Lam et al., 2018; Lemonsu et al., 2015; OECD, 2020; Revi et al., 2014; Satterthwaite, 2010; UN, 2013). Urban green infrastructure (UGI), such as public parks, forests, green spaces, private gardens, urban wetlands, agricultural lands, ponds, streams and single green elements (vertical greenery, green roofs and street trees), has recently gained increasing attention from research communities, local governments, and the general public (UN, 2013). As defined by Climate ADAPT (2023), UGI planning is a strategic approach which involves developing interconnected and multifunctional networks of blue and green spaces to offer a diverse array of advantages across environmental, social, and economic domains. Building UGI has the potential to simultaneously enhance the liveability and climate resilience of cities. Hence, UGI is increasingly becoming an essential component of the urban fabric (Meerow & Newell, 2017; Mell, 2013).

Increasing number of studies have focused on the benefits of UGI from the perspective of ecosystem services. Ecosystem services are a subset of ecological functions and the benefits people receive from physical, chemical and biological processes in the ecosystem (Haase et al., 2014; MEA, 2005). There are many reviews focusing on the ecosystem services of UGI. Yet, several key gaps can be identified, including a limited scope that focuses on only one of the urban ecosystem services (UES) or benefits, such as temperature regulation (Bowler et al., 2010; Yu et al., 2020), air quality regulation (Abhijith et al., 2017), climate change adaptation (Ramyar et al., 2021), and human well-being [30], or on only a single UES category, such as cultural UES (La Rosa et al., 2016) and provisioning UES (Haase et al., 2014). Some reviews focused on a single UGI type (Roy et al., 2012), or on UES in indoor environments (Y. Wang et al., 2014), while some reviews had limited geographic cover (Amorim et al., 2021; DasGupta et al., 2019; Lindley et al., 2018). Veerkamp et al. (2021) focused on multiple UES but stopped at six.

In light of these considerations, this review aims to investigate comprehensive, multifaceted benefits and co-benefits offered by UGI. Ecosystem service framework is adopted to identify and categorise these benefits and co-benefits. The review aims to consolidate and synthesise often fragmented body knowledge by casting a wide net to encompass the full spectrum of UGI benefits and co-benefits, and identify current and emerging hot topics through a systematic review approach, and identify remaining gaps through in-depth qualitative analysis, thereby inform researchers, policymakers and practitioners seeking to integrate UGI into urban planning and management.

2.2. Methods

Systematic literature reviews have been recognised as the standard for accessing, appraising, and synthesising scientific information (Collaboration for Environmental Evidence, 2013). This review combines a systematic review in literature search, filtering, and bibliometric analysis to identify key themes, following guidelines from Collaboration for Environmental Evidence (2013), and a narrative review within each theme to synthesise

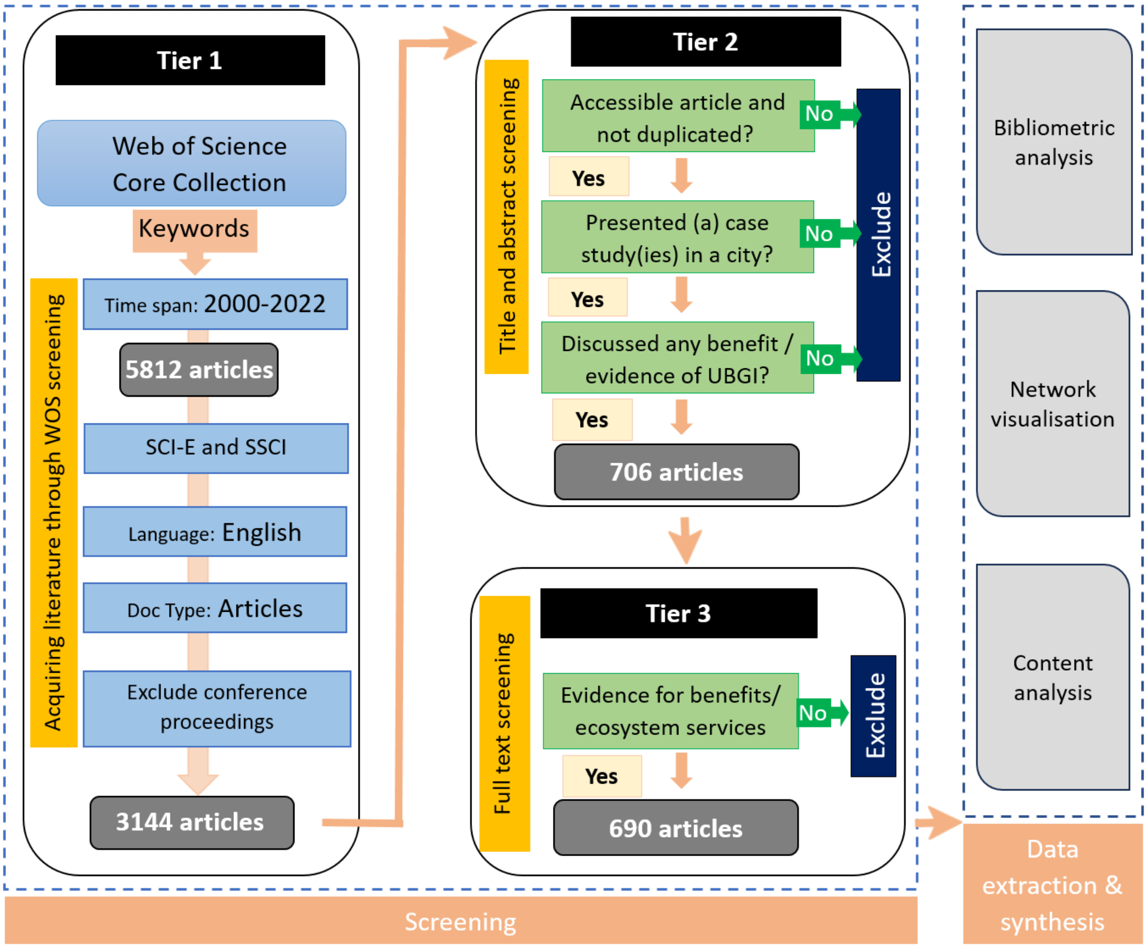

Figure 2.1 : 3-Tier screening framework for the review. After the full-text screening in Tier 3, selected 690 articles were subjected to data extraction and synthesis through a comprehensive content and bibliometric analysis and network visualisation.

and identify gaps. We used a set of keywords related to urban and green infrastructure and their role in environmental, economic, and social benefits and ecosystem services. Keywords for green infrastructure appeared in literature in multiple terminologies, including (but not limited to) urban green infrastructure (UGI), nature-based solutions (NbS), ecosystem-based adaptation (EbA), and blue-green infrastructure (BGI). These terms have similarities and disparities with their functional variance. For instance, NbS acts as an umbrella for all the other concepts. EbA includes adaptations with respect to biodiversity and ecosystem services, whereas UGI focuses on various interconnected green spaces in urban areas (Pauleit et al., 2017). BGI is defined as a network of interconnected natural and designed landscape components, including water bodies and green and open spaces (Ghofrani et al., 2017). In this study, we use the general term UGI to refer to both urban vegetation and water structures. Accordingly, all of these related keywords were combined in the Web of Science (WOS) core collection using Booleans AND OR, as necessary (search query is presented in the appendix). The expanded search across 22 years rendered 5812 publications, which were filtered through on the framework presented in Fig. 2.1.

In Tier 1, we screened articles published in English from 2000 to 2022 using the Science Citation Index-Expanded (SCI-E) and Social Science Citation Index (SSCI), which included in-scope keywords. Furthermore, quick filtering assisted in screening reviews and conference proceedings to focus on original and peer-reviewed publications. This step yielded 3144 articles, and they were directed to Tier 2 for title and abstract screening. Tier 2 screening facilitated filtering out duplicates and identifying studies that focus on the benefits of UGI in cities. This step filtered 706 articles and subjected them to full-text screening in Tier 3. The full texts of 706 articles were carefully assessed to identify case studies that presented empirical evidence. The filtered articles at this tier accounted for 690 original articles with individual and comparative case studies discussing the benefits of UGI from an environmental, social, and economic perspective. Those selected articles were then subjected to bibliometric and content analysis, and the keywords were visualised to represent the networks and co-occurrence in data extraction and synthesis. Based on the frequency of appearance in the network visualisation of keywords in all the 690 articles in VOSviewer, we identified the key areas which have co-occurred frequently with spotlight attention, which were later reorganised as six key themes. Content was extracted regarding UGI intervention, key benefits, other co-benefits, quantified modelling outcomes etc. Then, a narrative review on each of the six key themes provided an opportunity to identify the current trends and existing knowledge gaps in the related research area, which are presented in the results and discussion section.

2.3. Results and discussion

2.3.1. Identifying key themes

Through the screening process, we identified 690 articles on UGI that discuss different UES. These selected articles represent a wide range of research areas, including environmental sciences, ecology, urban studies, forestry, engineering, water resources, geography, and green sustainable science technology. This spectrum of research areas demonstrates the diverse functionality and applicability of UGI in different environmental, economic, and social domains.

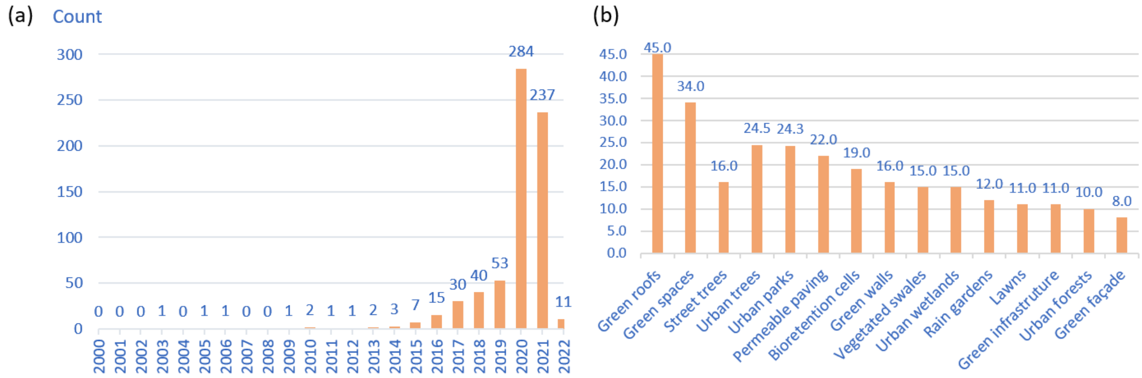

Figure 2.2 : (a) Number of articles that discuss UGI and ecosystem services between 2000 and 2022; (b) the top 15 most frequent terms for UGI types discussed in articles (the articles with more than one UGI type are counted as fractions).

The geographic distribution patterns of published articles agree well with previous literature findings- two-thirds of the reviewed studies were from the Global North, consistent with existing deficiencies in, and biases against, urban research in the Global South (Nagendra et al., 2018). Europe had the highest share of publications (38.6%), followed by Asia (29.3%) and North America (19.5%). Studies from Oceania, Africa and South America exhibited the lowest shares of 5.5%, 3.9%, and 3.2%, respectively. China had the highest number of case studies (18.2%) across all categories, followed by the United States (17.3%). Over 90% of studies in Oceania have been conducted in Australia.

The increasing number of articles published since 2015 indicates a growing recognition of the benefits of UGI (see Fig. 2.3a). The observation of a low number of articles from 2000 to 2013 agrees with the findings of Escobedo et al. (2019) about the appearance of each term with time: ES in 2006, green infrastructure in 2007, and NbS in 2015. Fig. 2.2b shows the fifteen most frequently discussed UGI types in the reviewed studies; the most frequently mentioned types comprised green roofs (10%), green spaces (7.5%), and trees (in terms of street trees: 5.8% and urban trees: 5.3%), indicating their popularity in urban areas. However, half of these types were discussed only once, whereas certain UGI types, such as rooftop farming and urban agricultural land, appeared to garner less attention.

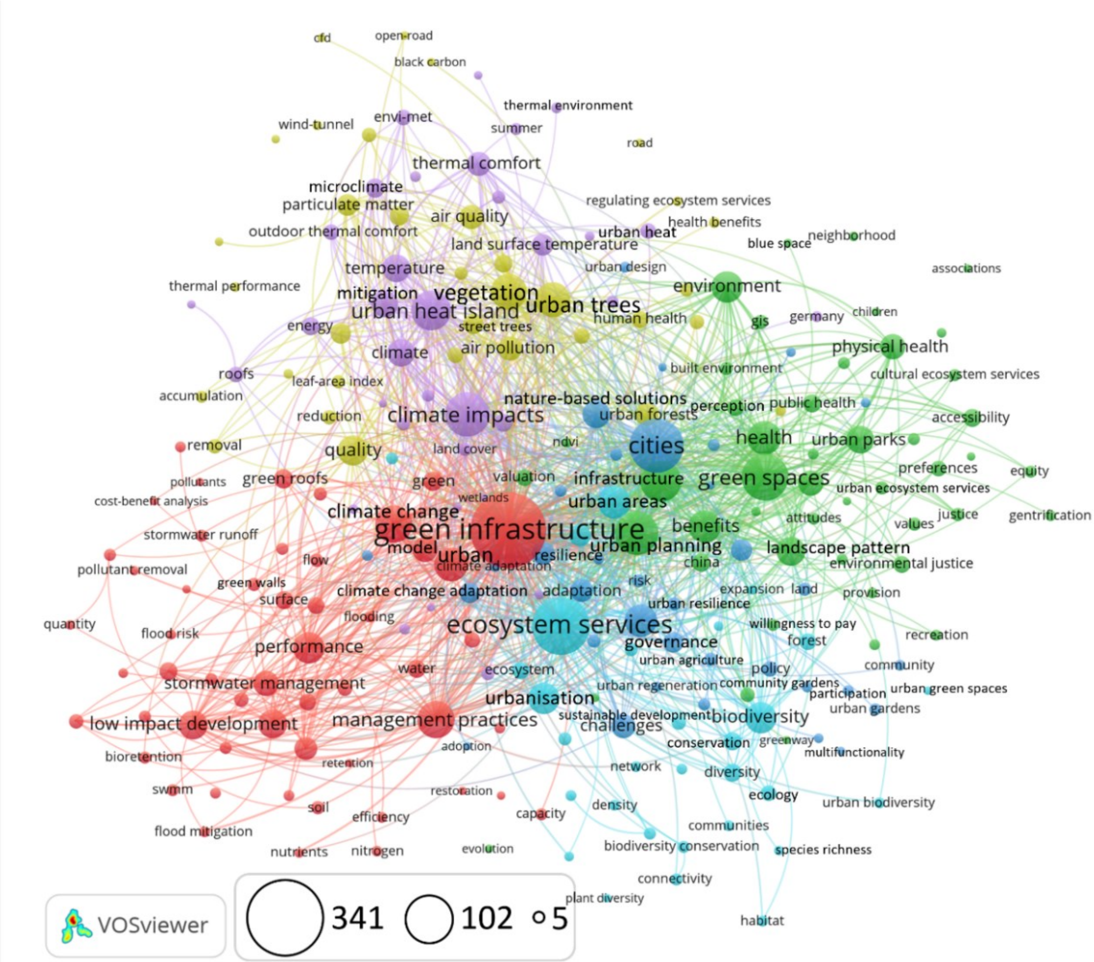

Figure 2.3 : Network visualisation of the co-occurrence of all keywords. Keywords appear on circles, and the circle's size is related to the frequency of occurrence. The assorted colours of each circle and links refer to the different clusters of the keywords. The width of the link between two keywords represents the strength of the link between them, such as bibliographic coupling links, co-authorship links, and co-occurrence links. The minimum number of occurrences of a keyword is 5 (234 meets this threshold out of 3359 keywords) and represents the smallest circle size in the scale.

Figure 2.3 illustrates the network visualisation of the co-occurrence of all keywords assembled by VOSviewer using network-analytic methods. Since the circle size shows the frequency of co-occurrence, this illustration helped us to identify hot research topics/areas with spotlight attention in the existing literature. By observing the frequency, links and cluster arrangement of keywords, six key areas were identified. Those were reorganised as key research themes of current trends, namely: 1) benefits of UGI as urban ecosystem services; 2) mitigating climate and urban climate impacts by UGI; 3) UGI contribution to sustainable development goals (SDGs); 4) reconceptualising greenspaces as 'safe havens'; 5) public acknowledgement and supportive governance for UGI, and 6) rethinking the operationalisability of UGI.

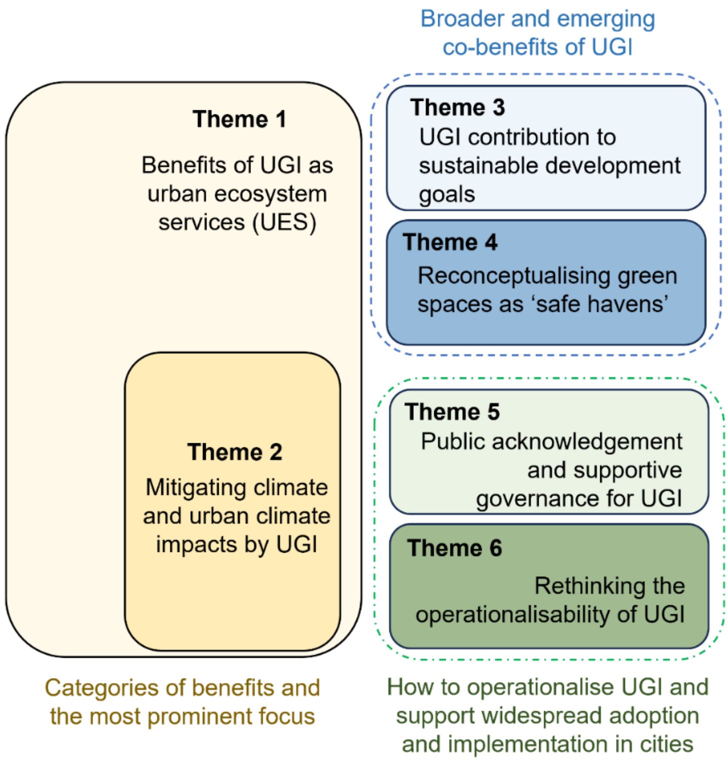

Figure 2.4 : Six key research areas with spotlight attention (based on the frequency, links and cluster arrangement in keywords visualisation), which are rearranged as the six themes, and the three thematic domains as clusters to show the possible interrelations between themes

The first two themes represent the 'categories of ecosystem services of UGI and the most prominent focus', the following two themes encompass 'broader and emerging co-benefits of UGI', and the last two themes focus on 'how to operationalise UGI and support widespread adoption and implementation in cities' (Fig. 2.4). For each of the six key themes, an in-depth content analysis was performed to identify the current trends and knowledge gaps in the related research area. Within Theme 2, which was the most frequently discussed category and, therefore, with the largest number of research, we further analysed the methods used and the content focus of existing literature.

2.3.2. State-of-the-art and remaining gaps within each theme

Theme 1: Benefits of UGI as urban ecosystem services

The possibility of reassessing the benefits of UGI under the purview of ecosystems has been implied during the last decade (Bai, 2018; Di Marino et al., 2019; Giedych & Maksymiuk, 2017); however, it has been limited to specific areas. Di Marino et al. (2019) discussed integrating the concepts of UGI and ES into land-use policy and planning strategies. To identify all interconnections between nature and cities, adopting the categorisation of ES in the Millennium Ecosystem Assessment (MEA) is possible (Alcamo et al., 2005; MEA, 2005), which entails provisioning, regulatory, cultural, and supporting services. Giedych and Maksymiuk (2017) studied the benefits of urban parks, although the study was limited to regulatory and cultural ES. Therefore, in this theme we explored the comprehensive benefits of UGI by linking them to MEA categorisation. The empirical data extracted from all 690 articles were categorised into the traditional MEA ecosystem categories using a treemap (Fig. 2.5). The treemap represents the number of cases discussing each UES to support the investigation on how different UES categories have been covered in the literature.

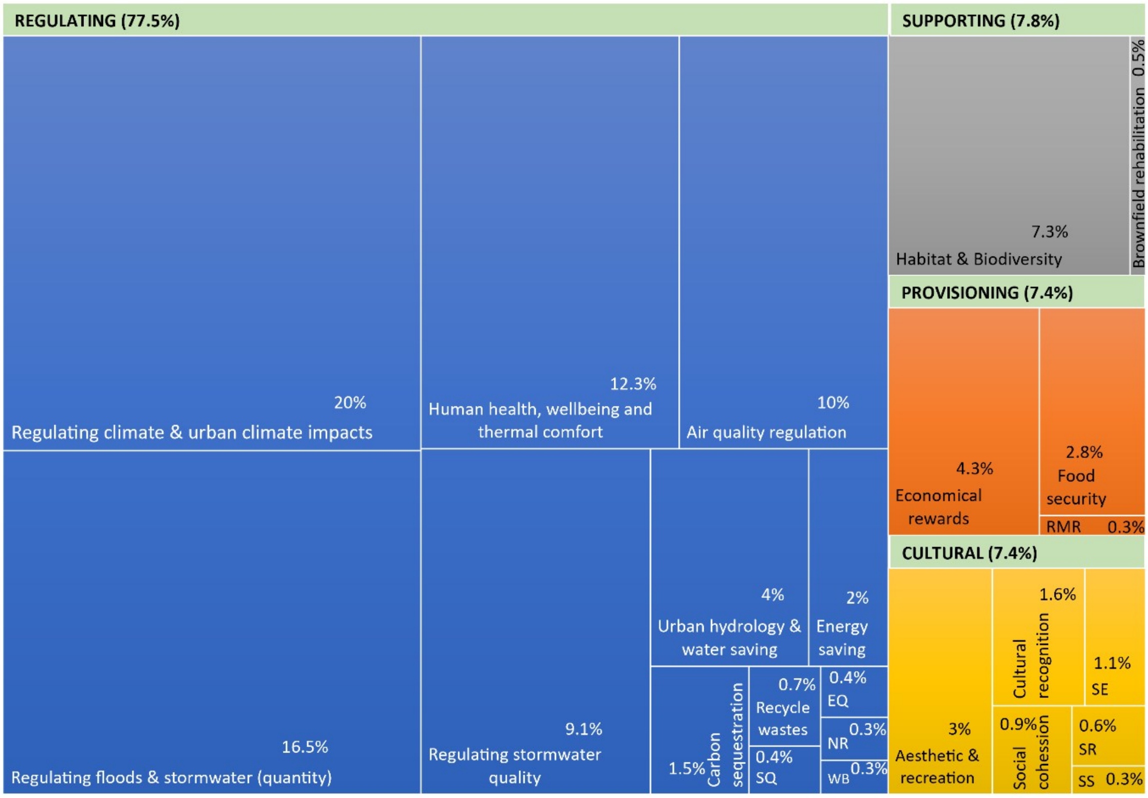

Figure 2.5 : Treemap for types of UES analysed in the 690 selected articles. The dimension of the nodule indicates the number of studies (percentage values are mentioned within the nodule). Multiple UES mentioned in one case study have been directed to each category (double-counted in some cases). SQ= Soil quality regulation; EQ = Environmental quality; WB = Windbreaks; NR = Noise reduction; SS = Social sustainability; SR= Spiritual rewards; RMR = Raw materials and resources; SE = Social equity.

Through this visualisation, we identified uneven coverage of UES categories[1] as the first research gap in the literature (Table 2-1). Regulatory services provided by urban ecosystems were the most frequently discussed category, appearing in 77.5% of the selected publications. Supporting UES was present in 7.8% of the cases as the second-highest category. Provisioning and cultural UES accounted for 7.4% of all cases. Studies that focused on more than one UES within the same category were counted multiple times.

Table 2-1: List of identified research gaps via narrative review of each theme

#	Associated theme	Identified research gap
1	Theme 1	Uneven coverage of urban ecosystem services (UES) categories.
2	Theme 2	Diverse effectiveness of UGI plans over different climate zones.
3		Limited availability of evidence-based measurements due to the lack of real-ground implemented evidence.
4		Existing research primarily remains in the experimental or modelling stages.
5		Lack of large-scale assessments of UGI for climate adaptation and overall effectiveness

6		Insufficiency of multi-year analysis studies in the literature.
7		Inadequacy of assessments focusing on the co-benefits approach.
8		Limited investigations of UGI performance during extreme heat conditions.
9	Theme 3	Limited understanding of mechanisms for investing in UGI plans while addressing existing inequalities
10	Theme 4	Under-exploration of potential misuse of public green spaces beyond idealistic uses.
11	Theme 5	Lack of clear pathways towards financing green infrastructure.
12	Theme 6	Insufficiency of a broader empirical basis to understand the effectiveness and co-benefits brought by hybrid infrastructure solutions.
13		Lack of a comprehensive evaluation and assessment of UGI effectiveness.
14		Insufficient exploration of the spatial configuration versus UGI efficiency.
15		Lack of research on context-specific, multi-year analyses in different climatic regions.

Regulatory services delivered by UGI play an essential role in human health and well-being in cities. As shown in Fig. 2.5, regulating urban microclimate impacts was the most frequently discussed UES, accounting for 20% of the total cases which was separately discussed in Theme 2. Many research shows an increasing use of UGI in regulating floods and urban stormwater (quantity, 16.5%) and stormwater quality (9.1%), with various terms, including stormwater harvesting, integrated water management (IWM), water sensitive urban design (WSUD), drained cities, and water sensitive cities. This regulatory service directly addresses essential aspects of flood hazard reduction and the sustainable management of water resources (Green et al., 2021; Khodadad et al., 2023). Another important service is the regulation of air quality, including the reduction of pollutants, such as NO_2, CO_2, CO, SO_2, O_3, particulate matter, $PM_{2.5}$, and PM_{10} from traffic emissions (Capotorti et al., 2019; Santiago et al., 2019; Simon et al., 2019) and carbon offsetting (W. Y. Chen, 2015). Regulation of human well-being through facilitating thermal comfort, waste management, water storage, and energy savings are other benefits described as regulatory services (Ghazalli et al., 2018, 2019; Santiago et al., 2019; Simon et al., 2019). Moreover, most UGI types, such as urban trees, green walls, green facades, green roofs, and other urban landscapes, support carbon sequestration as a 'soft engineering' strategy, which can be defined as supporting greenhouse gas (GHG) emission mitigation because CO_2 is recognised as a primary GHG (G. Kim & Coseo, 2018). In addition, natural vegetation in cities is known to improve the health and well-being of communities (Capotorti et al., 2019;

Santiago et al., 2019), and improve life expectancy (Jonker et al., 2014). The high water retention ability of urban wetlands, water bodies, urban forests, rain gardens, and urban parks supports stormwater regulation, storage, flood resilience, water conservation, and filtering of polluted water (Herslund et al., 2018; Hettiarachchi et al., 2022; Liquete et al., 2016; Rodríguez-Rojas et al., 2018). Hybrid and fabricated UGI types (vegetated swales, bioretention cells, and rain barrels) mimic natural hydrological processes. They can increase surface permeability (J. Chen et al., 2019; Miller & Montalto, 2019; Pierre et al., 2019) to promote infiltration and eventually reduce disaster risk by controlling urban flash floods (Fei et al., 2019; Gunnell et al., 2019; S. Y. Kim & Kim, 2017; Maragno et al., 2018; Shifflett et al., 2019; Tavakol-Davani et al., 2019). Additionally, we observed limited discussions on important regulatory UES, such as the improvement of soil quality, by retaining sediments and accumulating organic matter within urban landscapes.

The second category consisted of supporting the UES (7.8%). UGI provides habitats for urban flora and fauna (animals, insects, bats, native birds, beetles, bugs, and plants) (Threlfall et al., 2017). Urban green areas enhance biological processes while supporting the biodiversity of cities (Fattorini & Galassi, 2016; Gopal et al., 2019; Lopez et al., 2021; Riley et al., 2018). For example, insects promote pollination even though urban habitats are highly heterogeneous and occur in isolated patches (Lewis et al., 2019). Empirical evidence from Berlin, a ‘green city’, highlighted the promotion of biodiversity and cultural heritage in its green landscape (Kowarik, 2019). The presence of urban flora and fauna in cities, in turn, helps increase citizens’ awareness of efforts towards biodiversity conservation (Landor-Yamagata et al., 2018). However, negative impacts on health and well-being, such as ecosystem disservices, have also been identified (Azmy et al., 2016; Lyytimäki et al., 2008), as these sites can be habitats for harmful insects, mosquitoes, and fruit flies. By providing habitats for soil microorganisms, UGI promotes soil quality, which is also considered a regulatory UES. With fewer reports in the existing literature, an understanding of the ability of UGI to enhance the nutrient cycle by storing, processing, acquiring, and recycling soil nutrients in urban systems remains a knowledge gap.

Provisioning UES accounts for 7.4%, which covers the consumptive use of urban greenery. These services involve the provision of firewood, medicinal plants, craft materials, timber and peat. Providing food sources, including leafy vegetables, mushrooms, and edible insects often cultivated through rooftop farming, urban agricultural lands, community gardens, and allotments, is considered significant provisioning UES. Provisioning UES extends beyond tangible resources to encompass provisioning sustainable water, nutrient cycling, and genetic resources (Alves et al., 2019; Grard et al., 2018; G. Kim & Coseo, 2018; Matos Silva et al., 2019; Säumel et al., 2019; Shackleton et al., 2018; Y. Zhang & Dong, 2018). Furthermore, this category considers the direct and indirect impacts of these services on commercial activities and local economy. For instance, green spaces have demonstrated their ability to boost the business volumes and revenues of retail companies, attracting residents and shop owners to locations near green spaces due to the enhanced sense of space usability (Koppelaar et al., 2021). Recent literature also suggests that higher property values are associated with proximity to green spaces as economic rewards (Combrinck et al., 2020; Juncheng Yang et al., 2021). Moreover, the provision of fruits, seeds, blossoms, and leaves has been documented in research, and discussions have been conducted on equity in distribution and accessibility among different communities (Shu Feng et al., 2019; Lin et al., 2017; Orsini et al., 2020; L. Shi et al., 2020). Cities provide 'green collar jobs' for skilled and unskilled employees, which are rarely examined as provisioning UES. King & Shackleton (2020) identified 17,429 jobs related to the maintenance of UGI in Eastern Cape towns, South Africa, generating approximately US$37 million per year.

The final category was cultural UES, the "intangible and non-material benefits that people enjoy from ecosystems" (MEA, 2005). Among four main categories, cultural UES has been inadequately identified and under-studied in the literature (Cabana et al., 2020).

We found that 7.4% of publications reported evidence for this category. Well-managed greening strategies in urban settings provide aesthetic and recreational value to a city by improving regular visits and tourism, and facilitating picnics, outings, non-commercial hunting and fishing, water sports, and other activities. These strategies can considerably increase the outdoor time of city occupants by enhancing the perception of walking and cycling and, ultimately, the quality of life (Douglas et al., 2019). Developing UGI in urban areas can enhance the cultural heritage of a site. For example, the Berlin Belt adds value to a cultural site and increases people's engagement and visits to the area (Kowarik, 2019). Some studies have discussed how green spaces support people's religious beliefs, providing spiritual rewards and inspiration as a result of the quietness. In Bulawayo, Zimbabwe, several visitors from religious gatherings in urban green spaces said that outdoor worship is part of their religious practices. The majority (79%) pray in public green spaces 1–4 times per week; furthermore, the monetary value of spiritual services is estimated to be 93±79 USD/ha/year (Ngulani & Shackleton, 2019).

The mapping of existing empirical literature into the four MEA categories of UES clearly showed the multivarious benefits that UGI provides for cities. A comprehensive assessment for valuation and appraisal of UES is always necessary to transfer the knowledge of UES into practice, to address the gaps associated with methodological inadequacy and inconsistency among approaches and to overcome less institutional support (Cabana et al., 2020; Saarikoski et al., 2018). However, we identified overlaps between categories during categorisation, as most services are interconnected with direct and indirect benefits. At times, it was debatable to distinguish and place some services in the targeted UES category. For instance, in the case of air temperature reduction, it directly aligns with climate and urban climate regulation, while also contributing to human health and well-being and economic rewards. Assessing the monetary values through tangible indices, such as replacement costs, carbon taxes, afforestation costs, and market price methods (Xu & Zhao, 2021), can overlap provisioning UES with other categories. While a cascade approach (Potschin-Young et al., 2018; C. Zhang et al., 2022) could be suitable for capturing these gaps, there are ongoing debates about this approach as it simultaneously oversimplifies the complex reality and complexing the essential straightforward definitions unnecessarily (Costanza et al., 2017). Moreover, an evidence-based assessment of the effectiveness of UGI in comparison with that of traditional infrastructure is still required (Bai et al., 2018). Such a study would also be important for understanding the necessity, places, and people for whom UGI is required (Lopez et al., 2021).

Theme 2: Mitigation of climate and urban climate changes by UGI – the most frequently discussed function

Impacts from climate change challenge urban resilience, liveability, and justice; hence, cities require effective adaptation and mitigation planning. The existing literature identifies UGI as a climate change adaptation tool, environmental and land management planning tool, ecosystem-based planning tool, and nature-based solution to bridge the existing gaps in climate change mitigation and adaptation actions (Anderson & Gough, 2021; Salata & Yiannakou, 2020). UGI systems ensure sustainable, less vulnerable, and more resilient communities by delivering critical UES and climatic benefits.

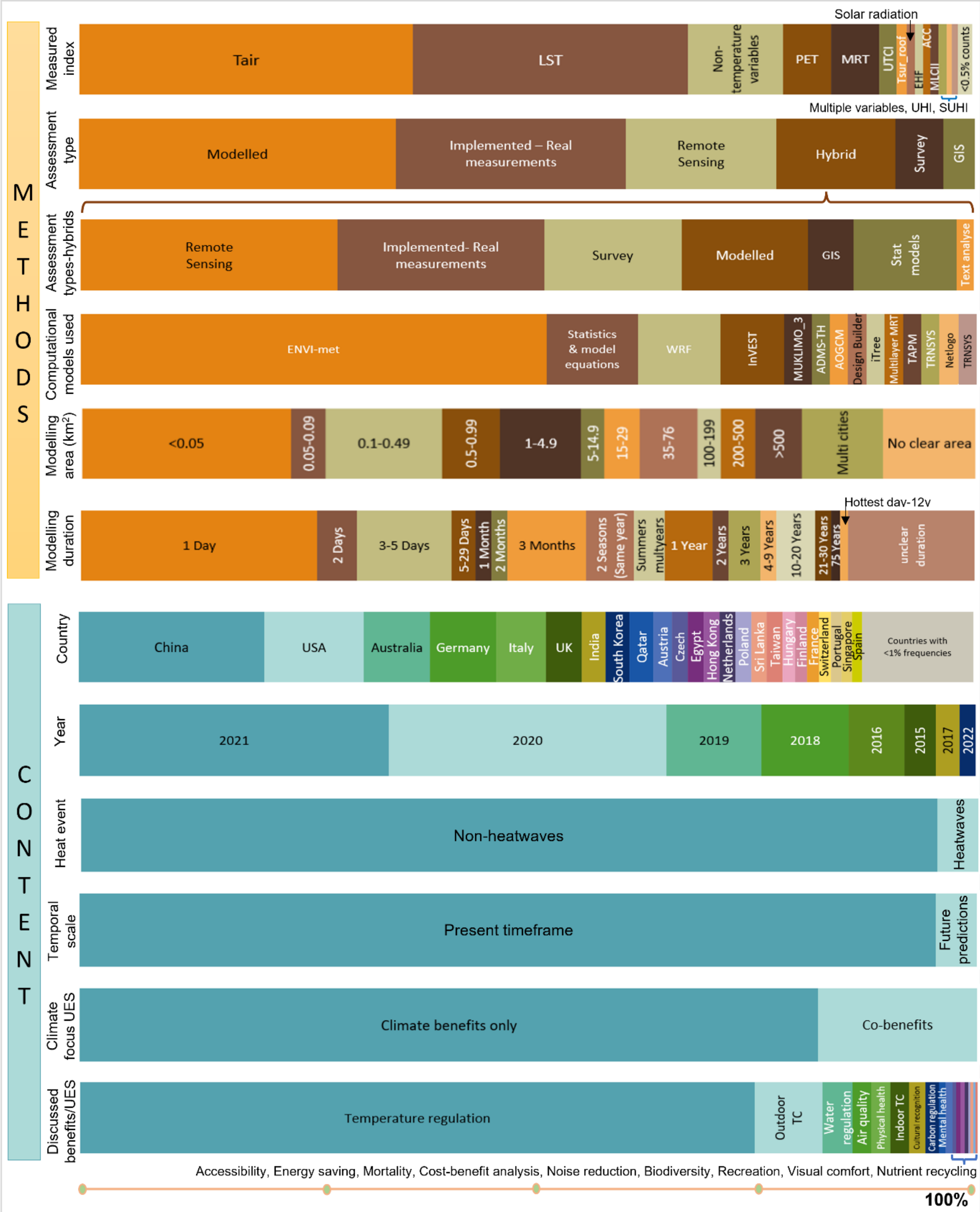

Figure 2.6: Overview of the proportions of the different aspects of content and method sections for selected climate-related articles. Multiple mentions are counted as decimals to maintain the fractional values. (Abbreviations: Climate models; WRF: Weather Research and Forecasting method, MUKLIMO_3: Microscale Urban Climate Model, AOGCM: Atmospheric Ocean Global Climate Models, TAPM: The Air Pollution Model, UT&C: Urban Tethys-Chloris model. Heat indices; T_{air}: air temperature, T_{max}: maximum temperature, T_{mean}: mean temperature, LST: land surface temperature, MRT: mean radiant temperature, UHI: urban heat island, SUHI: surface urban heat island, MLCII: maximum local cool island intensity, ACC: average cooling capacity, EHF: excess heat factor. Thermal comfort indices; PET: physiological equivalent temperature, PMV: predicted mean vote, UTCI: universal thermal climate index, TC: Thermal comfort)

Among regulatory services, nearly half of UES (44%) have focused on climate and urban climate regulating benefits. The most common expectations for urban greenery are the regulation of urban temperature and the provision of thermal comfort and air quality (Duan et al., 2018; Masoudi et al., 2019; Wong et al., 2017). Moreover, a well-planned UGI can provide UES related to climate adaptation and mitigation, including stormwater regulation and water storage (Salata & Yiannakou, 2020), GHG emissions (G. Kim & Coseo, 2018), and carbon storage and sequestration (Ariluoma et al., 2021). Heat regulatory services dominate climate benefits as the most discussed service, with 108 articles. In Fig. 2.6, the methods and contents are summarised to illustrate the diversity of those studies across 12 dimensions. By following the discussion trends, we assessed the heat regulatory climate benefits of UGI (from 108 heat-related case studies) at greater depths. Hereafter, we present an overview of Fig. 2.6 with a subsequent discussion while identifying key research gaps and limitations regarding both content and methods in the most frequently discussed UES or function in the literature.

By observing the methodological approaches of the selected literature with attention to assessment type, measured index, modelling area, duration, and used models, several research gaps were identified. Various indices and terms, such as UHI mitigation, urban cooling, indoor and outdoor thermal comfort, and human health and well-being across diverse climatic conditions and geographical locations, presented the association between urban green and urban heat. Urban green spaces regulate urban heat via evaporative cooling from transpiration and shading (Oke et al., 1989; Oliveira et al., 2011) and provide a land-use mix that improves the turbulence of the area. The vast majority of studies have analysed the association and impact of the behaviour of the general temperature (or the UHI) with urban growth, the urbanisation gradient, or land-use changes (Masoudi et al., 2019; W. Wang et al., 2019; Y. Wang et al., 2019; Jiachuan Yang & Bou-Zeid, 2019). Different primary indices, including air temperature (T_{air}), mostly within 1.4 – 5 m layer and land surface temperature (LST), and derivative indices, including UHI, mean radiant temperature (MRT), and surface urban heat island (SUHI), were used to study temperature (see Fig. 2.6 for other indices) (Arnfield, 2003; Grimmond, 2007; Howard, 1833). Thermal comfort is measured through indices, including physiological equivalent temperature (PET), predicted mean vote (PMV), universal thermal climate index (UTCI), and MRT, for which the temperate region has the highest discussion frequency of all indices. These universal thermal comfort indices are calculated based on primary heat indices, including T_{air}, radiation, humidity, wind, and personal factors (clothing and activity level) (Bröde et al., 2012; Höppe, 1999). Our review shows that a wide array of methods were employed, from implemented UGI interventions to modelling (including physical models, GIS and RS, and statistical models etc.), surveys and hybrid approaches combining two or more of the aforementioned methods. The substantial and growing contribution of LST and remote sensing to the findings is concerning, particularly given the method's acknowledged limitations in drawing definitive conclusions regarding UGI cooling benefits. However, extracting quantified reduction values/ranges for different indices was difficult. Out of the 108 cases, 14 presented outcomes in the form of map-based figures, statistical data, solar radiation results, or survey data, making it challenging to derive precise values. Consequently, the analysis presented in Fig. 2.7 is based on case studies with extractable outcome, which accounts for 87% of the cases.

The diverse effectiveness of UGI plans over different climate zones[2] is a broad and under-explored topic and was identified as the second research gap. Different UGI typologies have been observed to have different levels of effectiveness in different climatic zones (Fig. 2.7) and require further assessment. Urban green spaces (identified by the search terms of urban parks, blue-green spaces, green cover, urban vegetation, green area, allotments, and urban gardens) were the most popular (33.3%) UGI strategy in the temperate region for heat mitigation (average reduction of T_{air} and LST of 2 °C and 6.2 °C, respectively). Urban trees are the most frequently discussed UGI intervention for the subtropics (30.2%). Despite shading and evapotranspiration, urban trees modify wind flow

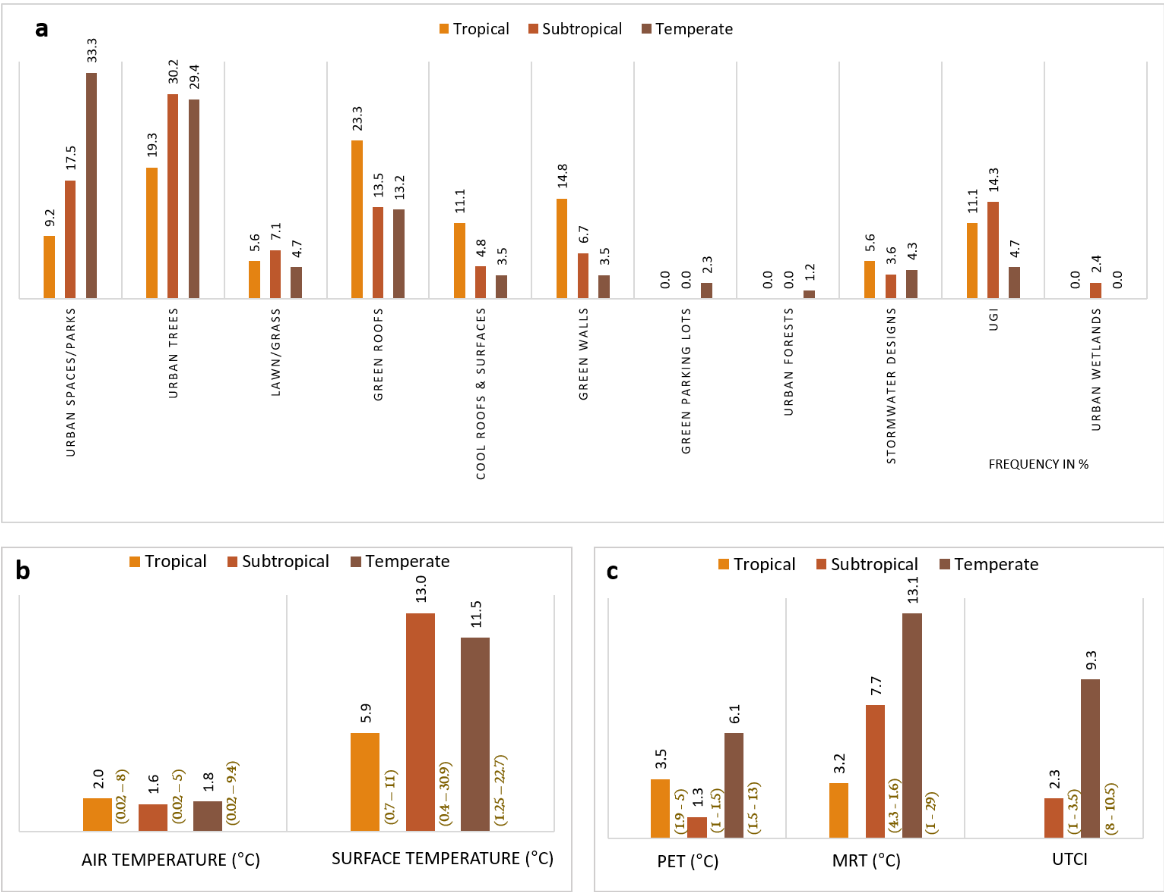

Figure 2.7: a) Number of case studies which mention UGI for urban heat mitigation in main climate zones in % (when the case studies discuss more than one UGI type, fractional values are counted); b) The cooling effect (reduction) of different heat indices when considering the mitigation scenarios in different climate types; left panel: for air temperature and surface temperature; right panel: for thermal comfort indices. MRT- tropical ranges are not given as they represent a single value.

to facilitate heat transfer in urban canyons (Oke et al., 1989). Green roofs are the dominant UGI intervention for heat mitigation in the tropics (23.3%), reducing the average T_{air} by 1.4 °C (0.02–2.6 °C). After applying UGI mitigation strategies, tropical climates show the maximum average T_{air} reduction (2.9 °C), but the broadest range is observable in the temperate region (0.02–9.4 °C). In the subtropical region, mitigating scenarios reported a maximum LST reduction of 14 °C (1.4–30.9 °C), whereas in the tropics, the reduction was at a minimum.

Our observations revealed the third research gap - the availability of evidence-based measurements, primarily due to limited practical and on-the-ground implementations[3]. In Fig. 2.6, we grouped the studies into six categories based on their assessment methods:

real-ground implemented, modelled, surveyed, GIS-based, remote sense-based (RS), and hybrid studies. Hybrid studies have combined two or more methods, including real-ground implementations, models, surveys, GIS/RS applications, statistical models, and text analyses. Approximately one-third (25.7%) of the studies investigated UGI predominantly through direct observation. Field measurements provide actual on-ground evidence, yet acquiring field data is challenging with time constraints, resources and instrumental limitations (related to data quality limitations, missing data), finances, and labour limitations (Hunziker et al., 2017; Mirzaei & Haghighat, 2010). In addition, field data can cause unpredictable instrument or human errors during replication and long-term observations. The rest of the direct observations came from surveying studies (5.3%), which can be used as the qualitative component; however, surveying studies can also be onerous and liable to errors because of possibly biased responses and non-representative samples.

Modelling and thermal mapping studies are advantageous for overcoming these limitations. As excess heat is a constant urban challenge with the predicted urbanisation rate and future population growth, preparing resilient and adaptive cities for future shocks is a part of urban planning, which requires modelling and forecasting. The *popularity* of UGI, evident through numerous modelling and GIS/RS-based studies, was observed to be limited *as a concept*. Most research primarily remains in the experimental or modelling stages[4], which was identified as the fourth research gap. Modelling-based studies that used physical and simulation models, statistical models, and GIS-based and remote sensing models represented the majority (55.8%) of the results. Additionally, 13.3% of the studies used hybrid approaches, among which GIS and RS methods accounted for the highest fraction (36.11%), whereas modelling approaches accounted for 10%. Remote sensing captures surface temperature responses only at the tree-top and roof-top levels, which is a major disadvantage of this method (Krayenhoff et al., 2020). Thermal data on pedestrian levels are essential for planning pedestrian thermal comfort in cities, which the above GIS/RS-based methods fail to provide. Climate models are useful tools that can provide a platform to investigate the response of climate systems to different forces (e.g. urban land use change) and evaluate potential mitigation plans based on past experiences and future predictions (Flato et al., 2013). In the case studies from our search (Fig. 2.6), mesoscale and microscale climate models were mainly used with various resolutions. The spatial scale is critical for providing accurate outputs from simulations and is essential for providing high-resolution temporal and spatial climate data to assess the effectiveness of mitigation plans (Hayes et al., 2022). Mesoscale climate models support regional-level planning with comparatively larger resolutions (downscaling with resolutions of 1 to several hundred kilometres) by capturing dynamic atmospheric processes under boundary conditions (Hayes et al., 2022; Herath et al., 2023). We observed that 20.4% of the studies used different mesoscale urban climate models, including the Weather Research and Forecasting (WRF) and Atmospheric Ocean Global Climate Models (AOGCM), coupled with urban canopy models (UCM) to represent urban characteristics (Imran et al., 2018; Jiachuan Yang & Bou-Zeid, 2019; Žuvela-Aloise et al., 2016). Most microscale models simulate detailed flow around terrain by resolving fine-scale turbulence using computational fluid dynamic (CFD) equations on the surface layer at the neighbourhood scale (further downscaled to metre-scale resolutions of 1 m–1 km) (ENVI-met GmbH, 2022; Haupt et al., 2019). Microscale models can estimate detailed information at the local scale, and this ability is highly important for pedestrian-level urban planning and thermal comfort assessments. However, the high computational demand and time required could limit the use of microscale climate models at the regional or city level. From our results, 52% of the simulation studies have used ENVI-met, a computational, microscale climate model (Bruse & Fleer, 1998).

The lack of large-scale assessments of UGI for climate adaptation and overall effectiveness[5] was identified as the fifth research gap. Because most studies have focused on a microscale, the focus in literature is mainly limited to smaller modelling extents of <0.05 km^2 or exclusively within an experimental setting. However, in reality, understanding the effectiveness of UGI at a larger scale, for instance, at the city scale, is also essential, particularly when considering the need for city-scale planning and management, and understanding the interactions of UGI with other urban infrastructure. Therefore, the literature should be expanded towards the efficiency of UGI on a larger scale as well as its implementation beyond small-scale individual success stories (Bai, 2018; Baró et al., 2015). In terms of modelling duration, most studies have presented short-term analyses (seasonal; e.g. for summer or across a year) (Fung & Jim, 2019; Herath et al., 2021), for a duration below 20 years (> 80%). Only 4.6% of the studies represented long-term analyses that used durations longer than 20 years (Cai et al., 2019; Di Leo et al., 2016; Herath et al., 2023). The insufficient number of studies in the literature with multiyear analysis[6] was identified as the sixth research gap; hence, long-term and multiyear findings are critical for capturing the considerable year-to-year variability in the climate in the context of adaptation plans.

In terms of content, two research gaps were identified, which are discussed below. Considering the discussion frequencies, the inadequacy of assessments of the co-benefits approach[7] is highlighted as the seventh research gap. Most studies solely assessed heat reduction climate benefits, whereas only 17.7% of the cases considered co-benefits. Figure 2.6 suggests that most studies evaluated climate benefits considering the present (and past) timeframes of UGI, whereas only 4.4% of cases presented predictions from simulations with future timeframes (Emmanuel & Loconsole, 2015; Fahmy et al., 2018). We highlight the limited number of assessments of UGI during extreme heat conditions[8] as the eighth research gap. Given the increasing frequency and severity of extreme events, the existing discussion frequency (only 4.4%) suggests a grey area with a lack of attention to UGI solutions for heatwave adaptation planning.

Theme 3: UGI contribution to sustainable development goals

Green areas are one of the seven essential factors determining urban carrying capacity in a sustainable city (Oh et al., 2005). Other UES from green spaces observed in this search also display direct and indirect benefits along with the other six factors, namely energy, roads, subway systems, water supply, sewage treatment, and waste treatment. Having functional green spaces in cities is directly compatible with Sustainable Development Goals (SDGs) targets. Target 11.7 is: ‘to provide universal access to safe, inclusive, and accessible green and public spaces’, and Target 11.6 is: ‘to reduce the adverse per capita environmental impact of cities’ under ‘sustainable cities and communities’ (United Nations, 2018). As shown in Fig. 2.8, the literature shows that the UES delivered by UGI could contribute to most other SDGs as well. For example, climate-related regulatory services, including air quality regulation, temperature regulation, water storage, and disaster risk reduction, through stormwater management directly contribute to the 13th SDG and climate action strategies. The UES provided by urban wetlands, such as purification, retention, and water replenishment, contribute to the 6th SDG, which considers clean water and sanitation. Hence, a city can apply the concept of ‘co-benefits’ during sustainability planning with maximum effectiveness owing to the interlinked and multidisciplinary nature of UES.

As identified in theme 3.2 (the 7th research gap under climate regulatory UES), our overall analysis confirms that there is room for enhanced recognition of the co-benefits of UGI. Most case studies (82.3%) included in our literature review focused on a single benefit/role of UGI, whereas 17.7% identified co-benefits. UGI often provides a golden payback, as it delivers several co-benefits beyond the initial planning. As proof of this, the green infrastructure plan, mainly intended to improve water quality and stormwater infiltration in New York, was found to ‘inadvertently’ deliver climate adaptation outcomes (Culligan, 2019). Harnessing the many co-benefits delivered by UGI could be a strategic way to reduce the cost of addressing urban challenges (Raymond et al., 2017). For instance, planning for climate adaptation and mitigation with UGI could be more cost-effective considering the social co-benefits (European Commission, 2013; Karlsson et al., 2020). However, in complex, interlinked systems, such as cities (Grimm et al., 2008;

Ngulani & Shackleton, 2019; Raymond et al., 2017; United Nations, 2018), interventions often deliver intended benefits and co-benefits along with unintended consequences, such as potential trade-offs, limitations, and disservices. For example, planning urban forests in Australia to target the goals of carbon capture and water or pollutant regulation should consider potential fire risks. Planning for a co-benefit-focused, climate-responsive, multidisciplinary and inter-scaler design (Tomasi et al., 2021), local level planning (Yin et al., 2021), and cross-over concern to bridge several knowledge bases, such as urban climatology, landscape planning, and urban governance, can help overcome some limitations and disservices.

Figure 2.8: Contribution of urban green infrastructure (UGI) to sustainable development goals (SDGs). References that substantiate the linkages a to k: (a) (Hurley & Emery, 2018; Landor-Yamagata et al., 2018); (b) (Grard et al., 2018; Orsini et al., 2014); (c) (Battisti et al., 2019; Geary et al., 2021); (d) (Chan et al., 2018; Wong et al., 2018); (e) (Greenway, 2017; Zölch et al., 2017); (f) (Capotorti et al., 2019; Herath et al., 2018b, 2018a, 2021; Threlfall et al., 2017); (g) (Viecco et al., 2018; Vojinovic et al., 2021); (h) (Grard et al., 2018; Mathey et al., 2015); (i) (Niu et al., 2010); (j) (Chou et al., 2017); (k) (Gelan & Girma, 2021; Hurley & Emery, 2018).

Urban green spaces play a vital role in social cohesion, promoting people's participation in community affairs and strengthening a community's social network and community care (Chou et al., 2017; Langemeyer et al., 2018). For example, establishing green spaces in urban settings promotes equitable sharing of urban spaces by urban communities (Quatrini et al., 2019). Urban agricultural efforts, rooftop farming, and community gardens improve active engagement, participation, cooperative work, mutual learning, and experience-sharing. Edible city concepts are conducive, to an extent, to alleviating poverty and inequality in urban areas (Säumel et al., 2019).

The mechanisms behind investing in UGI plans while addressing inequalities (Herreros-Cantis & McPhearson, 2021) remain unclear[9], which we identified as the ninth research gap. UGI draws attention to urban sustainability but is often limited, particularly in underdeveloped, low-income areas (Cheshmehzangi et al., 2021). For example, environmental, economic, and social injustice and inequalities are reported in cities (regardless of city size) while distributing services of UGI (e.g. New York, USA, and smaller towns outside Wuhan, China) (Dai et al., 2021; Herreros-Cantis & McPhearson, 2021). Several factors contribute to such inequalities, including supply and demand mismatch, income disparity, and racial factors (Dai et al., 2021; Herreros-Cantis & McPhearson, 2021).

Theme 4: Reconceptualising green spaces as 'safe havens'

A considerable number of recently published articles in our search results refer to COVID-19, with some of them specifically addressing the roles of UGI during the pandemic. As a result, we have identified this topic as one deserving separate attention. Urban parks, peri-urban forests, and protected areas are often used by local communities for exercise (walking, running, hiking, and cycling) and recreational purposes, thus supporting the physical and mental well-being of the community (Berdejo-Espinola et al., 2021; Liu & Wang, 2021; Venter et al., 2020). During the recent COVID-19 outbreak, urban green spaces have garnered increasing attention and have had a higher demand as *places to* *escape* (Sugiyama et al., 2021; Venter et al., 2020). For instance, in a survey conducted in Brisbane, Australia, 36% of participants reported increased usage of their local green spaces, whereas 45% reported visiting a new green space for the first time (Berdejo-Espinola et al., 2021). In Oslo, Norway, outdoor recreational activities increased by 291% during the lockdown compared with the previous three years (Venter et al., 2020). Using green spaces during the pandemic has offered benefits to the physical and mental well-being of city dwellers. For example, studies in the USA and Australia have assessed the mental health factors of adults and young people, such as COVID-19-related worries, distress, anxiety, and depression, in relation to nearby green spaces. They found that green spaces facilitated relaxation, enjoyment of nature, and enhanced resilience with better physical and mental well-being during the pandemic, with confirmed negative associations between tree-rich green spaces and mental health-related variables (Astell-Burt & Feng, 2019; Lopez et al., 2021; Oswald et al., 2021; Wortzel et al., 2021).

Addressing this urgent demand in some high-density localities while balancing social distancing measures and infection control has become increasingly challenging (Kleinschroth & Kowarik, 2020). For instance, private gardens and backyards provided an alternative for some communities, such as the residents of Brisbane, Australia, during the pandemic (Berdejo-Espinola et al., 2021). Moreover, scattered tiny pocket parks in vacant property spaces could be another innovative alternative (Liu & Wang, 2021).

However, public green spaces may not always provide safe spaces for the community. The possible misuses of public green spaces beyond idealistic uses are considerably under-explored in the existing literature[10] and were identified as the tenth research gap. When green spaces in city areas are poorly managed, they can be unsafe for park users and neighbourhood communities, especially at night, with threats of theft, violence, drugs, and other types of crime (Koskela & Pain, 2000). Lyytimäki et al. (2008) discussed situations where nature appears to be a nuisance to urban lifestyles with disservices, including pollen health risks and safety concerns in dark parks. Such issues need proper attention while planning multiple green spaces in cities.

The implications of these findings are clear for future planning. Firstly, urban green spaces must be considered an integral part of response plans for future pandemics, especially as the COVID-19 pandemic may become the 'new normal'. Secondly, in addition to large public green spaces, strategic planning through the installation of smaller pocket-sized green spaces could be an effective and resilient way to prepare for future disasters. Thirdly, planning and policy must be in place to ensure equity and justice in access to, and the safety of, urban green spaces for all communities (Calderón-Argelich et al., 2021; Y. Chen et al., 2022; Geary et al., 2021; Kleinschroth & Kowarik, 2020).

Theme 5: Public acknowledgement and supportive governance for UGI

Our review shows a generally positive public perception and acceptance of UGI. In most cases, city residents and visitors appreciate the UGI and associate it with positive feelings, such as beauty, peace, joy, excitement, hope, relaxation, desire to explore the site, interestedness, and safety (Lee & Kim, 2015; Mesimäki et al., 2019). Meanwhile, public acknowledgement of environmental and recreational UES, such as climate mitigation and adaptation (Lo et al., 2017), is very high owing to the straightforward, corrective, and preventive benefits with tangible evidence (Gashu & Gebre-Egziabher, 2019). Conversely, communities acknowledge economic and social UES to a lesser extent because these impacts are long-term and intangible (Gashu & Gebre-Egziabher, 2019). These public perceptions seem to be influenced by demographics, gender, and educational level. For instance, educated elders and females appear to be more sensitive to the environmental risks to human well-being in some communities, such as poor air quality and high temperatures (Culligan, 2019; Duan et al., 2018).

While largely positive, UGI also acquires some negative public acknowledgement. The main reasons for this include impacts on land value, parking loss, and the accumulation of trash and non-preferred plants/species (Culligan, 2019). Many of these negative public perceptions were mainly due to general dissatisfaction generated by a lack of public consultation before implementation (Culligan, 2019; Säumel et al., 2019), suggesting the importance of better public engagement/ involvement and community consultation prior to implementation. The operationalisation of UGI planning is simple and straightforward, with higher public acknowledgement and positive attitudes. For example, educational programs can train people to detect exotic pests during park visits (Norman-Burgdolf & Rieske, 2021). Such attempts help nature by reducing the risk of invasive species, whereas participants benefit in terms of their physical and mental health.

Institutional and policy support are essential for successful UGI planning and implementation. For instance, some European countries have policies to support mainstream UGI in spatial planning and terrestrial development (Pauleit et al., 2017). New York and Melbourne (Melbourne Green Plan) invested heavily in UGI to improve local environmental and social conditions (City of Melbourne, 2017; Culligan, 2019; Victoria State Government, 2017). In Canada, urban green planning is well-acknowledged in municipal plans; however, the concept of 'explicit use of the ecosystem' has not been considered (Thompson et al., 2019).

There are many concerns and doubts about financing green infrastructure in cities. The lack of clear pathways towards financing green infrastructure[11] was identified as the eleventh research gap in the UGI-related literature. We found very few supporting studies that sought to understand the involvement, perception, and agreements of different institutional and community stakeholder parties (politicians, planning administrations, citizens, and external service providers) in UGI planning, access to their services, and utilisation of public funds. One method to source funds for public infrastructure planning is through municipal revenues earned through local government taxes and fines (Lindfield & Teipelke, 2017). Therefore, positive public perception could be advantageous in financing UGI as such an attitude could substantially aid the moral authority to utilise public funds for developing UGI. Another method of financing UGI planning is through indirect participation of the community, such as accounting for willingness to pay (WTP). For example, some communities express a WTP elevated rentals and mortgages (up to 2%), whereas others are interested in paying for the development and quality enhancement of adjacent green spaces to live beside nature (Derkzen et al., 2017; Mell et al., 2016; Zhou et al., 2021).

Theme 6: Rethinking the operationalisability of UGI

Several limitations often impede larger-scale UGI projects during the planning, implementation, design, and management stages (Gelan & Girma, 2021; Mell, 2021), and raise doubts about operationalisation. Critical factors such as funding, space availability, infrastructure maintenance, institutional collaboration, responsibility-sharing, lack of supportive policy frameworks, resource availability (e.g. water and nutrients), and waste disposal are prevalent hurdles during different phases of an UGI life cycle (Herath et al., 2023).

The merits of innovative technologies can overcome some of the drawbacks during the maintenance and management phases. For example, novel technologies, such as wireless sensor networks (Le et al., 2019), real-time controls (Matasov et al., 2020), plant/tree-based sensors (Jones, 2019), and satellite-based representative methods with vegetation indices (Norman-Burgdolf & Rieske, 2021; Victoria State Government, 2017) are helpful in maintenance, monitoring of regular vegetation health, and evaluating the performance of large-scale urban forest planning in Melbourne, Australia, a city aspiring to become a forest city in the future (Fuentes et al., 2021). Guidelines, manuals, protocols, and training are essential for managing potential disservices and other challenges, such as weeds, water stress, invasive species, diseases, and flood risk (Reynolds et al., 2020).

Overcoming these limitations is essential to maximise the effectiveness of a UGI plan to enhance functionality and multifunctionality while being resource-efficient and cost-effective. For example, using recycled greywater for green walls and roofs has been a successful alternative to limit and reduce potable-water use (Fowdar et al., 2017; Prodanovic et al., 2017). Recycled aggregates and sludge from wastewater treatment have been investigated as substrates for green roofs and walls (Molineux et al., 2015). Coir and perlite were used as green wall substrates, whereas clay pellets from recycled aggregates for green roofs improved plant cover and diversity (Molineux et al., 2015).

Rehabilitation of abandoned urban spaces, such as solid waste dumps, mines, disused transportation routes (tram lines), and brownfields, can help ease the limitations of urban space availability for UGI (Shanshan Feng et al., 2019; Mathey et al., 2015; J. Zhang et al., 2019). Combined or integrated UGI strategies are reasonable choices, considering the potential high costs of implementing citywide green roofing for heat mitigation (Herath et al., 2023). For instance, integrating green roofs with reflective cool roofs could be a more feasible operational strategy with reduced cost/resource requirements and more cooling benefits than green roofs alone for heat mitigation (Herath et al., 2021, 2023). Moreover, integrating green roofs with solar panels shows a higher efficiency in energy production (increasing energy gain by up to 16%) compared with using conventional solar roofs, as this combination eliminates pollutants in the air while maintaining the panel surface at an optimum temperature range via cooling (Barcelona City Council, 2015; Cavadini & Cook, 2021).

Planning a hybrid infrastructure that combines green with blue and grey infrastructure can help maximise overall effectiveness (Fowdar et al., 2017; Molineux et al., 2015; Prodanovic et al., 2017). Generating a broader empirical basis on the effectiveness of such hybrid infrastructure solutions is essential for identifying the kind of co-benefits they bring[12], which was recognised as the twelfth research gap. As examples of hybrid infrastructure planning, we found six case studies in our literature search; however, all studies on this topic have focused on stormwater management (Bakhshipour et al., 2019; De Sousa et al., 2012; Jeong et al., 2016; Mulligan et al., 2020; Taghizadeh et al., 2021; Vojinovic et al., 2021). Assessment of effectiveness by counting the target benefits along with all potential co-benefits would provide a complete picture of effectiveness.

The operationalisability of a planned UGI should be a key consideration when analysing its effectiveness. Hence, the lack of a comprehensive evaluation and assessment of the effectiveness of UGI[13] was identified as the thirteenth research gap. The current literature tends to discuss the effectiveness of UGI based on functional effectiveness, such as cooling/heating/pollution control or stormwater holding potential, without much evaluation of the operationalisability, ease of implementation, cost-effectiveness, or comparisons with conventional infrastructure. For example, applying 90% or 100% citywide green roofs is effective in terms of cooling, but is neither realistic nor operationalisable. Selecting the most suitable NbS plan for the given context is critical during the planning stage.

Finally, the devil is in the detail; the minor details should be considered when implementing of UGI. We identified the insufficient exploration of the spatial configurational efficiency of UGI[14] as the fourteenth research gap in the existing literature. It is reasonable to assume that the differences in the configuration and spatial arrangement of UGI could lead to different outcomes. For example, some evidence suggests that street trees without appropriate spacing and with dense canopies could decrease MRT and increase air temperature (Meili et al., 2021; Park et al., 2019). Public open spaces benefit from a particular tree orientation for effective cooling (Privitera & La Rosa, 2018). With current technological advancements, these outcomes can be easily and accurately assessed using various empirical efforts in future studies. Furthermore, each city requires context-specific green policies, as each has a unique microclimate depending on multiple factors, such as climate, solar radiation, aerodynamic properties of urban materials, urban-rural gradient, morphology, and green spaces (Bherwani et al., 2020; Giyasova, 2021; D. Li et al., 2019; Martilli et al., 2020; Patricola & Wehner, 2018; W. Zhang et al., 2018). To inform practice at the city level, more research on context-specific, multi-year analyses in different climatic regions is needed[15], which we summarised as the final (fifteenth) research gap in this review.

2.3.3. Limitations of the review

As for the scope of our sample, we have restricted our literature selection to a single database, Web of Science, and have omitted articles published in languages other than English. Constraining the search period to 2000-2022 enabled us to focus on the most contemporary and novel literature. Although this approach may potentially omit significant papers published prior to this period, it is necessary to manage the volume of records and facilitate the screening process efficiently. Our comprehensive approach to UGI benefits involved a broad literature evaluation but revealed challenges in categorising them within the traditional MEA framework. This highlights the need for more adaptable categorisation methods that acknowledge the interconnected nature of UES, encouraging a more holistic assessment. Future studies should prioritise large-scale, real-world implementations across diverse climatic zones, geographic regions, and urban settings to enhance our understanding of UGI's impact.

2.4. Conclusions and future work

This review offers a comprehensive overview of the ecosystem services provided by UGI. It combines systematic and narrative review approaches to assess the multifaceted benefits and co-benefits provided by UGI. The existing knowledge is synthesised into six current and emerging themes, and within each theme, the state-of-the-art and existing gaps are discussed in-depth. The categorisation of the existing empirical evidence from the literature sheds light on the various UES provided by UGI. In particular, there is a strong focus on UGI's ability to provide urban climate adaptation and mitigation benefits, especially in the context of urban heat regulation and stormwater management.

Our analysis reveals that UGI contributes towards advancing most of 17 SDGs, particularly SDG 11 (Sustainable Cities and Communities). The UES interconnects and simultaneously creates several linkages with the SDGs, highlighting the inherent capacity of UGI to deliver cost-effective co-benefits beyond its primary functions and deliver across social, environmental, and economic domains. The positive public perception of UGI, magnified by the COVID-19 pandemic experience, can be a powerful aid in designing, managing, and financing the UGI. Planning and constructing UGI in advance can be a cost-effective option to provide safe space against shocks such as heatwaves and pandemics in the context of climate change and post-COVID-19 new normal.

Despite a sharp increase in the literature on UGI, there exist some important knowledge gaps. For example, much of the studies we reviewed remain at the concept level, and the evidences presented are predominantly from modelling rather than from real-world hands-on implementation or established effectiveness mostly from small-scale experiments that await macro-scale measurements and confirmation, to name several of them. These gaps need to be filled through future research in order to harness the full benefit of UGI.

2.5. Appendix

TS= ('*green infrastructure' OR 'nature*based solution*' OR 'blue*green infrastructure' OR ‘ecosystem*based adaptat*’) AND TS= (city OR cities OR urban OR metropolitan) AND TS= (role* OR advantage* OR function* OR capacit* OR mitigation OR modification OR adaptation OR control* OR adjust* OR service* OR impact* OR effective* OR improv* OR *climate OR "urban*island" OR "heat Island" OR "air pollut*" OR "air pollut* mitigation" OR "air quality" OR "ecolog*service" OR "eco*service" OR "environment*" OR "social" OR "societ*" OR "econom*" OR water)

2.6. Reference

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Chapter 3

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Statement of Contribution

This thesis is submitted as a Thesis by Compilation in accordance with
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I declare that the research presented in this Thesis represents original work that I carried out during my candidature at the Australian National University, except for contributions to multi-author papers incorporated in the Thesis where my contributions are specified in this Statement of Contribution.

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Endorsed

Primary Supervisor – Xuemei Bai	**Signature**	**Date**: 22 May 2023
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3. Assess the effectiveness of different urban surface parameters in mitigating excess urban heat.

Effectiveness of urban surface characteristics as mitigation strategies for the excessive summer heat in cities

Abstract

Extreme urban heat, influenced by surface characteristics, negatively affects human thermal comfort. Understanding the thermal behaviour of different urban surface parameters (USPs) at large spatial scales is essential for strategic heat mitigation. This study evaluates USPs from several perspectives to assess their comparative effectiveness as heat mitigation strategies. The Air Pollution Model (TAPM) is used to simulate the urban climate of Melbourne for summer 2019 – Australia's warmest year. Fifty–two simulations are tested to represent changes in USPs as in vegetation type, built–cover ratio, building height, green roofs and cool roofs. The results of each simulation are compared with the baseline in terms of heat indices. Roofs with high albedos are found to be the best heat mitigation for reducing daytime temperatures (0.85 albedo; –1.29 °C), while green roofs show the best nighttime efficacy (100 %, –1.15 °C). Vegetation ratio, green and cool roofs show near–linear negative relationships with heat. Cooling is found to be more effective with trees when distributed in both canyon and urban parks than only planted in street canyon. These findings underscore the significance of USP characteristics in heat mitigation that can inform strategic urban planning with spatial arrangements of green infrastructure.

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Effectiveness of urban surface characteristics as mitigation strategies for the excessive summer heat in cities

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ABSTRACT

Extreme urban heat, influenced by surface characteristics, negatively affects human thermal comfort. Understanding the thermal behaviour of different urban surface parameters (USPs) at large spatial scales is essential for strategic heat mitigation. This study evaluates USPs from several perspectives to assess their comparative effectiveness as heat mitigation strategies. The Air Pollution Model (TAPM) is used to simulate the urban climate of Melbourne for summer 2019 – Australia's warmest year. Fifty-two simulations are tested to represent changes in USPs as in vegetation type, built-cover ratio, building height, green roofs and cool roofs. The results of each simulation are compared with the baseline in terms of heat indices. Roofs with high albedos are found to be the best heat mitigation for reducing daytime temperatures (0.85 albedo; −1.29 °C) while green roofs show the best nighttime efficacy (100 %, −1.15 °C). Vegetation ratio, green and cool roofs show near-linear negative relationships with heat. Cooling is found to be more effective with trees when distributed in both canyon and urban parks than only planted in street canyon. These findings underscore the significance of USP characteristics in heat mitigation that can inform strategic urban planning with spatial arrangements of green infrastructure.

1. Introduction

1.1. Background

Urban areas are expanding continuously, to accommodate the rising urban population, which is 55 per cent of the global population in 2018 and is projected to reach 68 per cent by 2050 (UN, 2019). Urban surfaces are created by converting natural vegetative surfaces into built-up areas (Bai, Chen, & Shi, 2012; Chen et al., 2015; Ren, 2015; Zhao, 2018). Such large-scale urbanisation subsequently impacts the regional microclimate by increasing heavy rainfall (Patricola & Wehner, 2018; Rogers, 2018; Shi et al., 2017; Zhang, Villarini, Vecchi, & Smith, 2018) and exacerbating the urban heat island effect (Gao, Hou, & Chen, 2019; Li, Schubert, Kropp, & Rybski, 2020; Zhang, Shou, & Dickerson, 2009; Zhou, Rybski, & Kropp, 2017). Extreme weather events such as heatwaves are projected to be more intense in cities, as well as occurring more frequently due to global warming (King, Schrag, Dadi, Ye, & Ghosh, 2015; Shi et al., 2017; Zhang et al., 2018).

The Urban Heat Island (UHI) is a well-documented regional urban climate impact due to land-use changes, which is measured by the difference in temperature between urban and surrounding rural areas (Arnfield, 2003). Reduced vegetation in urban areas results in a reduction in evaporative cooling (Li et al., 2019; Oke, 1982) and the aerodynamics of urban materials typically support storing more heat (Li et al., 2019; Zhao, Lee, Smith, & Oleson, 2014). Changes in the urban energy budget affect the microclimate, including surface and air temperature, wind, and humidity (Liu et al., 2018; Manoli et al., 2019; Morris et al., 2017; Yang, Hou, & Chen, 2011). Furthermore, extreme heat events and their consequences impose an extensive threat on human thermal comfort levels in metropolises. UHI can exacerbate heatwave events in cities (both UHI and heatwaves are well-identified as extreme heat events in cities), where a heatwave is defined as three or more consecutive days with high maximum and minimum temperatures that are atypical in a particular location. Heatwaves are projected to be more frequent and intensive in the future due to global warming (Bureau of Meteorology, 2016; Chen et al., 2015; Papanastasiou, Melas, & Kambezidis, 2014; Papanastasiou, Melas, & Kambezidis, 2015; Watts et al., 2020). Thus, there is an urgent need for extensive research efforts to identify feasible and suitable mitigation strategies for extreme heat in current urban planning.

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1.2. Rationale and the scope of the paper

Some remedies for excess urban heat have been presented in the scientific literature. These remedies include adjusting the urban geometry by changing the building density, aspect ratio and street orientation (Coutts, Beringer, & Tapper, 2007; Mirzaei, 2015). Another approach is to change urban surface characteristics to change the thermodynamics as in thermal capacity, emittance and reflectivity (Akbari & Matthews, 2012; Song & Park, 2015). Other ideas include modifying the vegetation ratio to alter evapotranspiration and shading (Imran, Kala, Ng, & Muthukumaran, 2019; Mcpherson, 1994; Richards, Fung, Belcher, & Edwards, 2020; Zhang, Lv, & Pan, 2013; Zhou, Zhang, Fu, Xue, & Wang, 2021) or increasing the number of water bodies to increase evaporative cooling (Tan, Sun, Huang, Yuan, & Hou, 2021; Žuvela-Aloise, Koch, Buchholz, & Früh, 2016). The changes in discussed characteristics are identified as different heat mitigation strategies that can be introduced in the term of urban surface parameters – USP hereafter. However, experimenting with the urban geometry in an already existing urban area is economically and socially impractical. A recent trend in the scientific literature is to face urban climate challenges with the Ecosystem-based adaptation (EbA) approach or Nature-based Solutions (NbS). Approaches with EbA and NbS such as conservation, management, and restoration of ecosystems in urban areas are practised through green spaces, urban parks and other Urban Green Infrastructures (UGI) (Laros, Birch, & Clover, 2013; Marcotullio & Boyle, 2003; Munang et al., 2013). Establishing green corridors, urban parks and urban wetlands are beneficial for disaster risk reduction, carbon storage and improving biodiversity. These approaches are considered "no regrets interventions" due to their multiple economic, social and environmental co-benefits (Geneletti & Zardo, 2016). However, for such approaches to be successfully adopted at a larger scale, their long-term performance and their overall effectiveness need to be evaluated (Bai et al., 2018).

Different methods have been used to assess and compare the effectiveness of strategies for mitigating urban heat. These include computer modeling of the urban climate (Chapman, Thatcher, Salazar, Watson, & McAlpine, 2018; Herath, Halwatura, & Jayasinghe, 2018; Imran, Kala, Ng, & Muthukumaran, 2018; Middel, Chhetri, & Quay, 2015; Morini, Touchaei, Rossi, Cotana, & Akbari, 2018; Oswald et al., 2020; Song & Park, 2015) and observation-based studies (Xing & Jones, 2019). Microscale and mesoscale computer modeling of the urban climate allows multiple hypotheses to be compared before implementation in the real world. Impacts of different urban land-use scenarios have been analysed in many studies, such as a simulation of the tropical Indian city of Kolkata using the Weather Research and Forecasting (WRF) model (Li, Mitra, Dong, & Yang, 2018). When wetlands and croplands were converted to built-up areas, the regional temperature was "dramatically increased" while the irrigated cropland scenario demonstrated a cooling effect (Li et al., 2018). To assess the impact of cooling by urban parks as green infrastructure (GI), the WRF model was used to simulate Athens, Greece at 0.5 km resolution. A larger cooling effect of >5 °C was observed during the nighttime of a typical warm day by those urban park scenario (Papangelis, Tombrou, Dandou, & Kontos, 2012). Sharma et al. (2016) have simulated fractional green roof scenarios in Chicago with WRF (1 km resolution) and proved a temperature drop in roof surface by 5.08 °C with 100 % green roof coverage. In a study by Song and Wang (2016) in Phoenix, Arizona, a desert city showed the urban boundary layer (UBL) temperature to perform a relatively uniform reduction, proportional to the areal coverage. They have observed a UBL temperature reduction of 0.3 °C in the daytime and 0.2 °C at nighttime per 10 % increase in green roof coverage, respectively. A modeling study by Arghavani, Malakooti, and Bidokhti (2020) tested multiple scenarios of surface vegetation and green roofs with WRF in Tehran (Iran) and concluded that green roofs are more efficient at cooling than surface vegetation in high-density residential areas. Reflective cool roofs have been shown to reduce the local ambient temperature in simulations of the heatwave events in 2003 and 2006 for the West Midlands, UK (Macintyre & Heaviside, 2019). The study concluded that such an intervention could potentially offset 18 % of seasonal heat-related mortality. Using the Community Land Model (CLM) coupled with the Community Earth System Model (CESM), Wang et al. (2020) proved that painting roofs white is effective for cooling roofs with less water-holding capacity and low thermal admittance.

Heatwaves in Australia result in the highest number of deaths for any natural hazard including bushfires, floods, storms and tropical cyclones (NSW Government, 2015). Australian urban populations are highly vulnerable to heat-related consequences, as 86 % of the Australian population lives in cities (UN DESA, 2018). Different vegetation cover and urban expansion scenarios were studied for Brisbane (Australia) using the Conformal Cubic Atmospheric Model (CCAM), which showed that nighttime temperatures are higher in a zero vegetation area than in a high urban density area (Chapman et al., 2018). The WRF model was used to simulate Melbourne (Australia) to demonstrate that green roofs and cool roofs could have mitigated the higher temperatures experienced during the 2009 heatwave (Imran et al., 2018). The same authors also assessed the efficacy of vegetative patches to minimize extreme heat impacts experienced during the most extreme heatwave in Melbourne that occurred in January 2009. The simulation results revealed that mixed vegetation patches with forests, grasslands, and shrublands can reduce the near-surface UHI (Imran et al., 2019). Moreover, Jacobs, Gallant, Tapper, and Li (2018) used the WRF model to also simulate the Melbourne climate during several heatwaves and observed that vegetation patches have an effective nighttime cooling potential, while cool roofs provided a more effective daytime cooling potential. While providing essential insights into heat mitigation possibilities, the abovementioned mesoscale modeling studies tend to focus only on one or two USPs as mitigation options and have focused just on UHI and/or historical heatwaves. Most studies in the literature that have used microscale climate models have simulated UGI changes for a relatively small area.

The main objective of this study is to assess the effectiveness of a range of USPs for urban cooling. Urbanisation brings about different surface characteristics with land-cover and land-use changes. We focused on a combination of USPs based on vegetation type, built-cover ratio, green and cool roofs, as well as building height in this study that represent different mitigation strategies. We also analyse how the UPS scenarios impact urban cooling/heating in Melbourne's metropolitan area, which is a scale that is more relevant for city-level planning and policymaking. The correlation between individual parameters and the corresponding temperature reduction was calculated for multiple heat indices. The experiments were based on the one-at-a-time (OAT) approach, and used a sensitivity analysis for summer 2019, since 2019 was the warmest year for Australia as identified by the Bureau of Meteorology (2020). This study used the mesoscale climate model TAPM (The Air Pollution Model), which is dynamically coupled with the UCLEM urban canopy scheme for urban parameterization. By comparing the performance of a broad range of urban surface characteristics at a large metropolitan area, our results can be used to inform urban cooling strategies and adaptation planning. This will in turn help build a heat-resilient and livable city of Melbourne as well as other cities with a similar temperate oceanic climate.

2. Methods

2.1. Study site

Melbourne is the second-largest Australian city, covering 3770 ha. The city accommodated a population of 4.936 million in 2018 and is predicted to grow to 9 million by 2056 (Victoria State Government, 2019). According to the Köppen climate classification, Melbourne has temperate oceanic climate (Cfb) conditions with annual mean maximum and minimum temperatures of 19.9 °C and 10.2 °C, respectively. The Melbourne Central Business District (CBD), is expected to experience 2.2

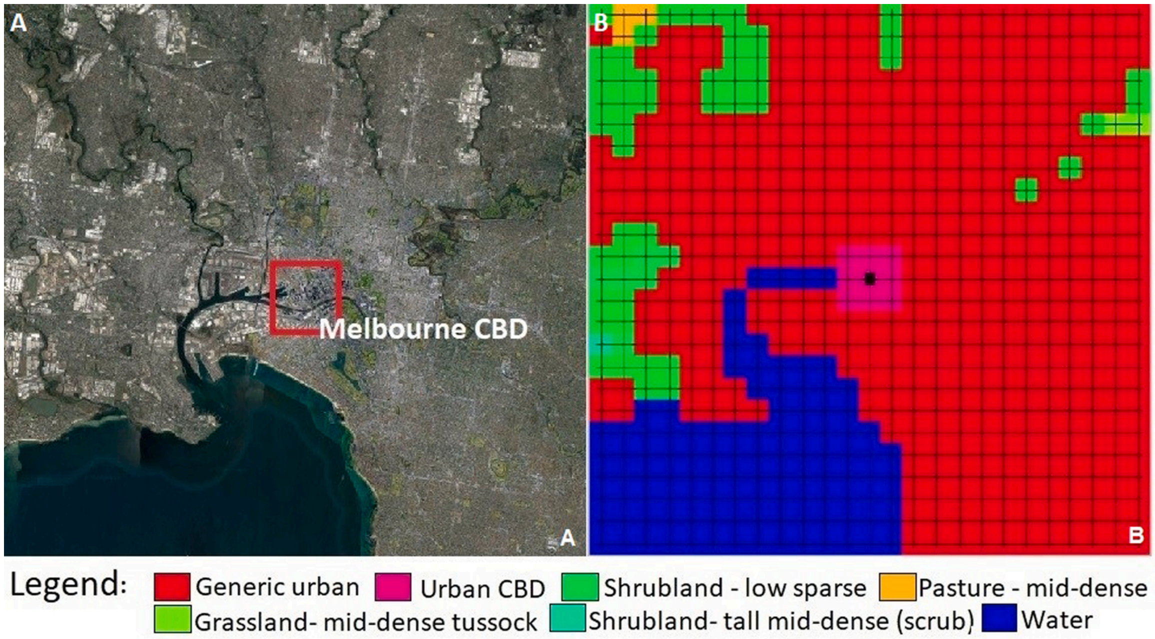

Fig. 1. Melbourne CBD from UCM-TAPM (A: Melbourne from Google Earth; B: TAPM default land-use representation; the black circle represents the point for temperature extraction).

additional days per year with temperatures exceeding 35 °C compared to non-CBD areas, and an additional heatwave every ten years. Hence, both the Melbourne CBD and the surrounded metropolitan area were included in this study's sensitivity analysis (Fig. 1A).

2.2. Model configuration

This study used the TAPM mesoscale climate model (Hurley, Physick, & Luhar, 2005) developed by CSIRO, Australia. The TAPM includes the Urban Climate and Energy Model (UCLEM) developed to represent the climate of Australian cities. In UCLEM, it represents the energy budget in roofs, two walls, roads, and vegetation (Chen et al., 2015). The TAPM supports 38 different land–use types, including eight urban forms (Hurley, 2008). The different urban forms have different canyon geometries, thermal properties of building materials, tree heights, and the fraction of vegetation area (Chen et al., 2015). TAPM uses multiple one-way nesting for dynamic downscaling of synoptic-scale analyses or weather forecasts that drive the simulation at the lateral boundaries of the simulation grid (Chen et al., 2015). This study used 30 km, 10 km, 3 km, and 1 km nesting grid levels, with 25 × 25 grids for each horizontal level and a vertical height up to 8 km above the ground. The results reported in this paper are from the simulation at 1 km resolution.

TAPM employs a tiled or mosaic approach where the surface temperature is comprised of three different land-use types. These three types are the urban impervious surfaces (a combination of roofs, roads and walls), the vegetation coupled to the urban street canyon (referred to as inside-canyon vegetation) and a separate vegetation tile that does not directly couple to the urban surfaces that represents natural vegetation as well as large parks (referred to as outside-canyon vegetation). The combined area fraction of the urban impervious surfaces with the inside-canyon vegetation is indicated by σ_U, with the outside-canyon vegetation represented by $1 - \sigma_U$. The surface temperature for the urban area T_U is calculated from the combined outgoing longwave radiation of both the impervious surfaces and the inside-canyon vegetation (Thatcher & Hurley, 2012). the surface temperature T_0 is calculated using a weighted tile approach for the combined urban area (T_U) and the outside-canyon vegetation surface temperature ($T_{g\&f}$).

$$T_0 = (1 - \sigma_U)\, T_{g\&f} + \sigma_U T_U \quad (1)$$

$$T_U = \left(\left[R_{\text{impervious}} + R_{\text{canyonveg}}\right]/\varepsilon\right)^{1/4} \quad (2)$$

where ε represents the net emissivity of the urban area, $R_{impervious}$ represents the upwelling longwave radiation from the impervious surfaces, and $R_{canyonveg}$ represents the upwelling longwave radiation from the in-canyon vegetation.

2.3. Initial and boundary conditions

For the experiments described in this paper, we simulate the December–February (DJF) 2018–2019 summer period. Observed values for daily T_{max} and T_{min} were obtained from the Olympic Park Weather Station (ID 86338, 37.83 °S, 144.98 °E, and 7.53 m above sea level) from the Bureau of Meteorology (BoM). The simulation domain is centred on the CBD central as 37.8136 °S, 144.9631 °E (as depicted in Fig. 1B).

TAPM uses data from several sources for surface and meteorology information. Terrain data is derived from the US Geology Survey – Earth Resources Observation and Science (EROS) Data Centre Distributed Active Archive Centre (EDC DAAC), Geoscience Australia, MODIS satellite data, and the United Nations Educational, Scientific and Cultural Organization's (UNESCO) soil class dataset. The mean sea-surface temperatures (SST) were sourced from the US National Centre for Atmospheric Research (NCAR). The meteorology and climate data were acquired as six-hourly synoptic scales derived from NCEP/NCAR 40-Years Reanalysis Project 1996 BAMS. The model used a three-month spin-up time based on some trial experiments discussed in Appendix B.

2.4. Experimental design

To investigate the cooling potential in the selected summer period, various urban parameters were selected from the literature to create 52 different scenarios (Appendix A: Table A1). The baseline (BSL) setup represents the existing land-use based on Coutts et al. (2007) values for vegetation and built-up area percentages. Other scenarios are constructed by changing parameters for vegetation coverage, building area coverage, average building height, building height to canopy width ratio, leaf area index, surface albedo, and green roof area.

Table 1
Heat indices used as efficacy measurements.

Indices	Term used	Definition
Hot day	HD	Day-count with $\overline{T}_{max} > 35$*
Very hot day	VHD	Day-count with $\overline{T}_{max} > 40$ °C*
Hot night	HN	Night-count with $\overline{T}_{min} > 20$ °C*
Very hot night	VHN	Night-count with $\overline{T}_{min} > 25$ °C*
	$\Delta\overline{T}_{max}$	Mean $\overline{T}_{max}$ of scenario – Mean $\overline{T}_{max}$ of the BSL
	$\Delta\overline{T}_{min}$	Mean $\overline{T}_{min}$ of scenario – Mean $\overline{T}_{min}$ of the BSL

* Sourced and adapted from the Australian Bureau of Meteorology.

2.5. Heat indices

Table 1 defines the heat indices that are used for efficacy measures in this study, as well as evaluating daily maximum and minimum temperatures T_{max} and T_{min}. The reduction in mean summer daily maximum and minimum temperatures ($\Delta\overline{T}_{max}$, $\Delta\overline{T}_{min}$) was also considered as a method to quantify the cooling potential of each scenario.

3. Results and discussion

3.1. Model validation

Model validation was performed by comparing simulated (SIM) results for the corresponding grid point from TAPM against observed (OBS) measurements from the weather station for the similar time period for the BSL setup. Air temperature is taken at 2 m above the surface in the simulation. A comparison between the SIM daily temperatures and the station observations is shown in Fig. 2.

A summary of the TAPM performance is shown in Table 2, where SIM values were compared with measured T_{max} and T_{min}. TAPM overestimated T_{max} with an absolute error of ~1.56 °C. However, the SIM T_{min} matched OBS station values with only a slight overestimation error of 0.18 °C. Both T_{max} and T_{min} indicate a higher Pearson's correlation (r) (expressing a higher correlation between two measurements) and a higher Spearman's correlation (r_s). For further confirmation, more statistics for model validation such as R^2 and Q-Q plots are provided in Appendix B2 (Fig. B2).

3.2. Simulation results for tested urban surface parameters

Table 3 illustrates the statistical summary of t-tests as the mean ($\overline{T}$), SD, p-values, and $\Delta\overline{T}$ for maximum and minimum temperatures for each of the 52 scenarios under $\overline{T}_{max}$ and $\overline{T}_{min}$ over 90 summer days compared to the BSL. The correlation, r was calculated in a range of four or more samples for every parameter tested (including the value represented in BSL). For example, the roof albedos in the CBD were tested with the values of 0.20, 0.50, 0.70, and 0.85 (namely BSL, CBDa5, CBDa7, and CBDa85, respectively). Therefore, r was calculated for those four sample scenarios. $\Delta\overline{T}$ was calculated according to $\overline{T}_{max}$ and $\overline{T}_{min}$ means of each scenario minus the BSL. The average values for minimum and $\overline{T}_{max}$ for DJF (the whole summer) are used in the discussion. The CBDv20, CBDv30, CBDb70, and CBDbh20 scenarios for $\overline{T}_{max}$, and the UGb40 for $\overline{T}_{min}$ are not statistically significantly different from the BSL, with the p-values being >0.05. All the other p-values for $\overline{T}_{max}$ and $\overline{T}_{min}$ were <0.01, revealing a significant difference from the BSL. The CBD building height scenarios revealed a statistically insignificant correlation when building heights were gradually increased, with a minimum r reported, while the other parameters revealed high correlations.

3.2.1. Significance of the natural vegetation scenarios' impact on temperature variations

Natural vegetation scenarios (grassland, shrubland, and forest) may be considered as unrealistic conditions as the entire urban area was converted to 100 % grassland, shrubland, and forest areas in the TAPM simulation (Table C1 in Appendix C). If the area had not been disturbed by human changes and had maintained the natural vegetation states of grassland and shrubland, then all the heat indices would have been reduced (Table 3). For example, the HDs and VHDs could be reduced by 23 % and 50 %, while the HNs and VHNs could be reduced by 79 % and

Table 2
Statistical summary for model validation (SIM, simulation; OBS, observation; BIAS, SIM – OBS; RMSE, root mean square error; r, Pearson correlation; r_s, Spearman rank correlation coefficient).

	Mean		SD		BIAS	RMSE	r	r_s
	SIM	OBS	SIM	OBS				
Max	28.29	26.73	5.66	6.02	1.56	3.1792	0.89	0.90
Min	16.63	16.45	3.11	2.75	0.18	1.6833	0.84	0.84

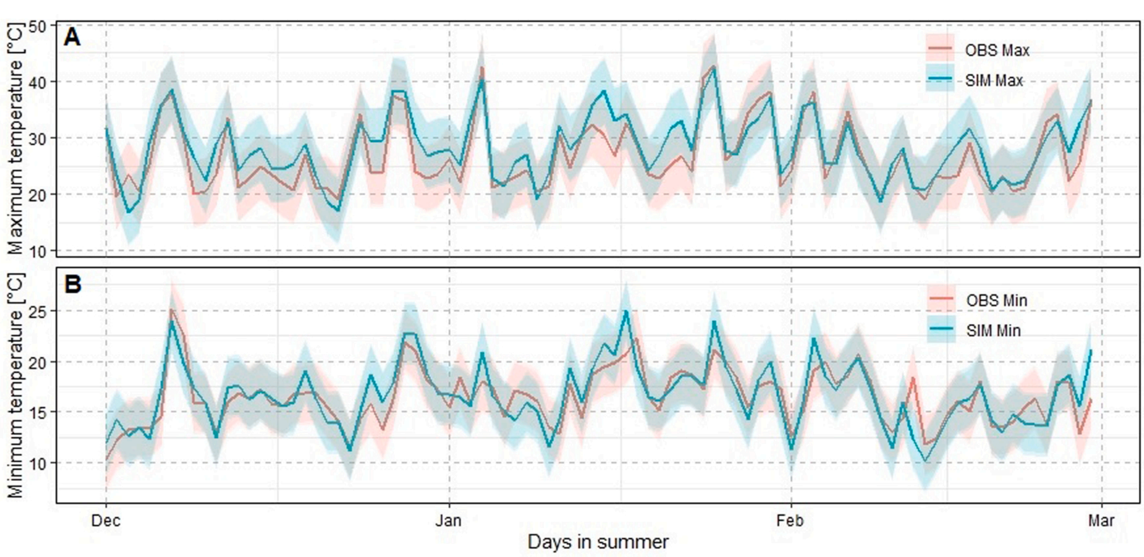

Fig. 2. Comparison between observed (OBS) and simulated (SIM) daily maximum air temperature (T_{max} from A and minimum air temperature (T_{max}) from B for summer (the shaded areas represent the standard deviation (SD) above and below the mean).

Table 3
The *t*-test result's summary for the scenario compared with the baseline (see Table A1 in Appendix A for scenario definitions, and * indicates statistically significant p-values).

Urban scenario	Maximum temperatures							Minimum temperatures						
	$\overline{T}_{max}$ (°C)	SD	p-value	$\Delta\overline{T}_{max}$ (°C)	HD #	VHD #	r	$\overline{T}_{min}$ (°C)	SD	p-value	$\Delta\overline{T}_{min}$(°C)	HN #	VHN #	r
BSL	28.0389	5.6174	NA		13	2		17.0489	3.0352	NA		14	0	
Grassland	26.9300	5.8047	<0.01*	−1.1089	10	1		14.3722	2.9094	<0.01*	−2.6767	3	0	
Shrubland	27.1967	5.7267	<0.01*	−0.8422	10	1		14.4433	3.0249	<0.01*	−2.6056	5	0	
Forest	29.3944	5.8583	<0.01*	1.3555	14	4		15.9044	3.5639	<0.01*	−1.1445	10	0	
UGv13	28.8933	5.7092	<0.01*	0.8544	13	2		17.5211	3.1644	<0.01*	0.4722	18	1	
UGv19	28.6333	5.6799	<0.01*	0.5944	13	2		17.3311	3.1299	<0.01*	0.2822	15	1	
UGv30	28.2722	5.6656	<0.01*	0.2333	13	2	−0.992	17.1522	3.0652	<0.01*	0.1033	14	1	−0.991
UGv45	27.9222	5.6050	<0.01*	−0.1167	12	2		16.9656	3.0024	<0.01*	−0.0833	12	0	
UGv49	27.9233	5.6149	<0.01*	−0.1156	12	2		16.9078	2.9933	<0.01*	−0.1411	11	0	
UGb23	28.2756	5.6642	<0.01*	0.2367	13	2		16.7633	3.0613	<0.01*	−0.2856	11	0	
UGb35	28.2289	5.6193	<0.01*	0.1900	13	2		17.0244	3.0562	<0.01*	−0.0245	13	1	
UGb40	28.1511	5.6048	<0.01*	0.1122	13	2	−0.983	17.0578	3.0327	0.117	0.0089	14	1	0.902
UGb50	27.9878	5.6053	<0.01*	−0.0511	13	2		17.0689	3.0312	<0.01*	0.0200	14	1	
UGb55	27.9422	5.5865	<0.01*	−0.0967	12	2		17.0622	3.0355	<0.05*	0.0133	14	0	
UGb50v30	28.1944	5.6496	<0.01*	0.1555	13	2		17.1656	3.0714	<0.01*	0.1167	14	1	
UGb60v20	28.3467	5.6635	<0.01*	0.3078	13	2		17.3044	3.112	<0.01*	0.2555	14	1	
UGgr25	27.9811	5.6035	<0.01*	−0.0578	13	2		16.8656	3.0111	<0.01*	−0.1833	11	0	
UGgr50	27.9578	5.5942	<0.01*	−0.0811	12	2	−0.994	16.6989	2.9991	<0.01*	−0.3500	11	0	−0.998
UGgr75	27.9011	5.6001	<0.01*	−0.1378	12	2		16.5489	2.9793	<0.01*	−0.5000	11	0	
UGgr100	27.8622	5.6008	<0.01*	−0.1767	12	2		16.4089	2.9633	<0.01*	−0.6400	11	0	
UGa5	27.8867	5.5894	<0.01*	−0.1522	12	2		16.9111	3.0201	<0.01*	−0.1378	11	0	
UGa7	27.7522	5.5742	<0.01*	−0.2867	12	1	−0.997	16.7589	3.0151	<0.01*	−0.2900	11	0	−0.988
UGa85	27.6511	5.5622	<0.01*	−0.3878	12	1		16.6256	3.0045	<0.01*	−0.4233	11	0	
Botha	27.3122	5.5163	<0.01*	−0.7267	10	1		16.7211	3.0352	<0.01*	−0.3278	11	0	
CBDv0	28.2611	5.6657	<0.01*	0.2222	13	2		17.2211	3.0296	<0.01*	0.1722	14	1	
CBDv8	28.1211	5.6463	<0.01*	0.0822	13	2		17.1244	3.0293	<0.01*	0.0755	14	1	
CBDv10	28.0989	5.6446	<0.01*	0.0600	13	2	−0.919	17.1056	3.0329	<0.01*	0.0567	14	1	−1.000
CBDv20	28.0089	5.6156	0.061	−0.0300	12	2		16.9933	3.0309	<0.01*	−0.0556	13	0	
CBDv30	27.9911	5.5957	0.101	−0.0478	13	2		16.8856	3.032	<0.01*	−0.1633	12	0	
CBDv0*	29.2900	5.727	<0.01*	1.2511	14	2		17.3233	3.2546	<0.01*	0.2744	19	2	
CBDv8*	29.2422	5.7086	<0.01*	1.2033	14	2		17.2744	3.2553	<0.01*	0.2255	19	2	
CBDv10*	29.2289	5.7105	<0.01*	1.1900	14	2	−0.996	17.2767	3.2535	<0.01*	0.2278	19	2	−0.995
CBDv15*	29.2022	5.6977	<0.01*	1.1633	14	2		17.2556	3.2531	<0.01*	0.2067	19	2	
CBDv20*	29.1878	5.6862	<0.01*	1.1489	14	2		17.2267	3.2525	<0.01*	0.1778	18	2	
CBDv30*	29.1322	5.6896	<0.01*	1.0933	14	2		17.1822	3.2466	<0.01*	0.1333	18	2	
CBDb33	28.4800	5.6214	<0.01*	0.4411	13	2		17.3056	2.9922	<0.01*	0.2567	15	1	
CBDb40	28.2756	5.5951	<0.01*	0.2367	13	2	−0.908	17.3089	2.9974	<0.01*	0.2600	15	1	−0.957
CBDb50	28.1111	5.6050	<0.01*	0.0722	13	2		17.2556	3.0037	<0.01*	0.2067	14	1	
CBDb70	28.0644	5.6182	0.075	0.0255	13	2		16.9567	3.0592	<0.01*	−0.0922	13	0	
CBDb50v30	29.2433	5.6633	<0.01*	1.2044	14	2		17.4111	3.2295	<0.01*	0.3622	19	2	
CBDgr25	27.8689	5.6131	<0.01*	−0.1700	12	2		16.8367	3.0592	<0.01*	−0.2122	11	0	
CBDgr50	27.7556	5.6057	<0.01*	−0.2833	12	2	−0.998	16.5211	3.0978	<0.01*	−0.5278	11	0	−0.998
CBDgr75	27.6000	5.5767	<0.01*	−0.4389	12	2		16.2122	3.1088	<0.01*	−0.8367	10	0	
CBDgr100	27.4244	5.6152	<0.01*	−0.6145	11	2		15.8989	3.1597	<0.01*	−1.1500	8	0	
CBDa5	27.5322	5.5581	<0.01*	−0.5067	11	2		16.8889	3.0555	<0.01*	−0.1600	12	0	
CBDa7	27.0922	5.5061	<0.01*	−0.9467	10	1	−0.997	16.6744	3.0843	<0.01*	−0.3745	11	0	−0.947
CBDa85	26.7444	5.4374	<0.01*	−1.2945	10	1		16.3289	3.0914	<0.01*	−0.7200	10	0	
CBDbh12	27.9522	5.6324	<0.01*	−0.0867	12	2		16.9800	3.0374	<0.01*	−0.0689	13	0	
CBDbh20	28.0822	5.6482	0.073	0.0433	13	2		17.0689	3.0404	<0.05*	0.0200	14	1	
CBDbh30	28.3344	5.6906	<0.01*	0.2956	13	2	0.586	17.1556	3.0316	<0.01*	0.1067	14	1	−0.302
CBDbh40	28.2900	5.7068	<0.01*	0.2511	13	2		17.0067	3.0175	<0.01*	−0.0422	13	0	
CBDbh50	28.1222	5.7105	<0.01*	0.0833	13	2		16.9433	3.0168	<0.01*	−0.1056	12	0	

64 % respectively. Forests did not contribute to the reduction in $\overline{T}_{max}$, but instead incurred an increase of 1.36 °C. Simulated forests were also associated with an increase in HDs and VHDs, but a reduced number of HNs. Minimum temperatures were found to have a significant drop of 2.68 °C for grasslands, 2.61 °C for shrublands and 1.15 °C for forests. However, we note that these scenarios are unrealistic compared to the other scenarios considered in this paper.

The cooling potential of vegetation arises out of the interactions between three main processes, namely evapotranspiration (ET), moisture availability, and shading (Taha, 1997; Tran, Uchihama, Ochi, & Yasuoka, 2006; Wang, Zhao, Yang, & Song, 2016). These processes are facilitated by the latent heat flux, reducing the sensible heat flux, and reducing incoming solar radiation (Taha, 1997; Tran et al., 2006; Wang et al., 2016). Many studies reveal that warming is determined mainly by ET and convection efficiency (Li et al., 2019; Manoli et al., 2019). According to our simulation results, the maximum cooling impact was provided by grasslands, with a minimum number of HDs, VHDs, and HNs. In TAPM the vegetation types for grassland and shrubland were mid-dense tussock and tall mid-dense scrub, respectively. The results for TAPM contradict the findings of previous researchers (Fung & Jim, 2019; Richards et al., 2020). Secondary forests in tropical Southeast Asia (Richards et al., 2020) and woodlands from Hong Kong (Fung & Jim, 2019) were more effective than grasslands in different studies. However, the plant species differ along with the climate zones and therefore may explain the different simulation results. In these studies, grass and shrub options did not show any significant contributions to temperature reduction, and the authors present the reason for this as insufficient shade and ET (Richards et al., 2020).

In comparison to the BSL, the forest scenario resulting in a higher $\overline{T}_{max}$, as tree canopies neither retain nor store heat in the same way that

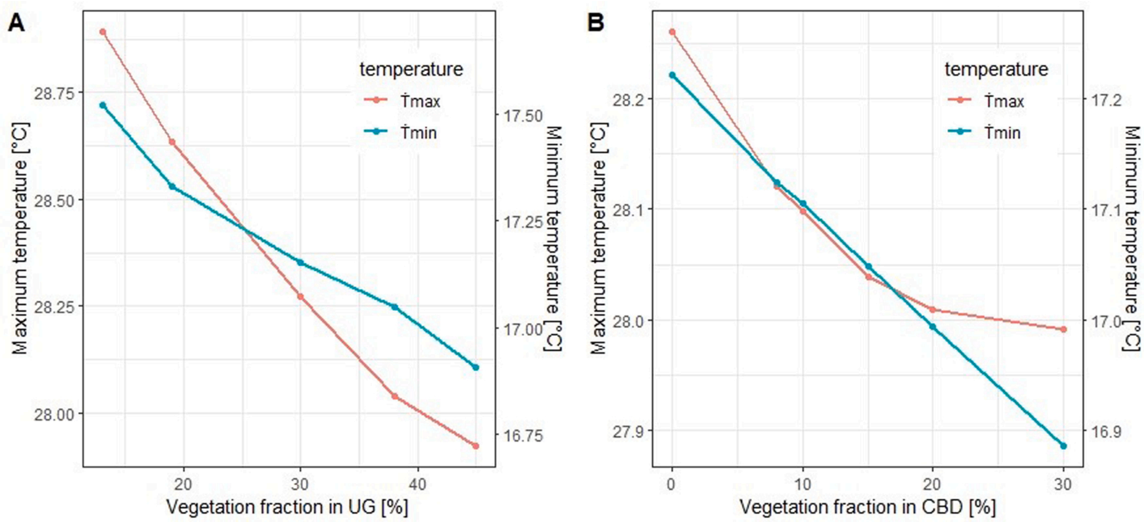

Fig. 3. Change of temperature indices with the fraction of vegetation: A) for UG and B) for CBD.

building materials do. Low sparse woodland vegetation is represented in TAPM with a 25 % vegetation area fraction, and, therefore, the remaining uncovered soil stored heat while still providing a higher surface roughness and increase air temperature above 2 m. Vegetation has been found to reduce the temperature for the surrounding areas; however, suitable vegetation should be selected considering the climate condition. Planning vegetation for urban cooling should be done with proper knowledge of the cooling capacities of different vegetation (Fung & Jim, 2019; Zhang et al., 2013).

The statistical relationships between the UHI and urban vegetation can be used to indicate the efficacy of vegetation as a mitigation strategy. Sun et al. (2019) presented the global relationships for UHI and urban vegetation, and these include characteristics such as plant height, leaf area index (LAI), vertical structure, and canopy density, which can manipulate ET, shading, and impacts on cooling (Shashua-bar & Hoffman, 2000). The UHI showed a weak negative correlation with grass and shrub cover percentages and a medium correlation with all other measures of vegetation cover. The percentage of total tree cover showed the strongest negative correlation with UHI (Sun et al., 2019). Moreover, their report proved weak to moderate negative relationships between UHI and urban vegetation types from both simple and multiple regression models.

3.2.2. *Significance of the impacts of urban vegetation ratio on temperature variations*

To investigate the impact of urban vegetation on heat indices, we ran climate simulations with different vegetative fractions in both UG and CBD. While TAPM supports up to eight different urban types, our research used two types, namely the Urban Generic and Urban CBD, as indicated in Table C2 in Appendix C. In this experiment, the vegetation fractions were changed in both the UG and CBD areas to assess the impact. The model has two ways to represent vegetation, being inside the canyon (directly coupled with the walls and road in the urban street canyon), or vegetation outside the canyon which is decoupled from the urban street canyon (e.g., larger parks or green space). We chose to use a 50:50 distribution of inside canyon and outside canyon vegetation for our study.

Fewer vegetative surfaces in the UG area were found to increase both $\overline{T}_{max}$ and $\overline{T}_{min}$ (Table 3). Less vegetation was found to promote the incidences of HNs and VHNs, signalling the UHI impact. The simulation also showed a reduction in the number of HDs and HNs when the vegetation area fraction was increased above 45 %.

We observed an increase in temperature as the built-up area was increased and the vegetation area was reduced using the scenarios UGb60v20, UGb50v30, and UGb40v49, while BSL represented a ratio of 45:38 (built:vegetation). Only UGb40v49 recorded a reduction for both temperatures compared to the BSL but represented a reduction in the existing build fraction. An increase in the built fraction from 45 % to 50 % is paired with a decrease in vegetation cover from 38 % to 30 % and resulted in an increased $\overline{T}_{max}$ and $\overline{T}_{min}$ by 0.16 °C and 0.12 °C, respectively. However, the increase in built fraction only resulted in 1 VHN. Further expansion of the built-up area to 60 % could be achieved by reducing vegetation to 20 %, which resulted in a near doubling of the temperature increase of 0.31 °C and 0.26 °Cfor $\overline{T}_{max}$ and $\overline{T}_{min}$, respectively.

As depicted in Fig. 3A, both $\overline{T}_{max}$ and $\overline{T}_{min}$ show a negative correlation, with r values of −0.992 and −0.991, respectively for UG (i.e., more cooling as the fraction of vegetation is increased). Generally, decreasing trends were observed in both mean temperatures in the CBD centre when the UG vegetation was increased.

Changing vegetation in CBD (Fig. 3B) indicated a negative-linear pattern for $\overline{T}_{min}$, with a correlation of r = −1. This was the strongest negative correlation reported for $\overline{T}_{min}$ in all scenarios. The $\overline{T}_{max}$ reduction resulted in a non-linear reduction with increased vegetation, with a correlation of 0.92. In comparison to $\overline{T}_{max}$, $\overline{T}_{min}$ was mostly reduced by a higher reduction in latent heat at night, which is consistent with lower transpiration at night. (Huang, Li, Zhao, & Zhu, 2008; Souch & Souch, 1993). The strong negative near-linear relationships between vegetation ratio and $\overline{T}_{min}$ for both the CBD and UG suggest that increasing the area of vegetation is an effective scenario for cooling the city. The number of HDs and HNs decreased by one day in a 20 % vegetation scenario. For the CBD, the reduction in temperature is smaller for a given increase in the vegetation fraction compared to UG. This result may in part be due to the CBD being a smaller land area compared to UG. When the vegetation was doubled by reducing the built fraction to 50 % (CBDb50v30), both $\overline{T}_{max}$ and $\overline{T}_{min}$ have increased to 29.24 °C and 17.41 °C, respectively. Therefore, the TAPM simulations suggest that it is useful to maintain a vegetation fraction of 15–30 % for the CBD vegetation to achieve better cooling.

It is important to note that changes in UG are able to affect the climate in CBD (and vice-versa). Therefore, attempts to improve thermal performance will need to include broader strategies in the overall city design, rather than focus on individual areas. This observation suggests several interesting opportunities for future work, such as identifying the distances over which the CBD is impacted by the surrounding UG, as well as highlighting the benefits of considering a more complex three-dimensional model of the atmosphere (e.g. using CCAM (Chapman

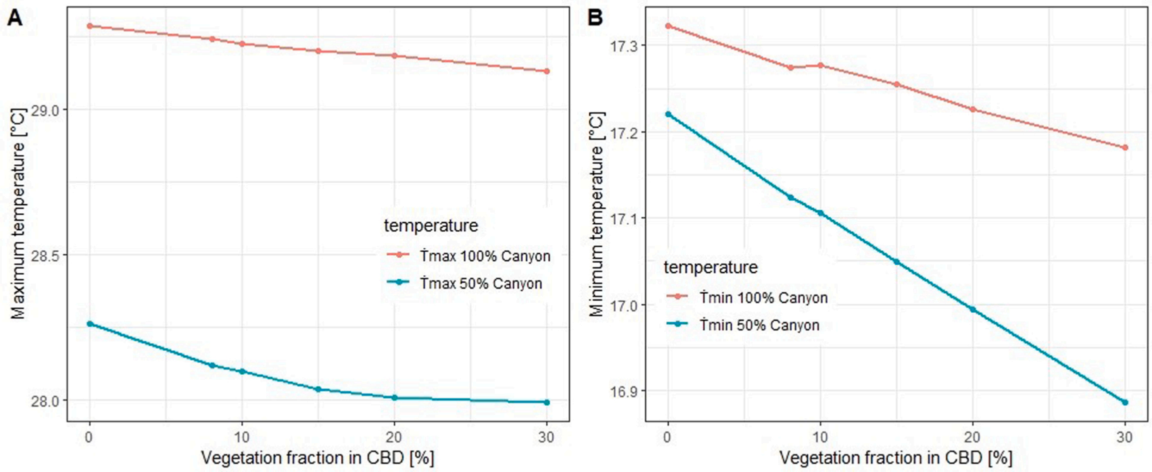

Fig. 4. Change of temperature indices with the fraction of vegetation, 100 % vegetation inside the canyon: A) mean maximum temperature; and B) mean minimum temperature.

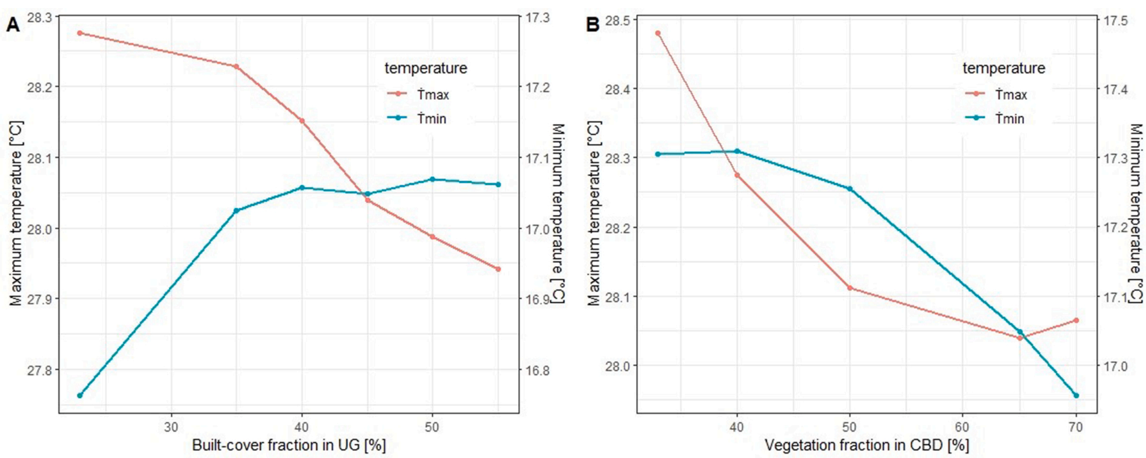

Fig. 5. Change of temperature indices with the ratio of built-cover: A) for UG and B) for CBD.

et al., 2018) or WRF (Jacobs et al., 2018)).

Many studies have attempted to establish the correlation between heat indices and vegetative fractions. A Melbourne study found the strongest correlation among their tested variables in reducing urban heat was with a tree canopy rather than grass and shrub cover (Sun et al., 2019). Imran et al. (2019) measured a non-linear relationship between the UHI reduction (in both the 2 m air and surface) and increased vegetative fractions based on diurnal data. Vegetation cover can have a greater impact on city temperature than other urban geometric factors, such as building height and height/width (H/W) ratio (Chapman et al., 2018). Vegetation coverage should be higher than 40 % to result in significant temperature reductions in Melbourne (Imran et al., 2019). Since the presence or abundance of vegetation is indicated by NDVI (with lower values for poor vegetation cover and vice versa) some studies have used the NDVI index instead of using vegetation fractions directly. A negative correlation (a weak value, $R^2 = 0.22$) was observed between the normalized difference vegetation index (NDVI) and the surface temperature in Metro Manila (Tiangco, Lagmay, & Argete, 2008). Tran et al. (2006) found strong relationships between the NDVI and daytime land surface temperatures (LST) in the eight Asian mega-cities of Tokyo, Beijing, Shanghai, Seoul, Pyongyang, Bangkok, Manila, and Ho Chi Minh City. Moreover, they stated that the slope of the relationship varies from city-to-city with their unique spatial distributions and vegetation canopy structures (Tran et al., 2006).

We performed a second set of experiments using the same vegetation fractions but we changed the ratio between vegetation parameterized inside the canyon and vegetation parameterized outside the canyon. These experiments considered a CBD with 100 % vegetation inside the urban canyon, with the results shown in Fig. 4. In order to achieve a fair comparison, a new BSL setting (15 % vegetation) with 100 % vegetation distribution inside the canyon used for this set of experiments.

This vegetation model coupled inside the urban canyon resulted in higher $\overline{T}_{max}$ and $\overline{T}_{min}$, than for the mixture of 50:50 inside and outside canyon vegetation represented previously. This method of representing vegetation in the simulation increased $\overline{T}_{max}$ by almost 1 °C, 1 HD, 2 VHNs, and 4–5 HNs. For this configuration of the vegetation, the taller trees in the canyon facilitated a higher heat transfer, due to turbulent mixing, and indicated a relative increase in the sensible heat flux. According to the simulation results, parameterizing vegetation with strong coupling to the urban canyon reduces the efficacy of vegetation for cooling the cities. Although more work is needed, the results could be indicating that vegetation is more effective at cooling a city when that vegetation is collected in parks rather than limited by proximity to walls and roads.

3.2.3. Significance of the urban built-cover ratio on heat indices

Dense built-up areas promote heat storage and eventually contribute to higher daytime and nighttime temperatures in cities. Urban built-up surfaces support reduced reflection of solar radiation due to the various materials used in their construction (Wang, Zhu, Xu, & Wang,

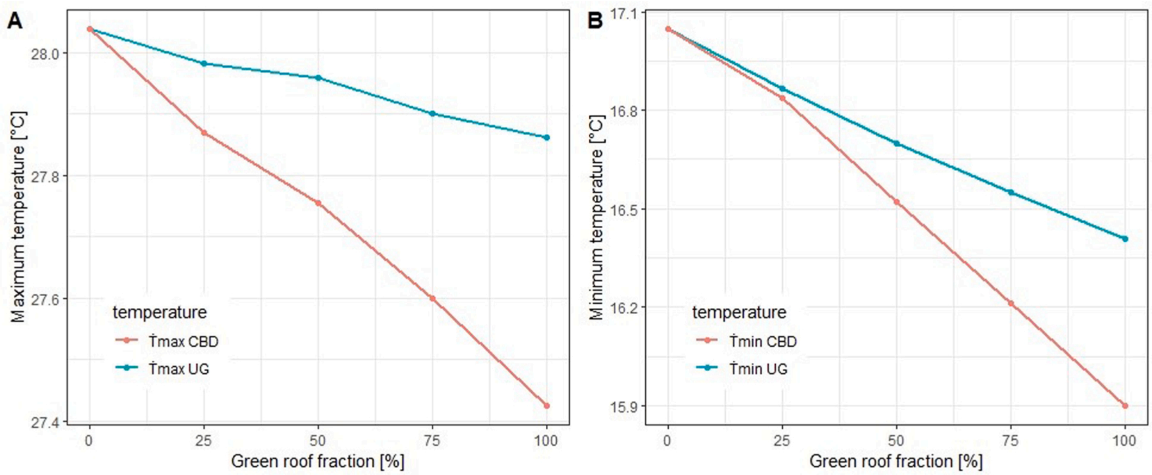

Fig. 6. Change of temperature indices with the percentage of green roofs: A) mean maximum temperature; and B) mean minimum temperature.

2018). Anthropogenic urban structures, such as roads, buildings, and pavements, absorb energy from incoming solar radiation, retain the energy in the form of heat, and then slowly release the heat to the adjacent environment (Zhao et al., 2014). The impervious materials used in constructing urban structures slow down heat release (Wang et al., 2018). Buildings are primary contributors to this phenomena due to their high thermal capacity and the higher surface of exposure through roofs and walls (Phelan et al., 2015). This is in addition to the heat released through air-conditioning units and electricity supply. Therefore, experimenting with the thermal behaviour of the urban built-up ratio or building density (urban geometric perspective) is essential in terms of rapidly increasing urban sprawl and future development considerations. Considering the contribution to the temperature variations shown in the literature, the following experiments were designed to study the built-cover ratio parameters. For BSL, 45 % and 65 % built cover ratios were used for UG and CBD, respectively (Coutts et al., 2007), and results are presented in Tables 3 and Fig. 5.

Increasing the built-cover ratio in UG urban types caused a temperature reduction in $\overline{T}_{max}$, with a correlation of $r = -0.966$ (for UG), while $\overline{T}_{min}$ increased non-linearly with the built ratio (positive correlation of $r = 0.843$). The correlation of $\overline{T}_{min}$ in UG was the highest positive relationship reported across all parameters considered in this paper. Changing built-cover ratios in CBD shows correlations of -0.908 and -0.957, for $\overline{T}_{max}$ and $\overline{T}_{min}$ respectively. Reducing the built-cover ratio by half increased $\overline{T}_{max}$ in both UG and CBD. In the TAPM simulations, this is associated with increasing the area fraction of roads and paved areas, which replace the contracting built-up areas as the vegetation fraction remains constant.

Surface temperatures are also driven by net longwave admission and thermal admittance and are controlled by heat storage capacity and conductivity (Oke, 1981). The built environment is the leading cause of complex changes observed in natural systems and processes. Since UHI is based on the difference in temperature between the natural (surrounding) and built environment, the urban built-up ratio is crucial in UHI terms.

A study in Debrecen (Hungary), established a relationship between land-use parameters and maximum UHI intensity (Rad, Rafieian, & Sozer, 2017). A 2019 study conducted in the Mueang Buriram district in Thailand proved a strong relationship between LST and urban built-up areas, with a correlation of $r = 0.9719$ (Rotjanakusol & Laosuwan, 2020). Downscaling techniques for MODIS LST data from four tropical Indian cities also revealed a higher surface UHI in highly built-up areas than UHI in suburban and rural areas (38.87 °C, 35.85 °C, and 32.41 °C, respectively) (Mukherjee, Joshi, & Garg, 2016).

3.2.4. *The impact of roof surface on heat indices*

Lower albedos for human-altered urban surfaces with a higher specific heat capacity can change the surface energy balance (Imran et al., 2018). The properties of roof areas are a significant consideration as they cover a substantial fraction of the city area. In this section, two different perspectives have been introduced to conventional roof surfaces in UG and CBD as vegetation surfaces and high-reflective (high albedo) construction materials; green roofs and cool roofs to facilitate heat mitigation (Akbari, Rose, & Taha, 2003;Morini et al., 2018; Phelan et al., 2015; Razzaghmanesh, Beecham, & Salemi, 2016).

3.2.4.1. Changing the green roof ratio. Different green roof ratios were tested for both UG and CBD as 25 %, 50 %, 75 %, and 100 %, with the BSL assigned to 0% green roof area. Changing only the green roof ratio in the UG area did not significantly change $\overline{T}_{max}$. This might indicate the impact of green roofs is more localized as the temperatures were always measured in the centre of the CBD. However, green roofs in UG could reduce the nighttime temperature in the CBD ($\overline{T}_{min}$). When the green roof ratio in was increased in the CBD, it clearly showed a reduction of $\overline{T}_{max}$ (consistent with the impact being localized). Increasing green roofs for the CDB revealed the best reduction in $\overline{T}_{min}$ for all realistic scenarios considered in this study.

Fig. 6 shows the reduction in temperatures arising from increasing the area fraction of green roofs to the UG and CBD areas. The maximum efficiency for reducing $\overline{T}_{max}$ and $\overline{T}_{min}$ was achieved by increasing green roofs in the CBD. The reduction in $\overline{T}_{max}$ was limited to 0.1–0.2 °C despite increasing green roof area fraction by more than 75 % for the entire UG area. In comparison, $\overline{T}_{max}$ was reduced by 0.6 °C when all the CBD's roofs were converted to green roofs. In this scenario the HDs were reduced by 15 % and HNs reduced by 43 %. $\overline{T}_{min}$ varied linearly with green roof area fraction in UG with $r = -0.998$ and in CBD, with $r = -0.998$. Green roof ratios proved strong negative correlations with *near-linear* values (~0.99) for temperature values, same as the vegetation ratio. Hence, increasing the area of green roofs in metropolitan areas will help with heat reduction, regardless of the size of the site (assuming green roofs are irrigating with enough water). Converting the entire CBD's roof area to green roofs (CBDgr100) could reduce the nighttime temperatures by 1.15 °C, and reduced HNs by 43 %. This reduction was the highest achieved by effecting a realistic urban parameter change in this study.

The results in this section are consistent with the findings in the scientific literature. Some modeling studies have tested green roofs by adjusting the surface albedos of conventional roofs to green roofs (Kusaka & Kimura, 2004). This technique does have certain limitations, as it does not consider specific physical processes (Imran et al., 2018). In

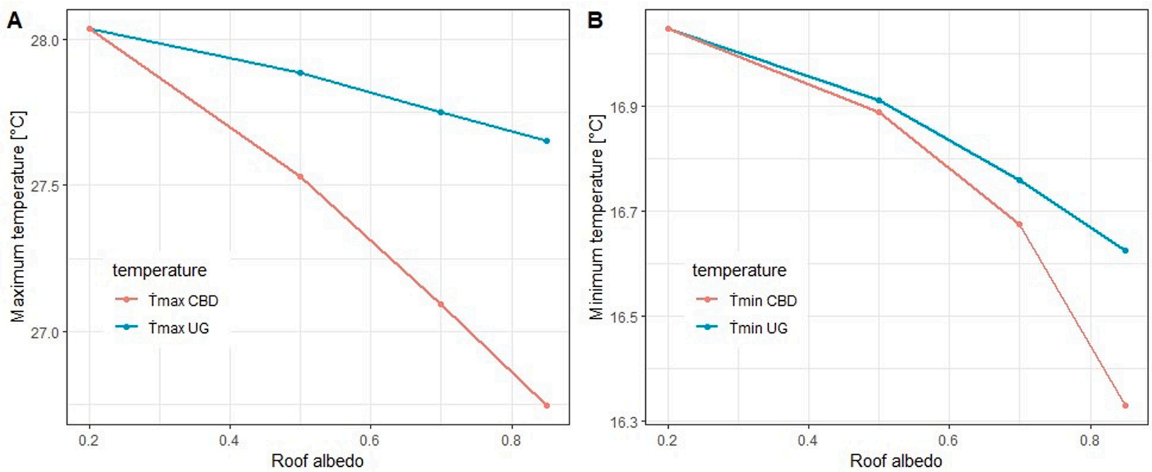

Fig. 7. Change of temperature indices with roof albedo values; A) mean maximum temperature; and B) mean minimum temperature.

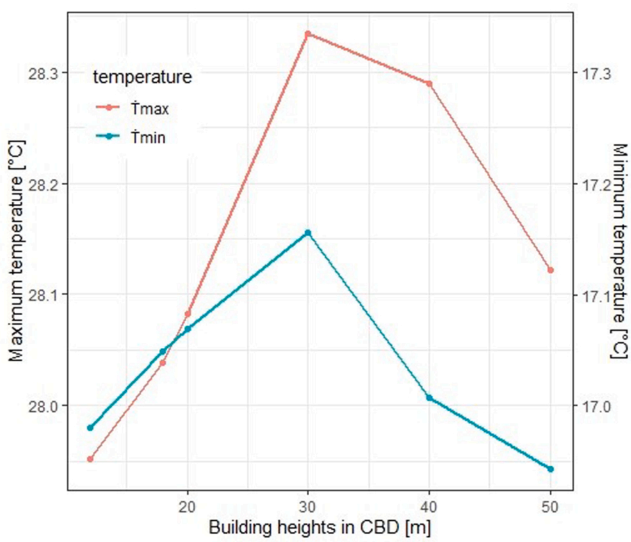

Fig. 8. Changes in mean maximum and minimum temperatures with different building heights in the CBD.

our study, it was beneficial that TAPM provided a parameterization for green roofs. The parameters used in TAPM's green roof parameterization are the albedo, vegetation emissivity, roof soil depth (m), roughness length of roof vegetation (m), LAI, and canopy stomatal resistance. For our study, these parameters were set at 0.2, 0.96, 0.1 m, 0.1 m, 1.5, and 100, respectively. A linear relationship was found for the reduction in UHI when increasing the green roof area fraction in Melbourne (Imran et al., 2018), and a near-linear relationship was observed by Li et al. for Baltimore (US). Both of these experiments were performed with WRF-PCUM (Princeton Urban Canopy Model) (Li, Bou-Zeid, & Oppenheimer, 2014). When the Chicago metropolitan area in US was modelled in WRF with different green roof ratios, the daytime roof temperature varied linearly with increased green roof area fraction (Sharma et al., 2016).

The vegetation in green roofs alters the surface energy balance and substantially reduces the sensible heat flux by shading and change available energy to increased latent heat flux via ET (Imran et al., 2018). Maintenance and irrigation are the main practical considerations for green roofs. In our study, TAPM assumes the vegetation inside the urban canyon is well-irrigated. Phelan et al. (2015) state that the demands for irrigating the rooftop vegetation may outweigh their other advantages. Because of this, high reflective roof materials or high albedo values come into play.

3.2.4.2. Changing the cool roof ratio. TAPM assigns a default albedo of 0.2 for conventional roofs. The BSL experiment also uses a value of 0.2 for roof albedo. Roof albedo values of 0.5, 0.7 and 0.85 were used to study the efficacy of cool roofs for both CBD and UG, separately. However, the 'Botha' scenario considered a roof albedo of 0.5 simultaneously for both the CBD and UG to assess the collective impact. In every experiment, the changes to roof albedo were applied to all of the roof areas, as TAPM-UCLEM does not have separate parameters for normal roofs and cool roofs.

Increasing the roof albedo for UG and the CBD resulted in a considerable reduction in both $\overline{T}_{max}$ and $\overline{T}_{min}$. The scenario CBDa85 demonstrated the greatest reduction in $\overline{T}_{max}$ of 1.29 °C. This suggests that green roofs may be a more viable strategy in some situations, while in other circumstances cool roofs may be the best option for cooling the city. A smaller reduction in $\overline{T}_{max}$ for the UG cool roof scenarios may again indicate a localized impact, as was discussed for the green roof scenarios. $\overline{T}_{min}$ was found to decreased gradually as the roof albedo was increased. Importantly, we found that the increased roof albedo could reduce the number of HDs, VHDs, and HNs (except VHNs for the UGa50 scenario). Changes to the roof albedo of 0.70, 0.85, and 0.50 in both UG and CBD (CBDa70, CBDa85, and Botha) similarly reduced HDs and VHDs by 23 % and 50 %, respectively. Furthermore, increasing the roof albedo reduced HNs by 21 %, 28.5 %, and 21 % (by each scenario), respectively. $\overline{T}_{max}$ varied almost linearly with increasing roof albedo (Fig. 7) while $\overline{T}_{min}$ changed non-linearly as a function of roof albedo. A strong negative correlation of $\overline{T}_{max}$ with roof albedo was found for both UG and CBD (r = −0.997). In comparison the correlation between $\overline{T}_{min}$ and roof albedo in UG and CBD were found to be r = −0.988 and −0.947, respectively.

The albedo (α) is defined as the reflectance of a material integrated over the wavelengths of incoming solar radiation. Higher solar reflectance and higher infrared emittance are associated with cool materials that promote less solar radiation absorption and faster heat release (Santamouris, Synnefa, & Karlessi, 2011). The redistribution of the energy budget of a cool roof with a high albedo also reduces the sensible heat flux, lowers the absorbed net radiation and reduces the surface temperature of the cool roof. A separate study also showed that high roof albedo was also effective in reducing the surface and adjacent air temperatures (Akbari & Matthews, 2012). Realistic albedos for conventional roofs range between 0.1 and 0.3, while values between 0.65 and 0.85 can be achieved by coating roofs or using roofing material for cool roofs (Imran et al., 2018; Macintyre & Heaviside, 2019; Santamouris et al., 2011; Wang, Berardi, & Akbari, 2015).

Cool roofs were found to be more effective for reducing $\overline{T}_{max}$ by 1.29 °C, while the most effective green roof option (CBDgr100) reduced the temperature by only 0.62 °C. However, green roofs appear to be efficient for reducing $\overline{T}_{min}$, with a maximum reduction of 1.15 °C. Reductions in temperature due to cool roofs have been discussed in the literature, such as a study for Toronto (Canada) which found that increasing the roof albedo from 0.30 to 0.70 reduced the roof surface temperature on a summer day by 9.6 °C in a high-rise area and by 11.3 °C in a detached residential area (Wang et al., 2015). A WRF simulation for West Midlands (UK), found a reduction in daytime 2 m air temperature of 0.5 °C on average and a maximum reduction of ~3 °C maximum (Macintyre & Heaviside, 2019).

Imran et al. (2018) found that the maximum roof surface UHI during the day was reduced by 2–5.2 °C after increasing the roof albedo from 0.50 to 0.85. In that experiment, the UHI reduction was slightly non-linear as a function of increased albedo. Cool roofs were also found to be more efficient than green roofs, with a maximum reduction of 1.4 °C for the cool roofs. In contrast, Xing and Jones (2019) established that green roofs perform better than cool roofs after monitoring performance during a heatwave, finding an indoor air temperature reduction of 2.5 °C. Phelan et al. (2015) observed a reduction in $\overline{T}_{max}$ of 0.7 °C after increasing both green roof area and the roof albedo. Rosenzweig et al. (2006), concluded that increasing green roof area is more effective than increasing their albedo. Nevertheless, increasing the roof albedo is easier to implement than developing the infrastructure for green roofs in existing urban areas. Since the impact of roof albedo can differ between summer and winter, then some studies propose a controllable roof albedo. This could be achieved by applying a thermochromic coating to the roof (Phelan et al., 2015). Furthermore, higher roof albedos are only desirable in cities that are located in warm climates or during the summertime (Phelan et al., 2015). Increased green cover and roof albedos are also more efficient in dry regions as mitigation strategies, while tropical cities require alternative solutions (Manoli et al., 2019). Hence, we propose that the term effectiveness should be associated with many factors, such as the purpose, the costs of installation and maintenance, the climatic conditions in the installed region, and the irrigation systems, and not just with the reduction in temperature.

3.2.5. *Significance of CBD building height on heat indices*

High-rise buildings promote vertical living in a growing urban population. The thermal properties of building materials can alter an area's surrounding temperature and influence the thermal comfort of the building (Deosthali, 1999). This section investigates how different building heights can influence heat indices. The aspect ratio (building height/canyon width) was also adjusted after changing the building height so that the width of the canyon was held constant. For all simulations, we use a wall albedo of 0.3 and a wall emissivity of 0.85. The emissivity of materials storing heat within the building (i.e., internal floors and walls) was set to 0.9.

Table 3 represents a comparison between building height scenarios in CBD and BSL. The results are shown in Fig. 8, where we consider building heights up to 50 m. Taller buildings were not considered due to a limitation within TAPM (constrained by a 10 m difference between the first atmospheric level compared to the displacement height associated with the urban area). The results in Fig. 8 show a peak temperature for 30 m tall buildings. Tall building structures can disturb wind flow and circulation and therefore influence the surrounding microclimate. Buildings of 30 stories or more have been shown to impact the vertical temperature lapse rate (Li & Donn, 2017). Local climate zones (LCZ) are expected to depend on parameters such as surface emissivity, albedo, roughness length, building height, vegetation ratio, anthropogenic heat, initial boundary-layer height (Li & Donn, 2017).

Shades from high-rise buildings promote a cooling effect in the urban canyon, while walls can absorb and store more heat. Several studies have demonstrated that the air temperature is lower for high-rise buildings and that the thermal comfort (measured through the predicted mean vote, PMV), is also improved due to the effect of shading (Perini & Magliocco, 2014; Yang et al., 2017). Narrow streets with tall buildings and shade trees are considered to promote the most comfortable conditions in tropical cities (Johansson & Emmanuel, 2006). Yang and Li (2015) observed a cooler urban street temperature with a small daily amplitude in the high-rise, high-density area as opposed to the low-rise, low-density urban area. However, a study conducted in Narmak (Tehran) observed an increase in the daily average air temperature by 1.38 °C, and stated that higher buildings could possibly increase the land surface temperature, which leads to UHI (Rad et al., 2017).

Mechanisms to explain the reduced temperatures for 50 m building compared to 30 m buildings shown in Fig. 8 are being investigated, although no firm conclusions have been reached to-date. However, the result is likely to be a consequence of competing influences such as shading, or changes in turbulent mixing due to tall buildings.

3.3. *Limitations of the study*

The required urban surface parametric data for this study, as TAPM model input, was adopted from a previous study in Melbourne by Coutts et al. which was produced in 2007. This was the most recent reliable data available for Melbourne. The higher warm bias reported in maximum temperature in model validation could have resulted from this temporal mismatch between the surface parameters and the 2019 climate data; although not confirmed in this study. Furthermore, this study result is based on one summer in 2019, which was the warmest year on record in Australia. The study may be extended to year-round or multiple years in the future, which will help eliminate the impact of climate variability.

4. Conclusions

This investigation performed a sensitivity, relation analysis to compare the effectiveness of different urban surface parameters in different mitigation perspectives in adapting to excessive urban heat. This included considerations of the types of vegetation, the area fraction of vegetation, the use of green roofs for increasing vegetation area, built-cover area and building height, as well as the albedo of cool roofs for assessing the surface characteristics. A mesoscale climate model, TAPM, was used to simulate the austral summer (DJF) in Melbourne, Australia. By taking the Melbourne metropolitan area as a case study, this study filled empirical gaps in simulating the heat mitigation performance of urban surface characteristics at a large spatial scale, which is important for supporting city-level planning and policymaking.

As the first phase of analysis, we calculated each scenario's heating/cooling potential using different heat indices. Natural vegetation scenarios with 100 % cover of grassland, shrubland, and forest, performed the best for $\overline{T}_{min}$, attested to natural vegetation's cooling characteristics. However, these are unrealistic scenarios for mitigating urban heat. When considering more realistic urban scenarios, we found that increasing the roof albedo up to 0.85 in CBD achieved the maximum reduction in $\overline{T}_{max}$ (−1.29 °C), and 100 % green roof area scenario in CBD achieved the maximum reduction in $\overline{T}_{min}$ (−1.15 °C). When only the roof albedos were changed in CBD and both the CBD and UG areas, the number of hot days- HDs (>35 °C) and very hot days- VHDs (>40 °C) were reduced (23 % and 50 %, respectively) to the level of grassland and shrubland (hot days = 10 and very hot days = 1 over the summer period). Converting the total roof area (100 %) to green roofs, provided a 43 % reduction in hot nights (>20 °C). Employing different methods to represent urban vegetation had a significant impact on the simulation results, where using vegetation that is strongly coupled to the urban canyon resulted in a much higher temperature. This result may suggest that collecting vegetation in parks away from urban walls and impervious surfaces might be more effective, although a more detailed analysis of how vegetation is parameterized will be required.

In reality, no city can establish 100 % cool roofs or green roofs. Therefore, we performed a correlation analysis to identify the relationship between the ratios of the parameters and the heat reduction/temperature variance. The CBD's building heights did not result in a statistically significant relationship between the height and the temperature change. A negative linear correlation was observed between the urban vegetation ratio in CBD and $\overline{T}_{min}$, ($r \approx -1$ for $\overline{T}_{min}$)was observed. The vegetation ratio ($\overline{T}_{max}$ and $\overline{T}_{min}$ in UG), green roofs ($\overline{T}_{max}$ and $\overline{T}_{min}$ in both CBD and UG), and cool roofs (for $\overline{T}_{max}$ CBD and UG) also demonstrated strong, near-linear negative relationships with $r = -0.99$. These results indicate that any increase in vegetation or cool roofs will provide a proportional benefit to cooling the microclimate regardless of their current level of cover. Moreover, it is essential to consider improving the surface characteristics in the overall city regardless of UG or CBD when planning strategies for thermal performances, imagining every change count. Green surfaces are the most effective option for heat mitigation at nights, while cool roofs appear to be most effective in daytime, indicating the importance of strategically combining different surface parameters to achieve a maximum cooling impact in practice.

Declaration of Competing Interest

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

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Appendix A

Table A1
Characteristics of tested urban scenarios for the Melbourne metropolitan area (*scenarios for 100 % vegetation inside the canyon; ǁ values for CBD; + values for green roofs).

Strategy	Urban scenario	Type name	Vegetation type	Vegetation area %	Building cover %	Green roof %	LAI-Canyon	Average building height	H/W ratio
Baseline	Urban generic	BSL	Mixed	38, 15[ǁ] (Coutts et al., 2007)	45, 65[ǁ] (Coutts et al., 2007)	–	3	6.0	0.4
Change the whole modeling area	Grassland	Grassland	Mid-dense tussock	100	–	–	1.2	0	0
	Shrubland	Shrubland	Tall mid-dense scrub	100	–	–	2.6	0	0
	Forest	Forest	Low sparse woodland	100	–	–	2	0	0
Changing UG conditions									
Change vegetation	1/2 of vegetation	UGv19	Mixed	19	45	–	3	6.0	0.4
	1/3 of vegetation	UGv13	Mixed	13	45	–	3	6.0	0.4
	30 % of vegetation	UGv30		30	45				
	45 % of vegetation	UGv45	Mixed	45	45	–	3	6.0	0.4
Change built-up ratio	1/2 of building cover	UGb23	Mixed	38	23	–	3	6.0	0.4
	35 % of building	UGb35	Mixed	38	35	–	3	6.0	0.4
	40 % of building	UGb40	Mixed	38	40	–	3	6.0	0.4
	50 % of building	UGb50	Mixed	38	50	–	3	6.0	0.4
	55 % of building	UGb55	Mixed	38	55	–	3	6.0	0.4
Change both vegetation & built-up	Leafy urban	UGb40v49	Mixed	49 (Chen et al., 2014)	40 (Chen et al., 2014)	–	3	6.0	0.4
	50 % of building	UGb50v30	Mixed	30	50	–	3	6.0	0.4
	60 % of building	UGb60v20	Mixed	20	60	–	3	6.0	0.4
Green roofs	25 % GR	UGgr25	Mixed	38	45	25	3, 1.5[+]	6.0	0.4
	50 % GR	UGgr50	Mixed	38	45	50	3, 1.5[+]	6.0	0.4
	75 % GR	UGgr75	Mixed	38	45	75	3, 1.5[+]	6.0	0.4
	100 % GR	UGgr100	Mixed	38	45	100	3, 1.5[+]	6.0	0.4
Cool roofs General BSL value is 0.20	0.50	UGa50	Mixed	38	45	25	3	6.0	0.4
	0.70	UGa70	Mixed	38	45	50	3	6.0	0.4
	0.85	UGa85	Mixed	38	45	75	3	6.0	0.4
	0.50 in both CBD & UG	Botha	Mixed	38	45	100	3	6.0, 18.0[ǁ]	0.4, 2.0[ǁ]
Changing CBD conditions									
Change vegetation (50:50 canyon:off canyon)	Zero vegetation	CBDv0	Mixed	0	65	–	3	18.0	2.0
	8 % (half) vegetation	CBDv8	Mixed	8	65	–	3	18.0	2.0
	10 % vegetation	CBDv10	Mixed	10	65	–	3	18.0	2.0
	20 % vegetation	CDBv20	Mixed	20	65	–	3	18.0	2.0
	30 % (double) Vegetation	CBDv30	Mixed	30	65	–	3	18.0	2.0
Change vegetation (100 % inside the canyon)	Zero vegetation	CBDv0*	Mixed	0	65	–	3	18.0	2.0
	8 % (half) vegetation	CBDv8*	Mixed	8	65	–	3	18.0	2.0
	10 % vegetation	CBDv10*	Mixed	10	65	–	3	18.0	2.0
	15 % vegetation	CBDv15*	Mixed	15	65	–	3	18.0	2.0

(continued on next page)

Table A1 (*continued*)

Strategy	Urban scenario	Type name	Vegetation type	Vegetation area %	Building cover %	Green roof %	LAI-Canyon	Average building height	H/W ratio
	20 % vegetation	CDBv20*	Mixed	20	65	–	3	18.0	2.0
	30 % (double) Vegetation	CBDv30*	Mixed	30	65	–	3	18.0	2.0
	33 % (half) building cover	CBDb33	Mixed	15	33	–	3	18.0	2.0
Change built-up ratio	40 % building	CBDb40	Mixed	15	40	–	3	18.0	2.0
	50 % building	CBDb50	Mixed	15	50	–	3	18.0	2.0
	70 % building	CBDb70	Mixed	15	70	–	3	18.0	2.0
Change both vegetation & built-up	Doubled vegetation and 50 % building	CBDb50v30	Mixed	30	50	–	3	18.0	2.0
Green roofs	25 % GR	CBDgr25	Mixed	15	65	25	3, 1.5$^+$	18.0	2.0
	50 % GR	CBDgr50	Mixed	15	65	50	3, 1.5$^+$	18.0	2.0
	75 % GR	CBDgr75	Mixed	15	65	75	3, 1.5$^+$	18.0	2.0
	100 % GR	CBDgr100	Mixed	15	65	75	3, 1.5$^+$	18.0	2.0
Cool roofs (change albedo)	0.50 roof albedo	CBDa50	Mixed	15	65	75	3	18.0	2.0
	0.70 roof albedo	CBDa70	Mixed	15	65	75	3	18.0	2.0
	0.85 roof albedo	CBDa85	Mixed	15	65	75	3	18.0	2.0
Change building heights	12 m buildings	CBDbh12	Mixed	15	65	75	3	12.0	1.33
	20 m buildings	CBDbh20	Mixed	15	65	75	3	20.0	2.23
	30 m buildings	CBDbh30	Mixed	15	65	75	3	30.0	3.34
	40 m buildings	CBDbh40	Mixed	15	65	75	3	40.0	4.45
	50 m buildings	CBDbh50	Mixed	15	65	75	3	50.0	5.56

Appendix B

a) Model Initialization

To ensure an appropriate spin-up time was employed for the simulations, we measured the time for the model to reach a statistical equilibrium in terms of 2 m air temperature. General urban conditions were modelled in the time frames of 1, 3, 6, and 12 months, and the T_{max} and T_{min} are plotted in Fig. B1.

Daily T_{max} and T_{min} for the timeframes of 3, 6, and 12 months (3 mx, 6 mx, 12 mx) predicted outcomes when compared to one-month (1 mx) spun-up time-frames. All results for T_{min} were found to be similar for all the spin-up time-frames considered. There are about 9 days on which the 1-month spin-up is about 1 degree lower for T_{max} than for the 12-month or 3-month spin-up periods. This corresponds to approximately 10 % for the entire DJF season. Hence, 1 month is considered inadequate for model stabilization. Based on these observations, a 3-month time frame was selected for the model spin-up.

b) Model Validation

Fig. B2A and B show strong R^2 values, 0.788 and 0.709 for T_{max} and T_{min}, respectively, proving the model's quality of fit. Fig. B2C and D represent the Quantile-Quantile (Q-Q) plots of the SIM (predicted) versus OBS station data for T_{max} and T_{min}, respectively. Overall, they indicate that the predicted daily maximum (or minimum) temperature values follow a similar distribution as observed counterparts. However, there is some inconsistency for T_{max} when T_{max} <32, which is not a major concern as these heat indices focus on T_{max} >35. By considering the above results, TAPM is confirmed as a valid model for this evaluation study.

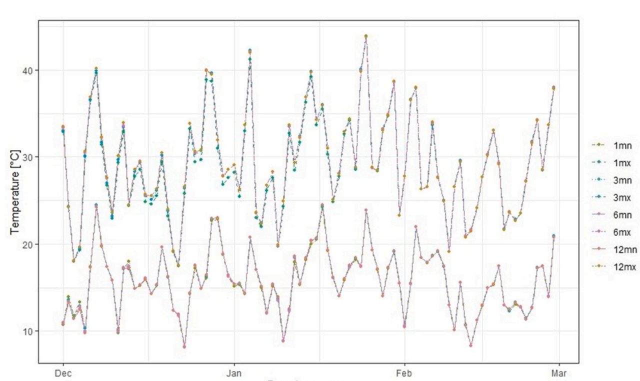

Fig. B1. Modelled temperature values for different time windows for the spin-up time (1mn, 3mn, 6mn, and 12 mn are the minimum temperatures for the timeframe, denoted by each number of months. 1 mx, 3 mx, 6 mx, and 12 mx are the maximum temperatures).

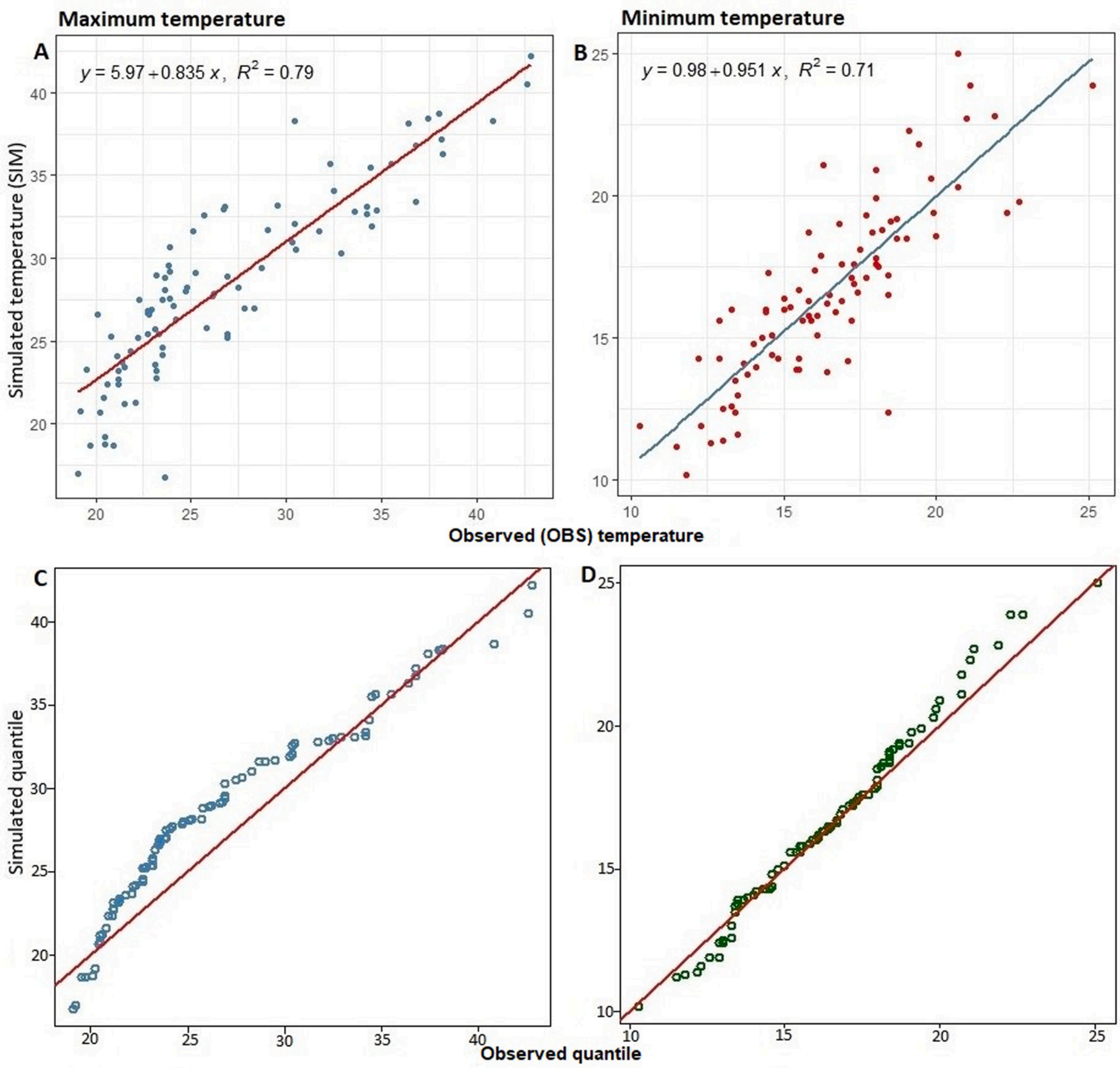

Fig. B2. Graphical statistical summary (A: R2 for T_{max} ; B: R2 for T_{min} ; C: Q-Q plot for T_{max}: and D: Q-Q plot for T_{min}.

Appendix C

Table C1
Change of temperature means and vegetation characteristics used in TAPM.

Vegetation type	BSL –	Grassland Mid-dense tussock	Shrubland Tall mid-dense scrub	Forest Low sparse woodland
Vegetation height (m)	–	0.6	3.0	5.5
Fraction of surface covered by vegetation	–	0.50	0.50	0.25
Leaf area index (LAI)	–	1.2	2.6	2.0
Minimum stomatal resistance (m^{-1})	–	80	160	110

Table C2
Vegetation characteristics for used urban forms in Melbourne.

Parametric data	31: Urban generic (UG)	35: Urban CBD (CBD)
Vegetation heights (m)	10	20
Fraction of surface covered by vegetation - σ_f	0.75	0.75
LAI	2.0	2.0
Minimum stomatal resistance r_{si} (m^{-1})	100	100

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Chapter 4

"Humanity is sitting on a time bomb. If the vast majority of the world's scientists are right, we have just ten years to avert a major catastrophe that could send our entire planet's climate system into a tail-spin of epic destruction involving extreme weather, floods, droughts, epidemics and killer heat waves beyond anything we have ever experienced – a catastrophe of our own making."

Al Gore

A Former American Vice President and environmentalist

Australian National University

Statement of Contribution

This thesis is submitted as a Thesis by Compilation in accordance with https://policies.anu.edu.au/ppl/document/ANUP_003405

I declare that the research presented in this Thesis represents original work that I carried out during my candidature at the Australian National University, except for contributions to multi-author papers incorporated in the Thesis where my contributions are specified in this Statement of Contribution.

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Prabhasri Herath		22 May 2023
Candidate	**Signature**	**Date**

Endorsed

Primary Supervisor – Xuemei Bai	**Signature**	**Date**: 22 May 2023
Delegated Authority – Rob Dyball	**Signature**	**Date**: 23 May 2023

4. Evaluate the combinations of different heat mitigation solutions to maximise the effectiveness as operationalisable strategies in real-world cities.

Comparing the cooling effectiveness of operationalisable urban surface combination scenarios for summer heat mitigation

Abstract

Extreme summer heat in cities exacerbates the vulnerability of urban communities to heatwaves. Vegetative and reflective urban surfaces can help reduce urban heat. This study investigated the impacts of urban trees, green roofs and cool roofs on heat mitigation during average and extreme summer conditions in temperate oceanic Melbourne, Australia. We simulated the city climate using 'The Air Pollution Model' (TAPM) at a 1 km spatial resolution over 10 years, which according to our review of the literature, was the most prolonged period for simulation in Melbourne. During a widespread heatwave event, some of the tested scenarios with combined surface parameters could reduce the extreme values of the energy budget components- sensible heat, latent heat, and storage heat fluxes up to seasonal averages compared to the existing situation for Melbourne (control). The scenario with the highest (reasonable maximum) ground-level vegetation, green roofs, and cool roofs could reduce air temperatures up to 2.4°C. The simulations suggest that a combined strategy with vegetative and high-albedo surfaces will deliver higher effectiveness with maximum cooling benefits, and cost-effectiveness than individual strategies in cities. These results suggest the importance of collaborative strategic planning of urban surfaces to make cities healthier, sustainable, and liveable.

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Comparing the cooling effectiveness of operationalisable urban surface combination scenarios for summer heat mitigation

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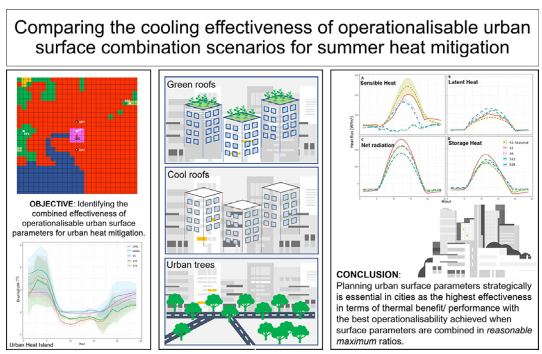
HIGHLIGHTS

- 18 scenarios were simulated over 10 years to determine the cooling effectiveness in Melbourne.
- Different urban surface parameters: vegetation cover, green & cool roof levels were used.
- Effectiveness of scenarios needs to be defined with both thermal and operational factors.
- Higher reductions observed for average & extreme summer heat with combined parameters.
- Hence, combined scenarios were found to be the most effective and operationalisable.

GRAPHICAL ABSTRACT



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ABSTRACT

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1. Introduction

A high concentration of population and urban functions intensifies the consequences of extreme heat in cities (Fischer et al., 2012). Heatwaves are critical extreme heat events in cities that directly affect the thermal comfort of city occupants while overloading every sector, such as energy, health, economy, environment, and critical social infrastructure (WHO,

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2018a; WHO, 2018b; AECOM, 2012; Hou et al., 2014; Ali et al., 2013; Wondmagegn et al., 2021). Extreme heat events persist for three or more consecutive days with high and unusual maximum and minimum temperatures at a particular location are defined as heatwaves (BoM, 2016). They are meteorological events driven by a persistent high-pressure system coupled with low soil moisture on the land surface (dominant sensible heat fluxes over latent in dry soil) (Perkins, 2015). Climate change has increased the likelihood and severity of heatwaves worldwide (Schiermeier, 2019; Phillips, 2020; Schiermeier, 2021; Coutts et al., 2007). Melbourne's maximum and minimum temperatures reached 45.1 °C and 25.7 °C, respectively, during the 2009- South-eastern Australian heatwave (VAGO, 2014). The health impacts of heatwaves are magnifying with increased maximum temperature during the day and more pronounced at night with elevated minimum temperatures (Williams et al., 2012). Urban Heat Island (UHI) effect is a microclimate phenomenon due to surface energy balance alterations, where near-surface air temperatures in cities are hotter than in adjacent non-urban areas (Roth, 2013). When UHI occurs during summer heatwaves (with low surface moisture and wind speeds (Li and Bou-Zeid, 2013), it can escalate the heatwave severity and increases health and human thermal comfort issues with intensified temperatures (Kueh et al., 2017). Therefore, investigating mitigation and adaptation strategies for extreme heat as well as UHI in cities is essential for a changing climate context.

Urban microclimate is determined by both natural and built environment-related (direct and indirect) factors. Natural factors range from latitude to elevation loss/gain, water bodies and natural land use, including wind direction and speed, air temperature, humidity, solar radiation, precipitation, soil type, greenery, to terrain conditions. The built environment factors include building materials, height, shape, colour, texture, urban green cover, canyons, built-up and open area ratio, anthropogenic water bodies and population density (Giyasova, 2021; Bherwani et al., 2020). Larger microclimates, such as cities, also reflect the influences back on temperature, wind, rainfall, snowfall, and air pressure (Shi et al., 2017; Patricola and Wehner, 2018; Rogers, 2018; Zhang et al., 2018). Inefficient evaporative cooling or reduced latent heat fluxes from insufficient green spaces and the aerodynamics of urban surface parameters cause changes in the energy budget that increase the surface temperature (Li et al., 2019; Zhao et al., 2014). Urban surface characteristics, such as vegetation cover, thermal properties of construction materials, density, form and fabric of buildings, city size, synoptic conditions, wind speed and flow, and anthropogenic heat, all act as drivers of UHIs (Oke et al., 1991; Zhou et al., 2017; Li et al., 2020).

Many studies have found a high correlation between urban heat and surface characteristics (Rogers, 2018; Zhang et al., 2018). Several strategic efforts on microclimatic heat mitigation via manipulating the above surface characteristics with urban planning and design measures have been highlighted in the literature. One example is applying engineering solutions with cool construction materials (low heat conductivity, low heat capacity, high solar reflectance and high permeability). This measure results in less heat absorption and storage during the day and subsequently low night heat emission. Another second example is using green infrastructure (GI) to reduce heat via evapotranspiration. Capturing solar energy for electricity generation, building underground, and leaving spaces between buildings are other proposed strategies in literature (Yenneti, 2020; Zeder, 2015; Yenneti et al., 2017). Retention of heat with water-sensitive urban designs is a useful mitigation strategy. Studies found water-sensitive urban designs can be useful as they hold and retain the excess heat. We found evidence that urban water bodies for reducing ambient air and land surface temperatures by 1–7 °C temperatures, depending on the season and the distance from the water body (Yenneti, 2020; Gupta et al., 2019; Jacobs et al., 2020). This is primarily due to the high heat capacity and evaporative cooling of water bodies. However, Theeuwes et al. showed that increased humidity during evaporation from waterbodies (when the water is warmer than the air temperature) may limit the cooling and thermal comfort or even increase the air temperature (Theeuwes et al., 2013). It has been demonstrated that individual independent design strategies are effective for different regions and climate zones (Jamei et al., 2021). Given that roofs and pavements (impervious surfaces) can cover around 60–90 % of urban surfaces in an urban area (Akbari et al., 2009; Stewart and Oke, 2012), changing their surface characteristics (e.g., increase surface albedos to reflect more light or enhance evaporative cooling using cool roofs and green roofs) could be a highly viable, effective option (Herath et al., 2021; Zinzi and Agnoli, 2012; Xing and Jones, 2019; Morini et al., 2018; Oswald et al., 2020; Herath et al., 2018a; Imran et al., 2018). Moreover, promoting vegetative surfaces by increasing street trees, urban parks, and other green spaces generally lowers the temperature by evapotranspiration and shade (Li and Norford, 2016; Imran et al., 2019a; Bowler et al., 2010; Richards et al., 2019), and also limits with some conditions such as irrigation and changes in urban aerodynamics with overcrowded urban trees (Heusinger et al., 2018; Park et al., 2019; Meili et al., 2021). Therefore, heat mitigation strategies for cities should be comprehensively planned and investigated to achieve expected outcomes.

In Australia, the death toll from heatwaves has exceeded that of any other natural environmental disaster (including bushfires, floods and cyclones) (DEA, 2020). Over 36,000 deaths were recorded associated with heat during 2006–2017, which was 2 % of total deaths in Australia (Longden et al., 2020). Some modelling results predict that future extreme heat events will increase in severity, duration, and frequency (Cowan et al., 2014). The occurrence of heatwaves in Melbourne, for example, has been frequent for the last two decades (Perkins-Kirkpatrick et al., 2016). Melbourne experienced a deadly, record-breaking heatwave in the summer of 2009, followed by another in 2014. With 1.52 °C above-average temperatures, 2019 was reported as the warmest year on record (BoM, 2020b). Several modelling studies on Australia have been conducted to find feasible mitigation strategies that minimise excessive heat. However, most studies have a limited scope because they consider a single event (either heatwaves or UHI) or a limited period of a single year (Zeder, 2015), except for Imran et al. (Imran et al., 2019b). Most studies on Melbourne have focused on the heatwaves in 2009, 2012, or 2014 (AECOM, 2012; Cowan et al., 2014; Morris et al., 2001). Jacobs et al. found a non-synergistic relationship between the cooling effect and the combined scenarios in an analysis focused on cool roofs and urban vegetation, using the Weather Research and Forecasting Model (WRF) in Melbourne (Jacobs et al., 2018). Chapman et al. performed a multi-year study by using the Conformal Cubic Atmospheric Model (CCAM) with urban vegetation and building density for Brisbane (Chapman et al., 2018) and found that vegetation cover had a more substantial impact on temperature than the building height and aspect ratio. Studies have also shown a significant increase in future nighttime UHIs with urban growth. For example, using The Air Pollution Model (TAPM), Coutts et al. showed nighttime UHI intensity would increase by 2030 with growing urban density (Coutts et al., 2008), and Imran et al. showed an increase in UHI in the range of 0.75–5.4 °C over the modelling area during the night, with predicted urban expansion by 2050 (Imran et al., 2019b).

The key objective of this study was to identify the combined effectiveness of different cooling strategies in terms of operationalisability for urban heat mitigation, using Melbourne as a case study. Since each city has a unique microclimate (Martilli et al., 2020; Masoudi et al., 2019), there are no one-size-fits-all planning solutions, and each city needs to identify their context-specific greening strategies for urban heat adaptation and mitigation. As one theory stated by Martilli et al. (Martilli et al., 2020), urban heat mitigation strategies do not define by the UHI intensity, and suggested as heat mitigation studies should shift beyond UHI mitigation to focus on the temperature difference between different urban areas instead of urban-rural based on recommendations of Stewart and Oke (2012). Therefore, this study presents empirical evidence in a mesoscale atmospheric model for Melbourne that tries a city-specific greening plan with operationalisable heat mitigation strategies which assessed with both urban-rural and urban-urban (between different Local Climate Zones-LCZs) gradients. The Melbourne metropolis was simulated in TAPM mesoscale atmospheric model to systematically investigate the combined impact of a mixed land use, land cover and surface properties: ground-level vegetation, green roofs, and cool roofs on several heat-related indices. This was to assess the effectiveness of the combined surface parameters with their maximum heat reduction potential. For that, we investigated the diurnal thermal behaviour with air temperature and energy budget variations under different climatic conditions such as extreme and seasonal heat conditions. This study used 18 scenarios over 10 simulation years, a much larger sample size over a longer period than prior simulation studies. This approach was important for clarifying the combined impact of the different surface properties, as well as minimising the impact of year-to-year climate variability and improving the confidence interval, thereby providing more robust and rigorous results.

2. Methods

2.1. Study area

Melbourne covers 3770 ha and is the second-most populous city in Oceania. Approximately 854,000 people use the city daily, on average (City of Melbourne, 2017). Following the classification of LCZs (Stewart and Oke, 2012), Melbourne CBD represents a compact high-rise (LCZ1) build type while surrounding general urban areas exhibit compact low-rise (LCZ3) and open low-rise (LCZ6) with different land-use types (Fig. 1B). Melbourne has a temperate oceanic climate (Cfb) according to the Köppen climate classification. Melbourne's summer climate (December–February) is changeable with frequent hot and dry days with cold and wet spells, experiencing the highest mean monthly maximum temperature and an average 9 h duration of daily sunshine. The maximum (T_{max}) and minimum (T_{min}) temperatures ranged respectively from 24.2 to 26 °C and 13 to 14.6 °C (Site 086071), based on data from 1855 to 2015 (BoM, 2020a). Heat-related incidents, such as the UHI effect and heatwaves, are often observed in Melbourne. The highest summer T_{max} recorded was 46.4 °C on 7 February 2009 (Osmond et al., 2017). The Bureau of Meteorology (BoM) reported, on average, 30 days per year exceeding 30 °C (BoM, 2020a). The Melbourne UHI was recorded as 1.13 °C in 2001 (Morris et al., 2001); the central business district (CBD) reported 0.8 °C of UHI effect when non-CBD areas had a 30 °C day in 2012 (AECOM, 2012). UHI for land surface temperature varies from −7.16 to 10.2 °C in different metropolitan locations (Sun et al., 2019). These recent observations suggest that Melbourne might increase in density in terms of population and built-up areas in future and that the city should support this urban expansion while ensuring thermal comfort and liveability.

2.2. Model configuration

TAPM, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia, was used in this study, and it dynamically downscales the three-dimensional meteorology and air pollution concentration to high spatial and temporal resolution over a small area (Hurley, 2008a). TAPM occupies an incompressible, non-hydrostatic, primitive equation model in its meteorological component, which supports the three-dimensional simulations with terrain-following vertical coordinates. A series of equations (momentum, incompressible continuity and scalar equations with turbulence kinetic energy and eddy dissipation rate) simulate different meteorological components, including horizontal and vertical wind flow and velocity, potential virtual temperature and specific humidity (Hurley, 2008b). In mesoscale modelling, urban parameterisations help to account for the area-average effect of urban interactions, including drag, turbulence production, heating, and the surface energy budget modification induced by buildings and urban land use (Brown, 2000). TAPM mesoscale modelling has also been coupled with the Urban Climate and Energy Model (UCLEM) to support this urban parameterisation, which is based on an urban canopy model (Thatcher and Hurley, 2012) and a building interior energy model (Lipson et al., 2018), intended to support multi-decade urban climate simulations in a computationally efficient way. Urban parameters in the simulations have been constrained to agree with available observations by Coutts et al. to provide the modelling process with as realistic and accurate parameters as possible for this location. The UCLEM is explicitly designed to represent the interactions between energy use and the urban environment in Australian cities over long time periods (e.g., decades). This model accommodates adjustments by the user for the parameters, including canyon and roof vegetation ratios, building height, density and the thermal and radiative characteristics of the building materials (Thatcher and Hurley, 2012; Lipson et al., 2018). As a result, it secures the mesoscale characterisations of urban surface parameters in large city-scale simulations.

The focus of this study was the urban canopy component of the model, where the canopy model supports 4 layers of building materials for road, roof and two walls, as well as an integrated canyon vegetation model and green roof parameterisation. Air circulation in the canyon for calculating

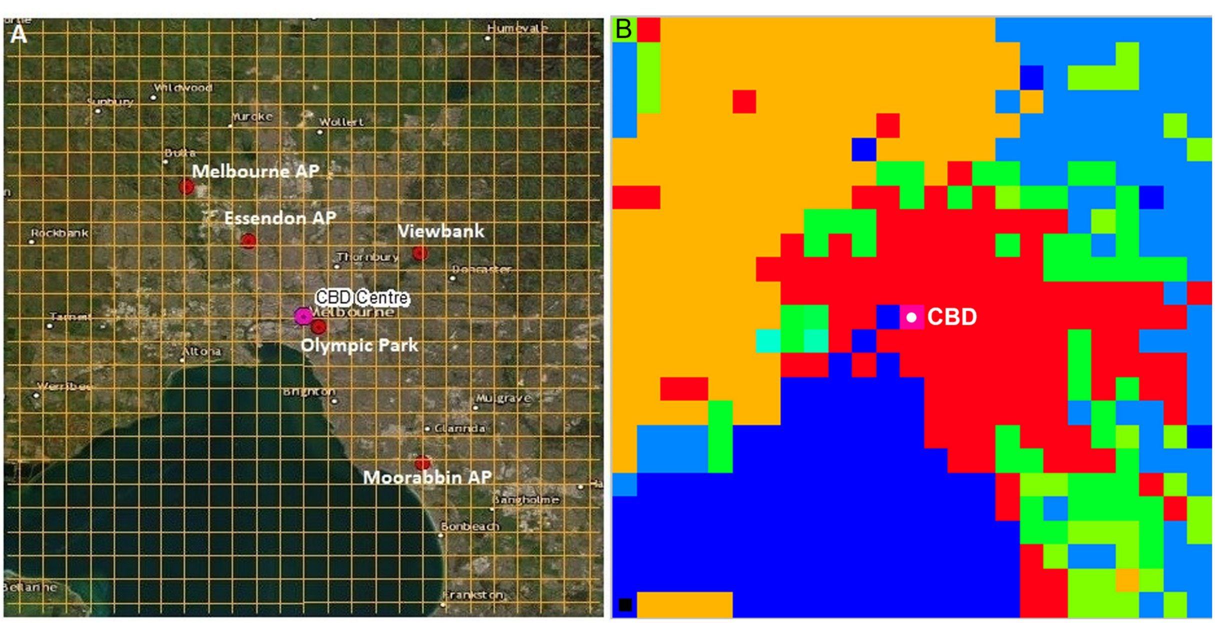

Fig. 1. Grid-level TAPM representation for the Melbourne CBD: A) ArcGIS image with 3 km grids developed for Melbourne with CBD centre and the weather stations used for model calibration, B) TAPM window of Melbourne with 3 km grid levels for different land uses (AP: airport).

turbulent fluxes is based on Harman et al. (Harman et al., 2004), which also facilitates the coupling of turbulent fluxes with the canyon vegetation. To improve the speed of the model over multi-decade timescales, the model employs a simplified big-leaf vegetation canopy parameterisation as well as tracking the vegetation water budget to a depth of 4 m, which provided a solution with reasonable accuracy for modelling latent heat flux despite the reduced number of prognostic variables (Thatcher and Hurley, 2012). The urban vegetation description is consistent with big-leaf canopy models used in climate land-surface models (Kowalczyk et al., 1994). The canyon floor is partitioned into vegetation and road areas, with separate albedo, roughness lengths and energy budget calculations. The canyon geometry is modified to account for changes in sky view factors (SVF) as well as accounting for canyon walls that are obscured by vegetation. This approach limits shading on the canyon floor to the vegetation tile, and there is no direct shading of the road 'tile' by the adjacent vegetation tile. Although there is an impact on the canyon floor due to the reflections of shortwave radiation between the walls, roads, vegetation, and the modified SVF.

Green roof vegetation is also based on a big-leaf canopy model, modifying the roof albedo and roughness length. The green roof water budget is also tracked, although the soil depth of the green roof is limited to 10 cm and thereby limits the maximum available water for evapotranspiration. A simple irrigation scheme was used where soil moisture was relaxed to a value of 75 % of the wilting value and 25 % of the saturated value over a 24-h period. Without irrigation parameterisation, the green roof typically dries out and becomes ineffective for reducing urban temperatures. Heat storage is represented by the roof, wall and road tiles, but not explicitly soil temperatures under the vegetation canopy, although the vegetation canopy has its own energy budget. This means that the model does not provide heating due to the green roofs at night; but instead, heating is provided by the heat stored in the impervious roof building materials. Despite this simplification, the model fluxes were still in reasonable agreement with measurements for Melbourne, Australia (Coutts et al., 2007).

TAPM can run for high-resolution (1 km grid cells) and downscale as 30, 10, 3, and 1 km nesting grid levels and each nesting grid consists of 25 × 25 horizontal grid points. Lateral boundary conditions for the 30 km simulation were provided by NCEP reanalyses (Kanamitsu et al., 2002). Vertically, grids extended up to 8 km above the ground. The relatively small 25 × 25 grid size was motivated by providing a simulation better constrained at the boundaries (i.e., its simulations reasonably match observations from weather stations), and its simulation efficiency is high. The efficiency saved significant computation time over the 10-year simulation period. Some simulations were undertaken with larger grid domains for a) 50 × 50 domain with 1 km × 1 km resolution and b) 25 × 25 with 3 km × 3 km resolution to test whether the predicted temperature changes between two scenarios are independent of the grid size used for the model. TAPM has limitations for choosing big outer grids (e.g., 150 km × 150 km domain at 1 km^2) as it violates model assumptions as discussed in TAPM user manual (Hurley, 2008a). Larger domains are often preferred for reducing the impact of lateral boundaries on the simulation results (Larsen et al., 2013). The 25 × 25 grid configuration was found to produce results more consistent with observations by having a reduced bias (see Appendix B for results). Simulations with the larger domain produced results qualitatively consistent with the predictions of the smaller domain but with increased bias. Hence, the 25 × 25 grid size results are reported in this paper. TAPM uses 38 land-use types based on U.S. Geological Survey data, and Australian terrain height data were obtained from Geoscience Australia. Synoptic-scale meteorological data were obtained from the Australian BoM (Hurley, 2008a). Although a drawback with our study is using a single modelling system, the TAPM results have also been compared with other modelling studies reported in the literature where appropriate.

2.3. Experimental design

While planning the experiments, we considered a sensitivity analysis in the same study area as Herath et al. (Herath et al., 2021). Based on these results, highly correlated urban surface parameters with urban heat were selected as variables, and experiments were designed to evaluate the impacts of urban green infrastructure (UGI) and reflective roofs on temperature indices. Since the CBD has a higher roof density, it is advantageous to use green and cool roofs for strategic adaptation planning. Green roofs are a promising adaptation strategy that provides a cooling effect to surrounding air temperature during day and nighttime, in summer, and during heatwaves across different climatic regions (Herath et al., 2018a; Imran et al., 2018; Herath et al., 2018b; Sharma et al., 2016). In addition, more green roofs associate with a higher reduction of UHI and roof surface temperature (Imran et al., 2018; Sharma et al., 2016). Cool roofs with high-albedo materials reflect more incoming solar radiation and absorb less heat than low-albedo materials during the day (Santamouris et al., 2011; Broadbent et al., 2021). Considering the evidence from Sharma et al. (Sharma et al., 2016) that green and cool roofs efficiently provide more cooling in highly urbanised regions with more roof area, we planned green and cool roofs for high-density Melbourne CBD. Moreover, cool roofs can be an effective solution with proven climate benefits when considering irrigation and other limitations in different case studies (Imran et al., 2018; Sharma et al., 2016). In most studies, highly reflective cool roofs have been modelled with albedo values from 0.65 to 0.9 (Imran et al., 2018; Santamouris et al., 2011; Gul et al., 2018). Evidently, as albedo values increase, cooling capacity increases (Herath et al., 2021), but having albedo higher than 0.85 is unrealistic. Limitations, such as the degradation of coating and roofing materials and the deposition of dirt on roofs, make the higher albedos impossible to implement (Bretz and Akbari, 1997). Considering timely degradation, discoloration, and dirt deposition, a 0.7 albedo is much more practical than extreme albedo values to maintain in an urban context.

Among other significant limitations imposed by costs, maintenance, and irrigation, another potential consideration for Melbourne is the competition of green and cool roofs against solar photovoltaic (PV) systems. Furthermore, a pre-planned and constructed city inevitably faces limitations when introducing new infrastructure by retrofitting the conventional built environment, as the planners have to consider and assess the feasibility of existing infrastructure to design for ecological use. For example, the transformation feasibility of an existing roof to a green roof should be weighed through building and roof characteristics, including the structure and the age of the building, slope and the bearable load of the roof (Joshi et al., 2020; Li and Yeung, 2014). Along with more limitations over implementation, justification for fractional quantities selection of variables is mentioned in detail in Section 4.5. Our prior study in Melbourne showed that green roofs are more effective than cool roofs in temperature mitigation at night and cool roofs provide higher cooling than green roofs during the day (Herath et al., 2021). Considering the trade-offs and the different diurnal effectiveness, we proposed limiting the green roof cover to a maximum of 50 % and allowing cool roofs to occupy the remainder.

The values for the control were adopted on the default values in the TAPM based on Coutts et al. (Coutts et al., 2007). The ratios of the different surface parameters were changed individually and combined to create scenarios (Table 1) to observe the impacts on the temperature variables. Every scenario was simulated with TAPM for 10 years, from 2011 to 2020. As discussed in the introduction and Section 4.5, some representation of irrigation is required; otherwise, the green roof dries out, and the vegetation is ineffective at cooling. Here irrigation is represented by a simple relaxation system that restores soil moisture to 75 % of the wilting and 25 % of the saturated soil moisture over a period of 24 h.

3. Model calibration

As depicted in Fig. 1, the grid centre was placed at the coordinates aforementioned CBD centre (37.8146°S, 144.9632°E). The modelling area was downscaled over 4 levels of 30, 10, 3, and 1 km nesting grids. All simulations used 1 month of spin-up time to minimise the impacts of the initial conditions. In the simulations, the ability of the TAPM to reproduce the meteorological and energy budget values was verified by model calibration. We have validated all the aspects of TAPM in normal conditions. The

Table 1
Experimental design for planning scenarios, including parameters for representing ground-level vegetation (T), green roofs (G), and changes to albedo to represent cool roofs (C).

Scenario name	Description of changing parameters		
	Urban trees - T (%)	Green roofs - G (%)	Cool roofs – C (Roof albedo)
S1 (control)	0	0	0.2
S2	0	0	0.45
S3	0	0	0.7
S4	0	25	0.2
S5	0	25	0.45
S6	0	25	0.7
S7	0	50	0.2
S8	0	50	0.45
S9	0	50	0.7
S10	5	0	0.2
S11	5	0	0.45
S12	5	0	0.7
S13	5	25	0.2
S14	5	25	0.45
S15	5	25	0.7
S16	5	50	0.2
S17	5	50	0.45
S18	5	50	0.7

green roof model has not been evaluated against observed data for Melbourne, although the parameters are based on values used by vegetation parameterisations from the literature. This is appropriate as process-based model predictions, which can be improved with real-world field tests in Melbourne. Therefore, the simulated (SIM) daily T_{max} and T_{min} values for 2 m above ground from the TAPM were compared with observational data (OBS) from five weather stations (WS) around the Melbourne metropolis for every 3 summer months from 2011 to 2020 (Fig. 1A, Table 2). For the observed data for T_{max} and T_{min}, each WS was directly obtained from the BoM databases measured daily for 24 h starting at 9 am. Simulated data were extracted from the corresponding or closest grid cross points in the TAPM. The corresponding data points from SIM were removed to OBS missing data in some WSs from the calculations.

The model proved to be valid for simulating Melbourne, with the smaller mean bias values for T_{max} and T_{min} of 0.19 and −0.16 °C, respectively. Therefore, the daily summer T_{max} from the model was 0.19 °C warmer than the observations, and the modelled daily T_{min} was 0.16 °C cooler. The highest bias for T_{max} was observed at Olympic Park WS, and Melbourne Airport reported the highest bias for T_{min}. Among statistic model evaluation metrics, we used mean absolute error – MAE (which measures the average magnitude of the errors in predictions without considering their direction) and coefficient of determination - R^2 (which shows the goodness of fit of the model). With MAE, the average absolute differences between the observed values and the predicted values are 2.22 for T_{max} and 1.66 for T_{min}. Both values generally represent low values which prove the ability of the model to fit the dataset. From R^2 for T_{max} of 80.07 % reveals that 80 % of the variability observed in the T_{max} variable is explained by the model, while 64.78 % of the variability is explained by the model for T_{min}.

4. Results and discussion

4.1. Overview

This section presents the analysis of results with extracted data from the finest grid level- 1 km and uses multiple temperature-related indices such as UHI, T_{ave}, T_{air}, T_{max} and T_{min} where necessary. First, all scenarios were compared with the control (S1) for UHI reduction and then for temperature variable changes. Next, each pair was compared to determine their different behaviours with temperature averages for the CBD. The average summer temperature (T_{ave}) was used as one of the temperature variables and was calculated from the daily simulated temperatures from 2011 to 2020. Finally, the 2 m air temperature (T_{air}), wind speed, latent heat, and sensible heat flux in the modelling area were compared with the control in three selected heatwave events for the scenarios with better performance.

4.2. Average seasonal Urban Heat Island effect in Melbourne

Since the UHI effect intensifies the negative thermal consequences during heatwaves, as mentioned above, this paper observed the difference between UHI temperatures for seasonal and during heatwaves. The most recent and accessible evidence for UHI Melbourne is based on 2018 vegetation cover and land surface temperature (LST) from Landsat 8 thermal infrared data (Sun et al., 2019). According to that study, the average UHI_LST in Melbourne ranges from −7.16 °C to 10.20 °C over different local government areas. Here we calculate the UHI for 2 m above ground air temperature using mesoscale modelling results as seasonal average UHI over 10 years.

In most scenarios, the existing UHI values exhibited statistically significant reductions. For example, S18 reduced the existing average UHI by 2.19 °C with a range of 0.94–3.92 °C. This reduction was mostly due to the drop in storage heat fluxes resulting in heat emissions at night. The statistical analysis that used ANOVA and the mean comparison that used Dunnett's method (S1 control) indicated significant differences ($p < 0.0001$) between the means of UHI (Table 3). Furthermore, these results coincide with the earlier findings of Imran et al. and Jacobs et al. for the Melbourne metropolitan area (Jacobs et al., 2018; Imran et al., 2018).

After validation, daily summer T_{min} values were extracted (as the most decisive impact of UHI is observed during the evening and nighttime (Martilli et al., 2020)) from the 1 km grid-level simulations. Temperature differences with T_{ave} were observed over 10 years for each scenario in the selected urban and rural areas. The UHI for Melbourne was calculated as the difference between the temperatures of the urban point (UP) and rural point (RP): UHI = T_{UP} - T_{RP}. For the analysis, to represent different urban characteristics, we extracted data from three locations: the CBD (CBD centre), UP1, and UP2 (inland and coastal points, respectively, in the urban generic [UG] area) from the same cross-section (Fig. 2). The daily T_{min} from the selected UP and two rural points (RP1 and RP2) were extracted from 2011 to 2020. Land-use characteristics of the CBD are represented by UP, while RP1 and RP2 describe different natural land-use types to interpret non-urban characteristics. The selection of RP1 was made purposely to locate in the same cross-section as UP and represents the ‘shrubland: low mid-dense’ land-use type. For RP2, inland ‘grasslands with mid-

Table 2
Bias of maximum and minimum temperatures (T_{max}, T_{min}), calculated between the simulated and observed weather station values of the control scenarios from 2011 to 2020.

Weather station		Temperature bias (°C)		MAE		R^2%		Data availability %	
Name	ID	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}
Olympic Park	86338	1.52	0.20	2.43	1.29	79.65	70.76	100	100
Melbourne Airport	86282	−0.59	−0.73	2.24	1.86	79.17	63.60	100	100
Viewbank	86068	−0.42	0.61	1.98	1.70	81.93	67.92	100	99.2
Essendon Airport	86038	0.71	−0.39	2.31	1.74	79.23	64.15	99.8	99.8
Moorabbin Airport	86077	−0.29	−0.50	2.13	1.69	80.36	57.47	100	98.8
Mean		0.19	−0.16	2.22	1.66	80.07	64.78	100	99.6

Table 3
Means, mean differences and standard deviations for temperature analysis for the CBD (from left: mean for average summer temperature, maximum temperature, minimum temperature, and air UHI). Except for S1, all mean values are listed as the d difference between S1 and scenario.

Level	Scenario	T_{ave}	T_{max}	T_{min}	*UHI*
S1		21.970 (1.48)	27.019 (2.00)	16.463 (1.15)	2.932 (0.63)
	S2	0.318 (1.45)	0.486 (1.96)	0.184 (1.14)	0.097 (0.59)
	S3	0.846 (1.41)*	1.143 (1.93)*	0.578 (1.14)*	0.287 (0.58)*
	S4	0.295 (1.45)	0.194 (1.98)	0.351 (1.14)	0.156 (0.59)
	S5	0.572 (1.43)	0.568 (1.97)	0.534 (1.14)*	0.253 (0.59)
	S6	1.037 (1.40)**	1.152 (1.93)*	0.875 (1.14)**	0.405 (0.59)*
	S7	0.604 (1.43)*	0.303 (1.99)	0.826 (1.14)**	0.409 (0.58)*
	S8	0.857 (1.42)*	0.645 (1.97)	0.998 (1.14)**	0.516 (0.57)**
	S9	1.179 (1.40)**	1.041 (1.94)*	1.246 (1.14)**	0.723 (0.59)**
	S10	0.059 (1.48)	0.073 (1.99)	0.051 (1.14)	0.051 (0.62)
	S11	0.464 (1.45)	0.638 (1.96)	0.294 (1.14)	0.147 (0.6)
	S12	1.016 (1.40)**	1.333 (1.91)*	0.694 (1.13)*	0.338 (0.58)*
	S13	0.375 (1.45)	0.266 (1.99)	0.418 (1.14)	0.203 (0.59)
	S14	0.701 (1.43)*	0.709 (1.96)	0.618 (1.14)	0.302 (0.58)*
	S15	1.127 (1.40)**	1.237 (1.93)*	0.932 (1.14)*	0.465 (0.58)**
	S16	0.722 (1.43)*	0.469 (1.99)	0.863 (1.13)**	0.483 (0.58)**
	S17	0.954 (1.41)**	0.773 (1.97)	1.015 (1.13)**	0.575 (0.58)**
	S18	1.244 (1.39)**	1.124 (1.95)*	1.248 (1.12)**	0.745 (0.56)**

* For significant p-values (<0.05) from Steel test to compare means of the scenarios with the control S1 (after significant p-value from one-way ANOVA tests for each).
** For p-values <0.0001: (UHI was represented as urban – rural).

dense tussock' land type was selected. Therefore, the UHI (calculated from 2 m above-ground air temperature) for the Melbourne CBD, was estimated as 2.93 °C (averaged from UP to RP1 and UP to RP2) with a range of 1.63–5.3 °C. Thus, Melbourne is 2.93 °C warmer than the surrounding suburbs on summer nights, proving the UHI effect.

4.3. Heat mitigation during extreme climate conditions

4.3.1. Mitigating excessive heat of Urban Heat Island effect during the heatwaves

Fig. 3 depicts the simulated diurnal variation of existing seasonal UHI (UHI_S) behaviour in Melbourne and how it sharply increased during the

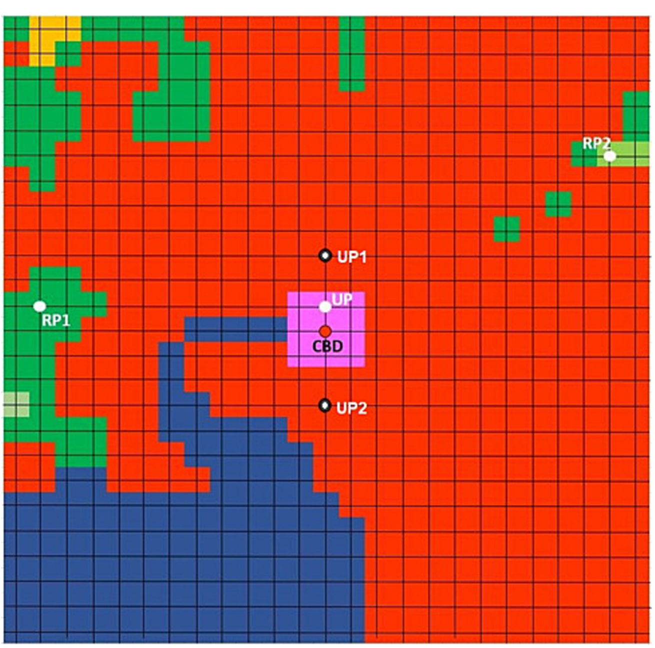

Fig. 2. TAPM 1 km grid window for Melbourne metropolitan (Data extraction points for UHI calculations: RP1 and RP2 – 'Rural points' and UP – 'Urban point'; Data extraction points for analysis: CBD – Centre of the CBD and UP1 and UP2 – Inland and coastal urban points, respectively.

heatwave event in 2009 from UHI_{hw}. Higher UHI values were observed during summer at night. The UHI during the heatwave has increased around 3 °C over the average seasonal UHI. The highest temperature difference between urban and rural was reported during 3–4 am. The three scenarios, S9, S12 and S18, made considerable reductions in diurnal UHI graphs during the day and night.

4.3.2. Number of hot days and nights

Based on the method described by Chapman et al. (Chapman et al., 2018), we determined the extreme threshold temperatures for each summer. Hot days in the CBD were specified when the T_{max} in the CBD was equal to or higher than the 97.5th percentile of the T_{max} of rural points (average of two rural points) in the S1-control. Hot nights were determined by using the same method as that for T_{min}, as shown in Table 4 (Appendix A). S1 recorded two average hot days and 5.6 hot nights per summer under the control scenario. We compared the means of all scenarios by using Dunnett's test (S1-control, significant level $p < 0.05$), and the average number of hot days was significantly reduced in the scenarios- S2, S3, S5, S6, S8, S9, S11, S12, S15, S17, and S18 (basically all items with a cool roof albedo > 0.2) compared with S1, and S4 increased the mean to 2.1 (not statistically significant). Only scenarios S9 and S18 significantly reduced the average number of hot nights than S1 (5.6 nights per summer), where both scenarios represented cool roofs with an albedo of 0.7 and green roofs with 50 % cover. S12 reported a minimum average of 0.3 for hot days; for S18, 2.8 average hot nights was the minimum record.

As shown in Table 5 (Appendix A) for the reduction of hot days and nights, all scenarios with the maximum realistic albedo of 0.7 had a significant reduction in hot days. High albedos prevent energy absorption by promoting the reflection of incoming solar radiation. This phenomenon leads to lower surrounding temperatures (Li and Norford, 2016; Taha, 1997). S9 and S18 have mutually claimed 50 % of green roofs and albedo 0.7 cool roofs and, a significant reduction in the number of hot nights was observed. These results support findings in the literature that urban vegetation promotes cooling during nighttime and reduces the UHI impacts on Melbourne (Herath et al., 2021; Jacobs et al., 2018).

4.3.3. Behaviours of temperature variables and energy budget components during heatwave events

Melbourne experienced three distinct heatwaves in our study period (2011 – 2020): in 2014 (14–16 January), 2018 (considered summer 2019, 6–8 December), and 2019 (28–30 January). An unprecedented heatwave occurred in 2009- the south-eastern Australian heatwave started on 25 January and lasted for 16 days. Our results showed that the average air temperature during the 2009 heatwave was ~12 °C higher than the seasonal summer average temperature. The 10-year average maximum (27.02 °C) and minimum (13.79 °C) temperatures were exceeded during the heatwave by 15 °C (T_{max}), and 11.4 °C (T_{min}). The magnitude of these extreme heat events highlights the need for urgent mitigation strategies to protect vulnerable urban populations. Although the two incidents in 2019 exceeded the thresholds, the temperature values were not comparatively significant in 2009. Although the 2009 heatwave was out of the selected timeframe, it best represented the worst-case scenario with the highest recorded temperatures. Therefore, we simulated the behaviour of air temperature with different wind speeds and energy budget components (e.g., latent and sensible heat), during the 2009 heatwave in Melbourne. We used hourly data for three heatwave days (72 h), and Fig. 4 illustrates the average spatial changes during the heatwave (scenario minus control). For the existing conditions (S1) in Melbourne, T_{ave}, T_{max}, and T_{min} were 34.31, 43.00, and 27.90 °C, respectively, for the 2009 heatwave.

Scenario selection in Fig. 4 was justified as S3 consists of 0.7 cool roofs only; S7 with 50 % F2, green roof only; S10 with 5 % F1, urban trees only; S12 shows the best performance for T_{max} with F1-Urban trees and F3-cool roofs, and finally, S18 performs the best for T_{min} consists of all strategies- F1, F2, F3. Each scenario was compared with control S1 by using a paired *t*-test to observe a significant change (depicted as dark-coloured dots in Fig. 4). Negative values represent the reduction in each variable value

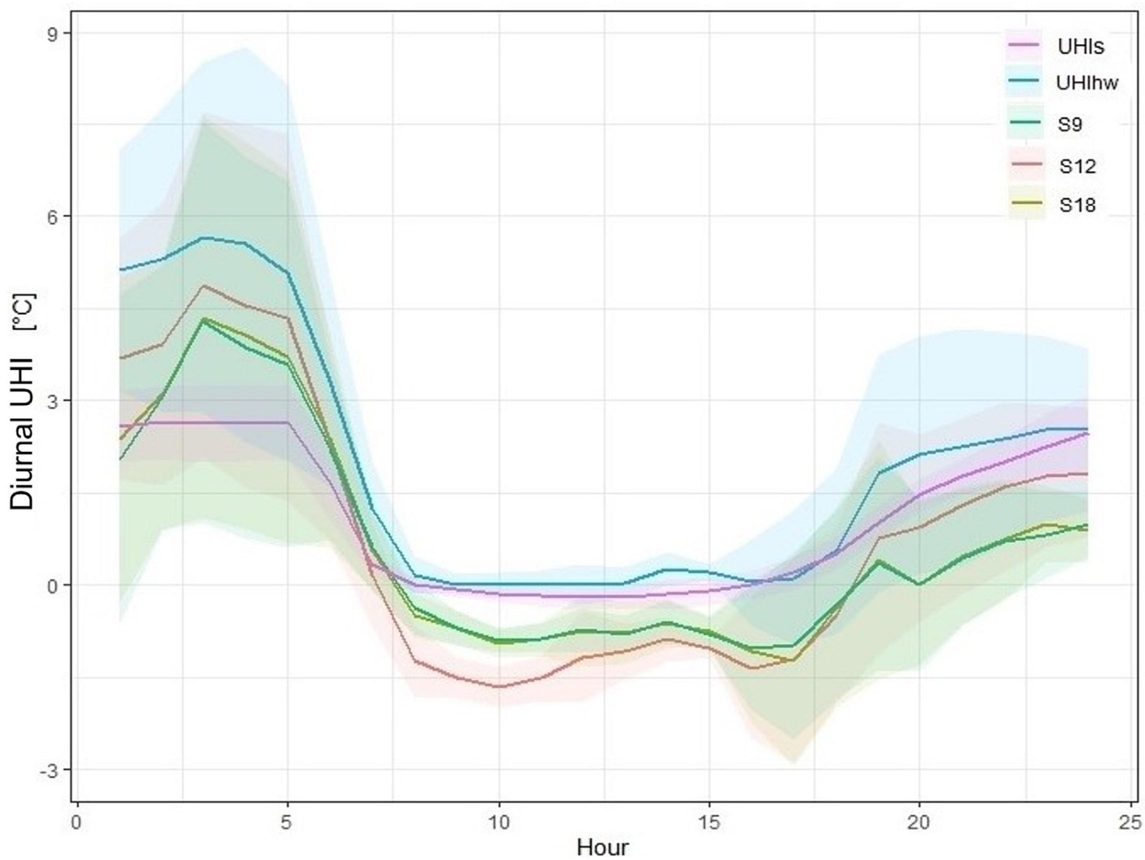

Fig. 3. The diurnal UHI (measured from air temperature at level of 2 m above-ground) variation by different scenarios. UHIs - Seasonal UHI (calculated average from 2011 to 2020), UHIhw – UHI during 2009 heatwave (average values for 3 heatwave days, represent the control), S9 (T = 0, G = 50 %, C = 0.7); S12 (T = 5 %, G = 0, C = 0.7) and S18 (T = 5 %, G = 50 %, C = 0.7). The shaded area represents 1 SD (standard deviation).

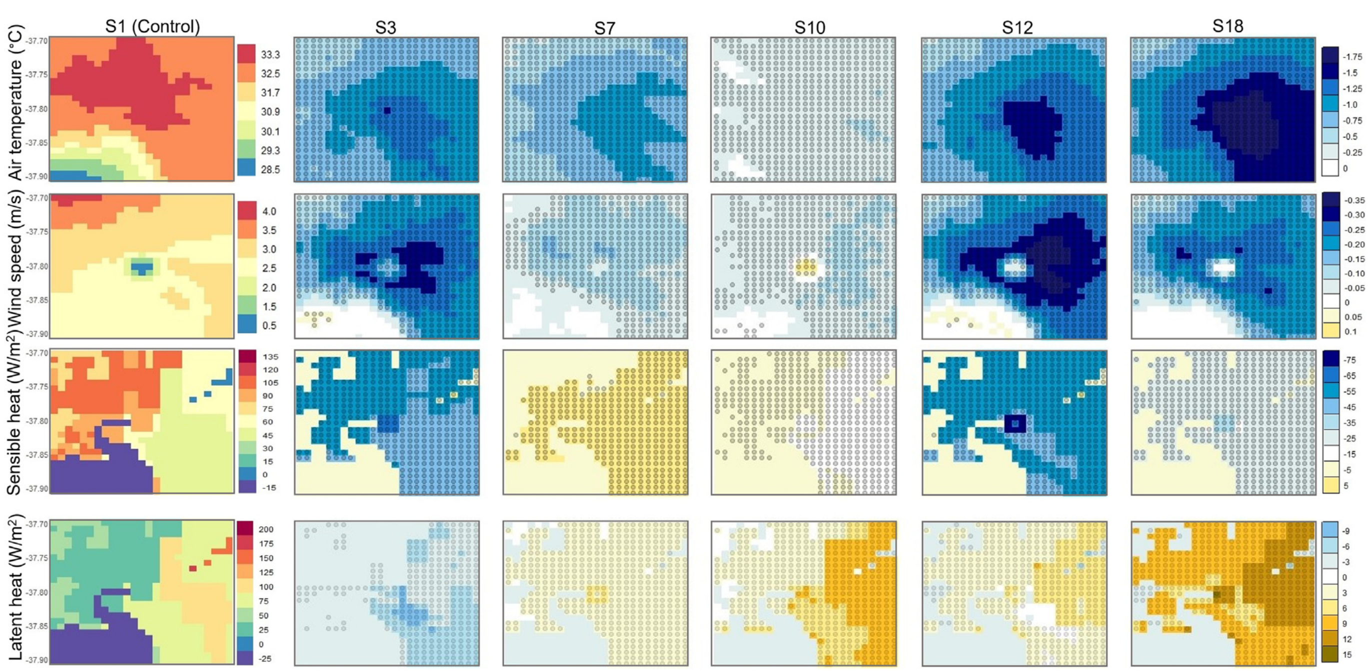

Fig. 4. Spatial maps for Melbourne for 2009 heatwave with values of the variables for S1 (control) and the differences of selected scenarios from S1. The difference is calculated as scenario minus the control. (Dark dots indicate the significant change between the control and scenario: CL- 95 %), Scenarios: S1(control, T = 0, G = 0, C = 0.2); S3 (T = 0, G = 0, C = 0.7); S7 (T = 0, G = 50 %, C = 0.2); S10 (T = 5 %, G = 0, C = 0.2); S12 (T = 5 %, G = 0, C = 0.7) and S18 (T = 5 %, G = 50 %, C = 0.7).

compared with S1. The measured temperature variables in different urban LCZs evidently showed differences. T_{air} was reduced to a maximum of 2 °C, and S18 offered a reduction metropolitan-wide, especially around the CBD. Notably, areas with higher temperatures showed lower wind speeds, higher sensible heat, and lower latent heat fluxes than low temperature areas. S10 showed slight or null declines for T_{air}, wind speed, and sensible heat; however, with increased urban trees, S10 offered a range map for latent heat with evaporation. Cool roofs seemed responsible for reducing sensible heat rather than the other scenarios, with evidence in S3 and S12. Roofs with higher albedos (S3) had significantly reduced latent heat fluxes. This reduction directly affects the energy budget by reducing the sensible heat flux and consequently decreasing net radiation and the surface temperature (Herath et al., 2021). S3 was arranged with 100 % cool roofs that did not achieve the highest reduction but achieved the maximum reduction when combined with urban trees in S12. Particularly notable is that S12 appeared to be an extreme case where a cool roof with a high albedo and no green roof was sufficient to minimise the sensible heat flux, partly due to the reduction in wind speed, and partly by reducing surface temperature. As shown in the results, S12 recorded the highest reduction in average seasonal T_{max}, which was measured during the day.

Meanwhile, Fig. 5 depicts the diurnal variations of the energy budget components during the heatwave extracted from the Melbourne CBD centre, which is compared with the seasonal summer averages. During the heatwave, the energy budget components in the CBD location showed higher latent heat, net radiation, and storage heat fluxes with lower sensible heat than the seasonal averages. S18 increased the latent heat flux, with a higher vegetative ratio of 50 % for green roofs with 20 % (5 % increase) urban trees. Conversely, S12 maintained the lowest sensible heat and net radiation values during the day. The significant lower sensible heat values in the diurnal cycle in Fig. 5A are discernible for S12, unlike S18 had 50 % green roofs as the only difference from S12. Higher albedos have a bigger impact on lowering temperature compared to increasing evapotranspiration. The presence of green roofs increases evapotranspiration while at the same time noticeably reducing the albedo. Removing green roofs in the model causes two consequences: evapotranspiration becomes unavailable for the surface energy budget and the lower albedo of the green roof is replaced with the much higher albedo of the cool roof. In UCLEM, heat storage is provided by the impervious roof component, whereas no heat is stored by the green roof. Therefore, in S12, the change in albedo reduced the heat being absorbed by the roof to a much greater extent than the reduction in evapotranspiration. This led to an overall cooling in the roof surface temperature with a cool roof. The net result is that the model predicts a reduction in sensible heat flux with respect to a cool roof, as the change in albedo had a larger impact on the energy budget than the changes in latent heat flux. Notably, the sensible heat during the heatwave (S1) was lower than the seasonal average. However, excessive heat from the net radiation appeared to have remained in the system as stored heat. Thus, all three scenarios can reduce or increase air temperature (Li and Norford, 2016). Therefore, for S12 and S18 scenarios, TAPM predicts lowered fluxes with upward curves to almost seasonal averages, directly showing thermal comfort benefits for city occupants.

4.4. Heat mitigation under average climate conditions

4.4.1. Seasonal temperature changes with scenarios

Summer T_{ave} changes for each scenario were observed using the data extracted from the centre of the CBD. For S1, the existing urban condition which is the mean for T_{ave} for 10 years was 21.97 °C and ranged from 18.40 to 25.66 °C. The average 10-year T_{max} was 27.02 (22.36–31.99) °C, and T_{min} was calculated as 16.46 (13.79–18.64) °C. The p values of all three ANOVA tests for T_{ave}, T_{max}, and T_{min} were reported as significant (<0.0001), indicating differences in the mean temperature values among scenarios. The existing setup for Melbourne (S1) was then compared with the other scenarios by using Dunnett's test (Table 3). Each scenario exhibited a different behaviour for different temperature variables. However, the p-values of S3, S6, S9, S12, S15, and S18 were significant compared with S1 for all temperature measurements, T_{ave}, T_{max}, and T_{min}. We selected the aforementioned six scenarios for further analysis among all significant scenarios.

4.4.2. Seasonal variations of temperature and energy budget components among LCZs (urban types)

This study used three receptor points in two urban types: the CBD with high-rise and compacted buildings (LCZ1) and UP1 and UP2 in general urban areas (Fig. 2) with low-rise buildings (LCZ3) characteristics. All three points were chosen on a straight line to avoid biases, where UP1 is

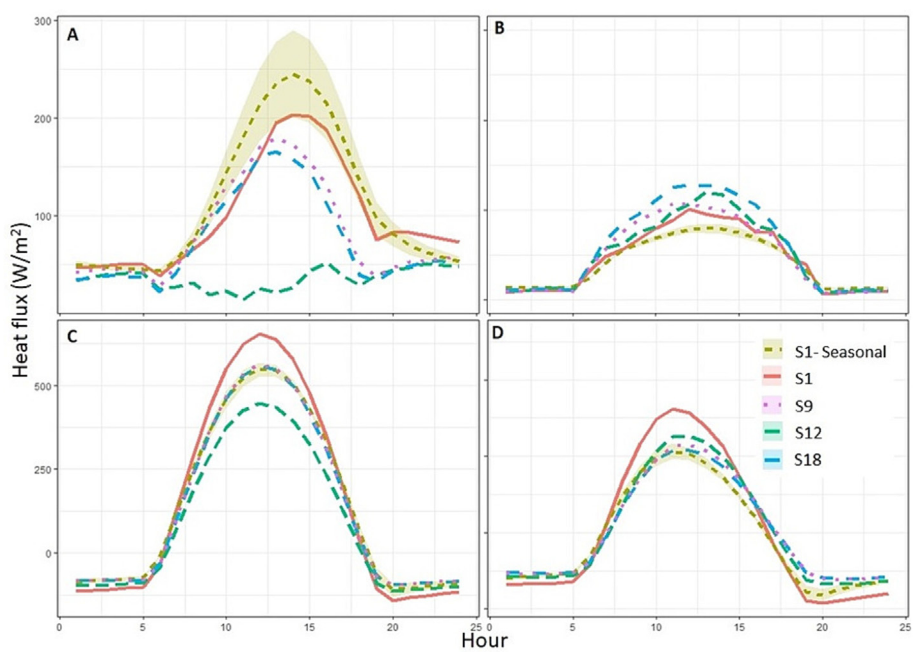

Fig. 5. Diurnal variation of energy budget components in the CBD location during 2009 heatwave; A: sensible heat flux; B: Latent heat flux; C: Net radiation, and D: Storage heat flux for selected scenarios (S1- (control, T = 0, G = 0, C = 0.2; S9-(T = 0, G = 50 %, C = 0.7); S12- (T = 5 %, G = 0, C = 0.7) and S18- (T = 5 %, G = 50 %, C = 0.7) compared with Seasonal S1).

the inland location and UP2 represents near-coast urban locations. Martilli et al. pointed out that analysing temperature differences within different urban areas (various LCZs) is more meaningful for temperature evaluation studies than focusing on urban-rural differences. Below we discuss the temperature and energy budget variations within different urban types in Melbourne.

Urban surfaces release terrestrial radiation slowly, and vegetative surfaces promote less trapping of solar radiation than urban surfaces and rapid release of terrestrial radiation (Papangelis et al., 2012). Studies have established that rural areas consume 50 %–60 % of available energy as latent heat while budgeting 15 %–30 % as sensible and subsurface heat fluxes at noon (Mcpherson, 1994). However, in cities with fewer vegetative surfaces (5 %–20 %) and higher ratios of impervious surfaces, 30 % of available net radiation is absorbed as latent heat. Therefore, more energy remains as sensible heat (45 %) to heat the air at noon (considering it as an irrigated hypothetical city) (Mcpherson, 1994). After implementing the mitigation strategies, S12, with the total roof surface of cool roofs and 20 % urban trees showed the lowest sensible heat and net radiation curves. Cool roofs have been proven to reduce the net radiation and sensible heat more effectively than green and conventional roofs (Imran et al., 2018). Moreover, S18 drew the highest curve for latent heat with greener surfaces because green roofs are known to convert net radiation into latent heat with evapotranspiration (Fig. 6) (Imran et al., 2018; Mcpherson, 1994). This scenario decreased the net radiation by approximately 125 Wm^{-2} in all urban locations of the CBD and UPs. Urban trees increased by 5 %, promoted evapotranspiration, provided shading, and decreased the incoming solar radiation. In UCLEM, shading reduces the amount of shortwave solar radiation absorbed by the canyon walls, effectively modifying the canyon geometry proportional to the height of the vegetation. Hence to first-order the surface temperature is reduced by the reduction in solar radiation heating the walls of the canyon. Additionally, 50 % of roofs as green roofs promoted latent heat and reduced sensible heat simultaneously, and the remaining roofs reflected the incoming solar radiation. Therefore, S18 is an excellent combination for reducing the net radiation of the system. However, implementing scenarios always yields better balanced curves for the energy budget components than the existing S1.

With high heat-absorbing urban materials, CBD promotes heat storage which is released during the night and eventually increases T_{min}—the nighttime temperature (Environmental Protection Agency, 2011; Wonorahardjo et al., 2020). The results of the seasonal summer averages for the existing temperature indices demonstrated that T_{min} showed a statistically significant difference in the CBD from both UPs (similar for UPs) and that T_{max} and T_{ave} were nonsignificant. The high T_{min} in the CBD can be explained by Fig. 6, because the storage heat fluxes were higher in the CBD than in the UPs. The energy stored from solar radiation is released from the construction materials of buildings and all impervious surfaces during the night by increasing T_{min} (Imran et al., 2019b). This difference, even between high- and low-density urban areas, created temperature gradients, leading to UHI, and we can predict that this will intensify in rural settings. Adding the S12 and S18 scenarios to the study site did not cause significant mean changes in T_{max} and T_{ave}; however, the temperature drops were still observable. S12 also showed significant differences in T_{min} among all three urban locations: CBD, UP1, and UP2. Notably, S18 reduced the mean values of T_{min} without creating temperature gradients in the urban profile. In the UPs, higher T_{max} was recorded, and this occurred at higher wind speeds than in the CBD. Urban generic areas were recreated in the model with low-rise buildings of similar height and low surface roughness to represent less drag on the wind, allowing for increased wind speeds (Wever, 2012). High wind speeds caused low turbulent mixing and prevented the heat from being carried away. This will increase the T_{max} of the study area and intensify the UHI effect (Gunawardena et al., 2017).

Fig. 6 presents the hourly variations in the energy budget components (net radiation, storage, latent heat, and sensible heat flux) for 24 h. The seasonal mean values were used from 2011 to 2020 for the selected scenarios

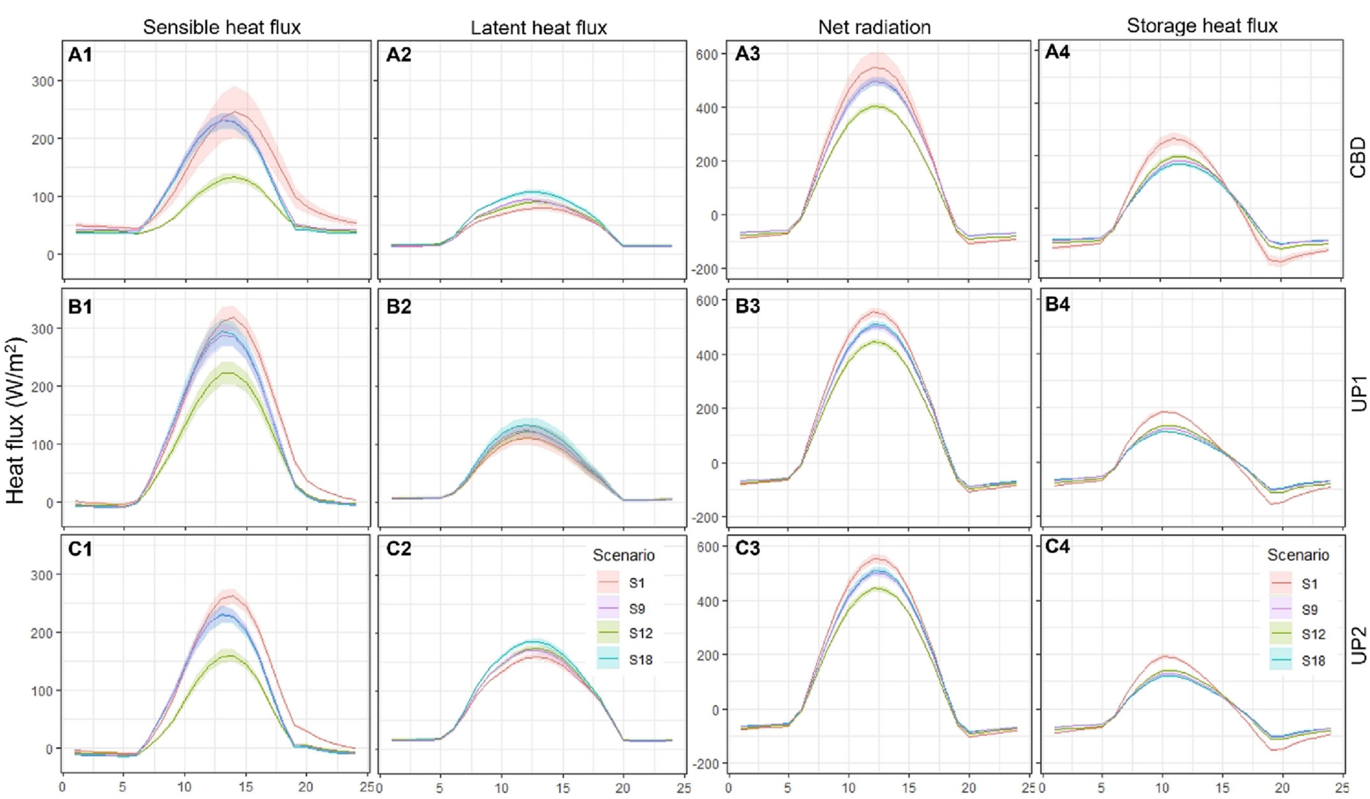

Fig. 6. Seasonal mean for diurnal variation of sensible heat flux (left:1), Latent heat flux (left:2), Net radiation (right:3) and storage heat flux (right:4) for summer 2011–2020 for selected scenarios (S1-(control, T = 0, G = 0, C = 0.2); S9 (T = 0, G = 50 %, C = 0.7); S12 (T = 5 %, G = 0, C = 0.7) and S18 (T = 5 %, G = 50 %, C = 0.7)) at A: CBD, B: UP1 and C: UP2.

for three urban locations: CBD, UP1, and UP2. The scenarios – S12, and S18 were chosen because they showed the highest reductions for temperature indices of T_{max}, T_{min}, T_{ave} and UHI, while S9 acts almost similar to S18. The sensible and latent heat fluxes increased during the daytime and decreased at night. As shown in B1, UP1 reported higher sensible heat fluxes during the day than CBD and UP2. This difference could be due to its spatial variability: UP1 is located farthest from the sea and is surrounded by urban surface characteristics. The minimum sensible heat flux was reported with S12 for all urban locations because 100 W/m^2 was constantly reduced by S12. S12 corresponded to a purely cool roof with a high albedo of 0.7 (and a 5 % increase in urban trees), whereas the other scenarios- S9 and S18 had 50 % green roof coverage that effectively reduced the roof area with 0.7 albedo, but potentially included more evapotranspiration. Despite the minimum impact of 5 % urban trees, the cool roofs with a high albedo could cause the low sensible heat for S12. S9 and S18 overlap for each graph (Fig. 6); therefore, regardless of the 5 % increment in urban trees in S18, both scenarios acted similarly, involving the energy budget. Every scenario showed higher latent heat than S1, promoting cooling in the urban area. The maximum latent heat was reported in S18 through increased evapotranspiration, with the maximum vegetation fraction among all scenarios.

Urban points were graphed with higher sensible and latent heat fluxes than the CBD in the existing energy balance for seasonal summer averages in the modelling area. However, the CBD had higher storage heat fluxes than the UP locations, which might be due to the dense and high-rise building characteristics. The characteristics of the CBD differ from those of UG areas: the CBD has more built-up and road ratios than it has vegetative surfaces, and UG areas are less built-up with more vegetation than the CBD. Storage heat is a crucial cause of the UHI effect, and this storage occurs because of the thermal conductivity and heat capacity of urban surface materials and the greater 3-D surface area in a city (Oke, 1988). According to Fig. 7, the CBD has higher storage energy than UP1 and UP2, and this difference leads to UHI at night. However, a reduction was observed with S9, S12, and S18, whereas S18 always showed the lowest curve. This observation can be explained by scenario S18 having the greatest urban vegetation ratio (no energy is stored in the vegetation canopy in the UCLEM) and the highest cool roof albedo. The net radiation peaked at approximately noon, and the peak was almost the same for all three urban locations. However, the curve was lowered the most in S12 by reducing the total net radiation to approximately 125 W/m^2 for the CBD, UP1, and UP2.

4.5. Operationalisability of these scenarios in urban areas

4.5.1. Practical and cost limitation

We acknowledge that effectiveness is used in different ways in literature. For example, the effectiveness of urban blue-green infrastructure (UBGI) strategies for mitigation purposes is defined differently as in Imran et al. (2018), Imran et al. (2019a), Sharma et al. (2016), Jiao et al. (2017), Lin et al. (2013), Li et al. (2014), Di Giuseppe and D'Orazio (2014), Pugh et al. (2012), and Chen et al. (2016). Krayenhoff et al. used two indices to measure effectiveness, vegetation cooling effectiveness (VCE) and albedo cooling effectiveness (ACE), to quantify the cooling ability of strategies that use vegetation and higher albedo values (Krayenhoff et al., 2021). Bai raised the necessity of measuring the functional effectiveness of UBGI against conventional engineering-based infrastructure (Bai, 2018). We argue that effectiveness needs to be defined combining functional performance and operationalisability, including cost-effectiveness and feasibility. In this study, the term effectiveness is used to refer to the degree of cooling effects delivered combined with operationalisability or feasibility, in relative terms, of the combined strategies. However, a detailed cost evaluation is beyond the scope of this paper and is planned for future work.

In the literature, most of the modelling studies have tested the extreme fractions to observe the impact of changing variables, such as zero and 100 % (Chapman et al., 2018; Herath et al., 2018b). Despite the promising results for success, most scenarios cannot be practically implemented on the ground, and as such, questions remain regarding their operationalisability. For example, there are constraints in financeability and design standards for installation, maintenance, space, and resources (e.g., water). Moreover, some concerns regarding ownership of the property, and socio-economic

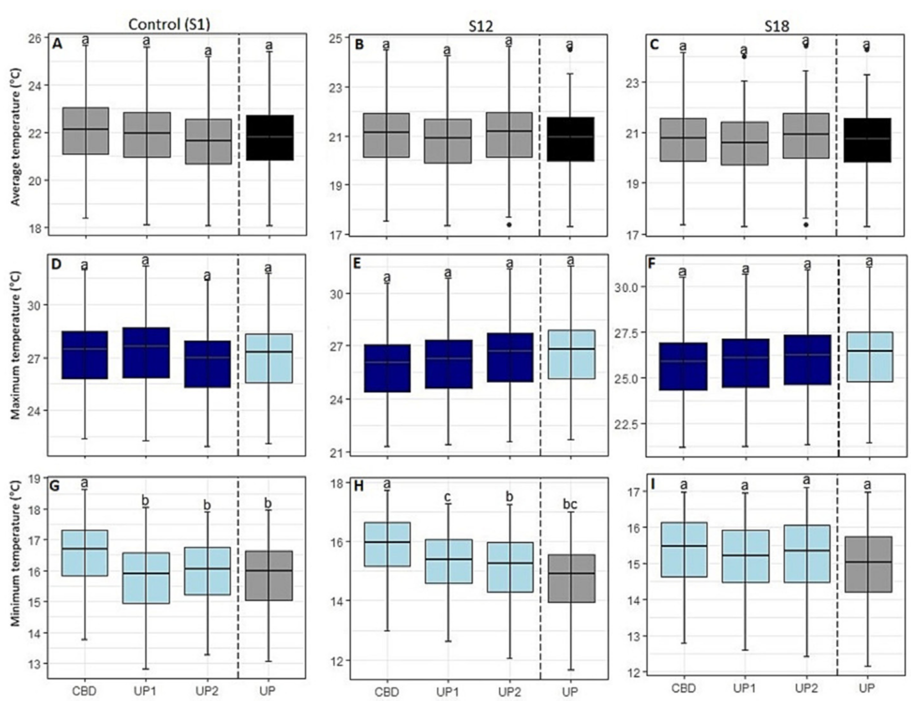

Fig. 7. TAPM mean summer temperatures (2011–2020) for average, maximum and minimum temperature (whiskers for error bars) for different urban types in Melbourne; A, D and G represent the existing condition for Melbourne (control); B, E, H for S12 (T = 5 %, G = 0, C = 0.7) and C, F, I for S18 (T = 5 %, G = 50 %, C = 0.7); (UP represents the average value for UP1 and UP2). The letter "a" indicates when the change of temperature variables was not significant at $p < 0.05$, and "b" and "c" indicate significant differences of means among different urban locations (performed in a Tukey multiple means comparison).

considerations, such as public perception, policy constraints, administrative restrictions, technology, and innovation are also significant constraints on implementation (Zuniga-Teran et al., 2020; Reimer and Rusche, 2019; Onori et al., 2018). Because operationalisability is one of the objectives of this study, we concentrated on selecting feasible and optimum implementation ratios through a literature survey for Melbourne.

Melbourne is planning a low-carbon city with greener spaces to cope with the effects of climate change (Victoria State Government, 2017). *Plan Melbourne, 2017–2050*, is policy documentation that promotes increasing vegetation cover to 40 % (from 22 %) by 2040 (City of Melbourne, 2012) in city planning. Subsequently, a study of Melbourne demonstrated that >40 % vegetation was necessary to increase temperature reductions (Imran et al., 2018). Therefore, our experiments planned an affordable and most ambitious vegetation fraction of 43 % in the non-CBD (UG) area and 20 % in the CBD—a 5 % increase in the existing percentages of both areas to overcome the above limitations for irrigation and space availability. Moreover, irrigating urban green is a critical limitation as Australia's water availability is under pressure because of its low rainfall and rising population (ABS, 2008; Dey et al., 2019). In our model simulation, TAPM assumed the greening options to be well-irrigated with 100 % irrigation. Heusinger et al. quantified as an unrestricted irrigation condition on green roofs can reduce 48 % - 75 % of excess urban heat compared to black roofs, while sustainable irrigation conditions drop up to 15 % - 51 % in different cities (Heusinger et al., 2018). During heatwaves, soil moisture of substrate tends to drop critically, making cooling unsuccessful. Unirrigated green roofs dropped the heat reduction by 3 %, which causes more heating (Heusinger et al., 2018). Therefore, green roof plans should seek adaptive and innovative strategies to compete with water requirement stress during heatwaves and average conditions. For example, green roofs can use recycled greywater as a successful alternative to potable water (Fowdar et al., 2017; Prodanovic et al., 2017). Using different substrates with high water holding capacity (Grard et al., 2018), and modifying substrates with water retention gels (Young et al., 2017) are successful and manageable strategies to reduce irrigation water requirements to reach the saturated condition.

However, roof surfaces have multiple trade-off relationships because roof areas should facilitate solar PV, green roofs, and cool roofs. Recently, most households have been shifting to renewable energy, and Australia has planned for 2.2 million small-scale solar panels (Australian Energy Council, 2020). Therefore, green roofs must compete for space with solar panels. An alliance of solar panels with green roofs can produce up to 16 % more energy than plants from green roofs, provide a cooling effect with evapotranspiration and maintain solar panels at their ambient performance temperature (Barcelona City Council, 2015). Moreover, green roofs prevent the latching of suspended particles on solar cells (Barcelona City Council, 2015) by providing dry deposition of particulate matter from traffic pollution (Tong et al., 2016; Viecco et al., 2018). Our study did not include an alliance of green roofs and solar PV panels in the same space; however, we considered 50:50 availability for the same roof. Therefore, considering these trade-offs, this study maintains the green roof levels practically and adequately to provide maximum climate benefits.

The construction techniques, implementation, and maintenance of UGI require extra expertise, attention, and capital. For example, green roofs require higher life cycle costs than average for three main phases: installation, lifetime, and replacement. Green roofs have lower short-term investment returns than conventional roofs but excellent long-term returns (Downton, 2013; Chen et al., 2019). These high-cost requirements become limitations when there are widespread doubts regarding who would pay and how the initial and maintenance costs, retrofitting of existing buildings, irrigation, and plant nutrition would be conducted (City of Melbourne, 2017). Some municipalities (55 %) identified a lack of public funding as a major barrier to sustainable urban growth (Lindfield and Teipelke, 2017). To avoid these high-cost limitations linked to size, design, and type (Broadbent et al., 2021), strategies, such as small projects at the domestic level or do-it-yourself (DIY) installations, are being promoted among communities. The cost of a small green roof in Melbourne with reasonable access would cost 150–400 AUD/m^2 (according to the 2013 prices), excluding fees for designing, planning, permits from local councils, permits for lifts and cranes, demolition or relocation of existing infrastructure, and additional specific infrastructure, such as shade, decking, paving, and trailing (DEPI, 2014; Gibson, 2021). As empirical evidence, a 50 m^2 green roof installed in Coburg is valued at approximately AUD 30,000 which most architects consider a high budget (O'Donoghue, 2016). According to Wilkinson et al., each life cycle phase costs from AUD 19.08 to 215.76 for installation; AUD 0.49 to 2.83 for maintenance per m^2 and AUD 55.54 to 2.28, AUD 1.06 to 1.27 for demolition and replacement per square meter for building owners (Wilkinson et al., 2017).

Cool roofs are more advantageous than green roofs because the former has lower installation and maintenance costs and no irrigation needs (Imran et al., 2018; Sharma et al., 2016). Typical, conventional roofs have an albedo ranging from 0.1 to 0.3 (reflecting 10 %–30 % of incoming solar radiation, with the rest absorbing) (Wang et al., 2016), and cool roofs have high reflectivity with higher albedos than conventional roofs. Due to the high reflectivity of roofs, incoming solar energy tends to radiate back with cool roofs instead of being absorbed and transferred inside the building. This eventually reduces air conditioning costs while promoting thermal comfort and human health (Uni.Melbourne, 2011). Moreover, in addition to the cooling benefits, the maintenance of cool roofs is more manageable, and implementation costs are lower due to less sophisticated designs, reroofing, and retrofitting than green roofs (Uni.Melbourne, 2011; City of Melbourne, 2014). However, as proved in this study and some of the literature for Melbourne, cool roofs are only effective for daytime temperature reductions (Herath et al., 2021; Imran et al., 2018; Jacobs et al., 2018), and are highly beneficial during summertime (Macintyre et al., 2021). The Melbourne City Council promoted a building retrofitting project in 2010. The '1200 Buildings Program' aimed to improve energy (and water) efficiency by retrofitting 540 commercial buildings with higher roof albedos in Melbourne (City of Melbourne, 2014,2016). Therefore, cool roofs are effective, practical, and affordable for most temperate cities such as Melbourne.

4.5.2. Importance of using the reasonable maximum ratio

The results showed different heat reduction effectiveness for different scenarios. As demonstrated in this study, all parameters had the highest efficiency with the maximum cooling potential when greater ratios/values were applied. Increasing urban trees (F1) and green roof (F2) ratios have proven effective in urban environments because urban vegetative surfaces increase the moisture availability of the surrounding. Urban trees induce cooling via transpiration and shading (Meili et al., 2021; Taha, 1997; Krayenhoff et al., 2020). Every bit of urban vegetation contributes to heat reduction (Herath et al., 2021), and higher tree cover promotes a more significant cooling potential. For example, according to Imran et al. (2018), >40 % of total vegetation significantly reduces temperature. However, new studies show that the increment of urban trees after a certain level is associated with some limitations (Park et al., 2019; Meili et al., 2021). Since trees in the urban environment tend to alter the wind flow and urban aerodynamic roughness, they restrict heat dissipation (Meili et al., 2021). With well-irrigated urban trees, cooling happens with transpiration; however, restricted irrigation limits further cooling. Apart from these facts, we also focused on practical restraints in Melbourne, such as the existing fractions of buildings, roads, and other impervious surfaces. In Melbourne, built-up areas and ground-level vegetation cover occupy 65 % and 15 % of total CBD areas, respectively, and they are 45 % and 38 % in the UG area (Coutts et al., 2007), and what remains is 20 % and 17 % for roads in the CBD and UG, respectively. Assuming the ratios of roads remain constant, we considered the urban tree cover of 20 % and 42 % as reasonable maximums in the CBD and UG areas, respectively. These increased tree cover ratios led to a reduction in the T_{max} and T_{min} by 0.07 and 0.05 °C, but the reduction values were relatively small. In addition, the scenarios with a vegetation increase showed more substantial impacts on nighttime temperature than on daytime temperature, which is consistent with findings in the literature (Herath et al., 2021; Imran et al., 2019a; Grimmond, 2007). When we changed only the vegetation ratio, the heat reduction of those scenarios was relatively small. However, heat reduction was significant during the nighttime with a maximum green ratio (e.g., 50 % green roofs). Our results proved that attention should be paid to diurnal cooling capacity as some scenarios' effectiveness varies day and night. However, this study did not aim to assess the seasonal cooling capacity, which could have different levels of effectiveness during summer and winter as confirmed by Krayenhoff and Voogt (2010).

In addition to the effectiveness, each parameter has different advantages and constraints. Operationalising plans with surface characteristics is always costly. Moreover, there are limitations to space availability for increasing tree canopy cover in canyons, urban parks, and gardens in existing cities. To overcome these limitations, planning should be case-specific. The feasibility of the selected plan should be evaluated by studying similar and different empirical evidence from different geographic locations. Choosing the most suitable parameters for a particular urban area should be financially sensible. For example, in cities where the cost of UGI, such as green roofs, is unaffordable, cool roofs and urban trees to mitigate daytime temperatures are still practicable. Planning UGI to reuse and recycle water and other resources is another means to be cost-effective, which could be efficient in a water-scarce context such as Australia. As we firmly grounded in this study, combined scenarios with high-albedo materials and vegetative surfaces are highly effective, and the best performance is achieved by overcoming most of the aforementioned limitations. Combined scenarios strategically alter urban plans to occupy reasonable maximum surface ratios while achieving maximum cooling benefits, which equally improves day and nighttime thermal benefits. These equal benefits eventually lead to excessive heat and UHI mitigation and directly to energy saving (Akbari and Konopacki, 2005).

For most temperature indices, such as T_{ave}, T_{min}, and UHI, the highest reductions were rendered by the combined scenario of 20 % vegetation, 50 % green roof, and 50 % cool roof with 0.7 albedo (S18), with a reduction of seasonal average T_{air} of 1.25 °C, and in the CBD, a maximum reduction of 2.1 °C during heatwaves. This scenario also showed preferable performances for T_{min} and UHI, making it the best strategy for mitigating UHI effects in Melbourne. Combined scenarios are most effective in terms of the maximum cooling benefit and can be cost-effective for Melbourne. This cost-effectiveness is enhanced when the costs are compared with the benefits of UGI because the added greenery from UGI can provide co-benefits, including many ecosystem services, and enhance the ecological value of the urban area. As discussed, when green roofs tend to be expensive and often impractical in an existing urban context, combining them with less expensive cool roofs can be a much more cost-effective strategy.

Recent urban literature suggests that urban planning should focus more on the spatial layout of the mitigation solutions with the allocation ratio. Most available case studies have reported plenty of successful case studies on microscale, but with the level of individual or isolated implications. However, urban planning requires confirmation over large-scale ecosystem integration in cities (Bai, 2018) before going for mitigation solutions at individual levels. Therefore, identifying suitable and reliable city-specific mitigation strategies from a wide range of green infrastructure solutions is inevitable, which should be done in the context of the regional climate of the area. Mesoscale modelling efforts are essential to fulfil that requirement in the pre-planning stages, and the importance of this stage remains overlooked. This specific resolution of 1 km is often used in the literature for much shorter experimental designs. This case study targets climate timescales (e.g., decades), and the spatial resolution of 1 km fits well with the objectives and requirements of this study. After identifying and specifying effective mitigation strategies for the selected area, urban planning should go beyond that by downscaling to microscale models into spatial layout perspective for all ecosystem services (which is not in the scope of this study). This study focused only on the summer. To achieve a complete understanding of the effectiveness of each surface parameter, a year-round assessment, including seasonal variations, is necessary. In addition, a cost-benefit analysis of each scenario would provide further support for decision-making.

5. Conclusion

This study investigated the effectiveness of combined urban surface parameters (natural and built) in mitigating seasonal average and excessive urban heat during summer in a temperate city, Melbourne, while considering operationalisability. Eighteen scenarios with different combinations of urban surface parameters, that is, urban trees (F1), green roofs (F2), and cool roofs (F3), were examined. The results demonstrate different levels of heat reduction benefits and limitations across the scenarios. Additionally, different scenarios proved effective for different heat indices. For example, higher ratios of cool roofs significantly reduced daytime temperatures, and vegetative surfaces promoted cooling at night.

Our results demonstrate the cooling ability of carefully planned urban surface parameters in a city. Most scenarios achieved reductions in heat indices, for example, seasonal averages, maximum and minimum temperatures, and extreme temperatures during heatwaves and UHI. The highest reduction was found for the scenario with maximum combined surface parameters, 20 % urban trees, 50 % green roofs, and cool roofs with a 0.7 albedo (S18) for multiple heat indices, such as average summer temperature (T_{ave}), minimum temperature (T_{min}), and urban heat island measured with the air temperature at 2 m above-ground (UHI). Another scenario, when the total roof area was converted to cool roofs of 0.7 albedo with 5 % increased urban trees (S12), could achieve the highest reduction for maximum summer temperature (T_{max}).

Implementing some strategies can be significantly more expensive than implementing others. The effectiveness of UGI should be defined based on both their thermal performance and operationalisability. Combined strategies seem to deliver the best diurnal thermal performance with practicality and cost. Our results showed that a combination of 20 % total urban trees, 50 % green roofs, and 50 % cool roofs with a 0.7 albedo (S18) had the highest effectiveness in Melbourne. Strategic planning with combined urban surfaces is more effective than adopting a single strategy for cities. Therefore, city planning should be strategically explored to achieve enhanced thermal benefits from a combination of urban surface parameters. Planting more trees in street canyons, establishing urban parks, and motivating urban residents for urban gardening are some of the methods to increase urban vegetation cover. Green and cool roofs can be promoted by encouraging investments and incentives for DIY and by changing and imposing regulations on construction for builders and developers. Establishing a UGI enhances the ecological value of a city while providing multiple ecosystem services. Therefore, these measures would enhance the diurnal thermal comfort of the city during heatwave events and ultimately promote liveability.

CRediT authorship contribution statement

Prabhasri Herath: Conceptualization, Methodology, Formal analysis, Investigation, Writing- Original Draft preparation, Editing and Visualization.

Marcus Thatcher: Conceptualization, Methodology, Software, Reviews & editing and Overall supervision.

Huidong Jin: Conceptualization, Methodology, Reviews & comments, and Overall supervision.

Xuemei Bai: Conceptualization, Methodology, Reviews & comments, Editing and Overall supervision.

Data availability

Data will be made available on request.

Declaration of competing interest

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

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Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.162476.

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Appendix 1

Table 4: Threshold values for Hot days and Hot nights for each year 2011-2020 (97.5th percentile of maximum and minimum temperature at a rural point in the S1-control scenario)

	Maximum value (°C)	Minimum value (°C)
2011	39.485	21.163
2012	36.955	21.290
2013	39.758	19.980
2014	42.190	23.590
2015	38.601	22.699
2016	40.475	21.575
2017	38.213	23.595
2018	40.043	21.800
2019	40.229	22.775
2020	42.375	20.455

Table 5: Mean number of Hot days and Hot nights per summer, compared to S1 with Dunnett test (* significant p-values, ** p-values <0.0001)

Scenario		Hot days	Hot nights
S1		2	5.6
	S2	1.2*	5
	S3	0.4**	4.3
	S4	2.1	5.2
	S5	1.1*	3.9
	S6	0.4**	3.6
	S7	1.6	3.6
	S8	1.1*	3.5
	S9	0.5**	2.9*
	S10	1.9	5.3
	S11	0.9*	4.8
	S12	0.3**	4
	S13	1.6	4.3
	S14	0.9	3.8
	S15	0.4**	3.6
	S16	1.3	3.6
	S17	1*	3.5
	S18	0.4**	2.8*

Appendix 2

Domain size and resolution

In the study, we focused on a 25 km × 25 km domain with 1 km × 1 km resolution with a better agreement of results with model calibration. However, this selection can be subjected to the argument with a smaller domain size, in which the domain is closer to the target area. To include the impacts of complexities of land-sea boundaries, the used domain could be argued to expand more. In TAPM, we have the initial advantage of including broader boundaries up to 300 km in the first grid level with nesting grids. Encouraging model downscaling, we used the last grid level up to 25 km × 25 km with 1 km^2 resolution, which provides more detailed urban characteristics than larger grid sizes. Accepting the inevitable, models are a closer approximation of the reality with some limitations, such as the time taken for running the simulations; we could not perform 180 simulations in TAPM for larger domain sizes (e.g., 100-150 km, with 1 km grid resolution) in this study. Moreover, TAPM limits the grid size so that the outer (lowest resolution) grid does not violate the model assumption that the curvature of the earth is negligible over the domain (Hurley, 2008). Therefore, considering the limitations and capabilities, we had to limit the domain size to 75 km × 75 km by using the results of 3 km resolution with less granularity to obtain evidence to compare both domain sizes.

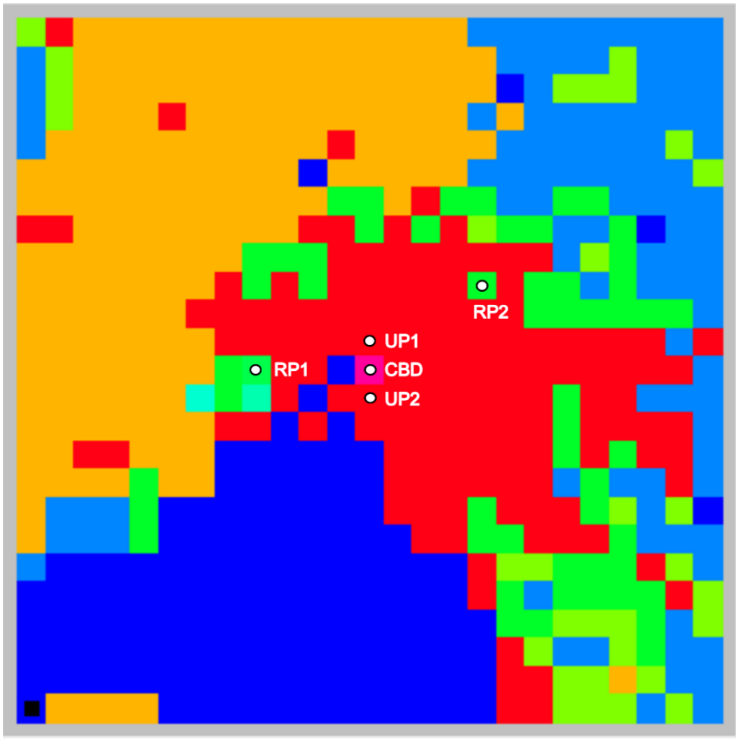

Figure i: TAPM 3 km grid window for Melbourne metropolitan (Data extraction points for calculations: RP1 & RP2− 'rural points', UP1 & UP2 – Inland and coastal 'urban points' and CBD – Center of the CBD

The data extraction points were adjusted as illustrated in Fig.i, with the changed grid size. The CBD area is limited to one grid with a bigger resolution, while UP1 and UP2 represent generic urban conditions with different LCZs. RP1 and RP2 represent the shrubland land-use characteristics, with low mid-dense and law-sparse, respectively.

Before the simulations, we compared the results of domains with both boundary conditions of 25 × 25 km^2 and 75 × 75 km^2 with 1 × 1 km^2 and 3 × 3 km^2 resolutions for two selected scenarios, S1 and S18, respectively, for every 24 hours of air temperature measured at 2 m above ground level during three summer months for 10 years (2011-2020). A reasonable value for the absolute difference between S1 from 1 km resolution minus S1 from 3 km resolution and S18 from 1 km resolution minus S18 from 3 km resolution was obtained as 0.428 with ± 0.54 standard deviation. These values provide evidence that the two boundary conditions have small differences in temperature changes from S1 to S18, which the conclusions based on simulations from 25 × 25 grids by 1 × 1 km^2 domain will not substantially change by the bigger grid. However, it is expected to use models such as CCAM (Chapman et al., 2018; CSIRO, 2020) in future studies to observe any changes if it occurs due to boundary conditions.

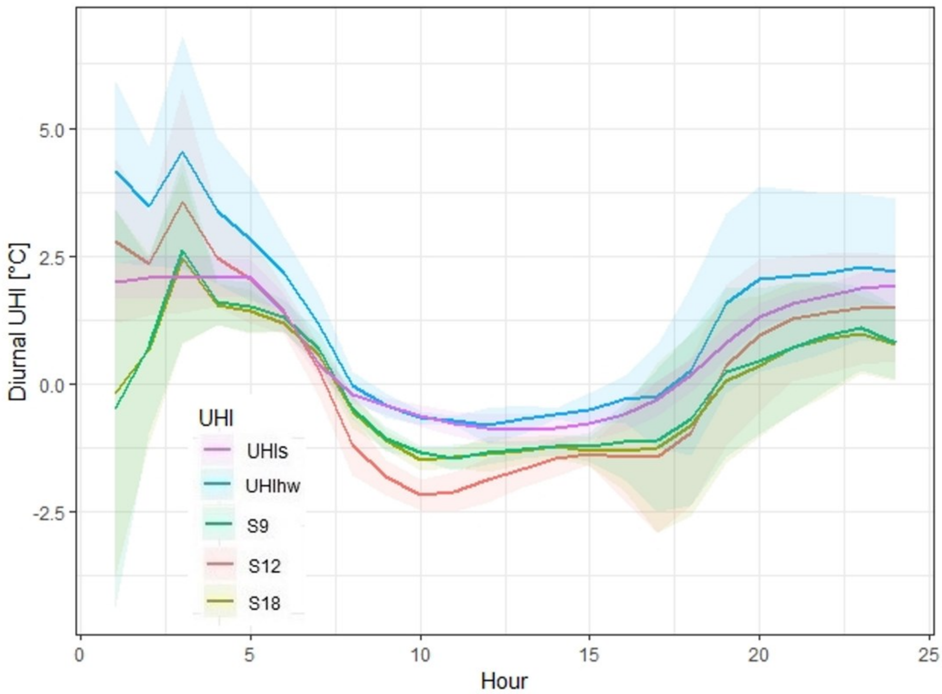

Figure ii: The diurnal UHI (measured from air temperature at 2m aboveground measured for 3 km resolution) variation by different scenarios. UHIs - Seasonal UHI (calculated average from 2011 to 2020), UHIhw – UHI during 2009 heatwave (average values for 3 heatwave days, represent the control), S9 (T=0,G=50%,C=0.7); S12 (T=5%,G=0,C=0.7) and S18 (T=5%, G=50%, C=0.7). The shaded area represents 1 SD (standard deviation)

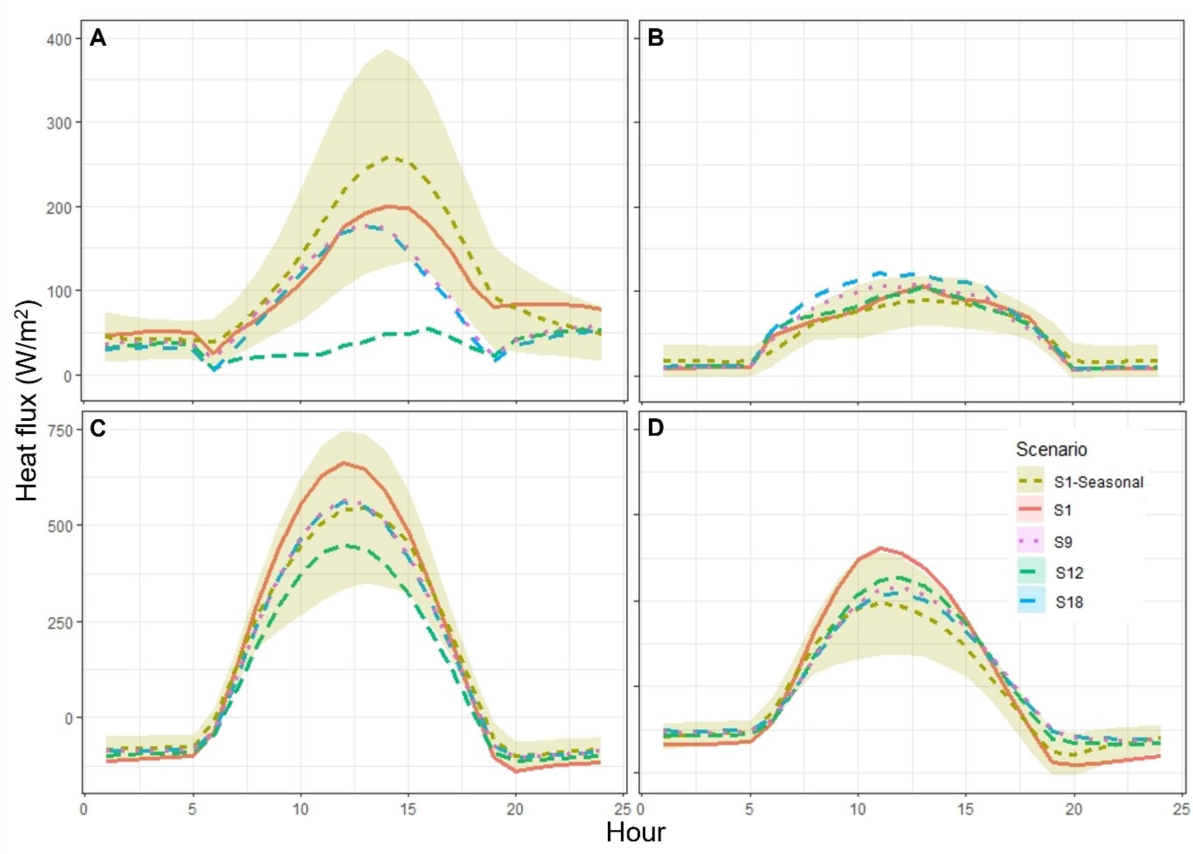

Figure iii: Diurnal variation of energy budget components in the CBD location during 2009 heatwave measure for 3 km x 3km resolution in larger domain; A: sensible heat flux; B: Latent heat flux; C: Net radiation, and D: Storage heat flux for selected scenarios (S1- (control, T=0,G=0,C=0.2; S9-(T=0,G=50%,C=0.7); S12-(T=5%,G=0,C=0.7) and S18- (T=5%,G=50%,C=0.7) compared with Seasonal S1).

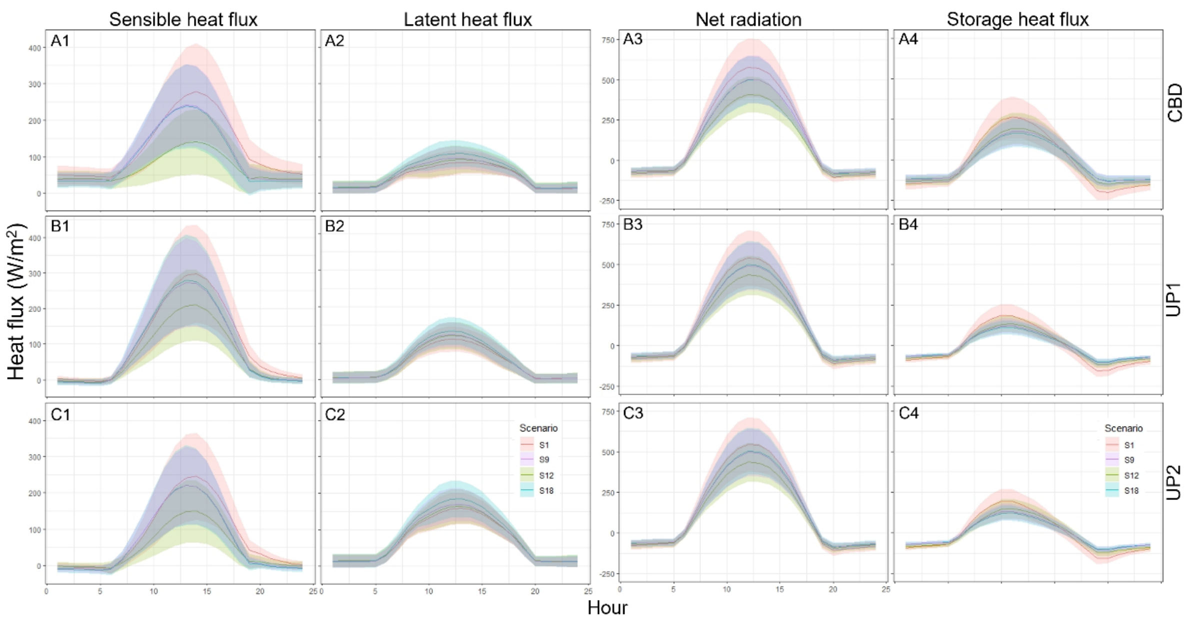

Figure iv: Seasonal mean for diurnal variation of sensible heat flux measured in larger grid (left:1), Latent heat flux (left:2), Net radiation (right:3) and storage heat flux (right:4) for summer 2011–2020 for selected scenarios (S1-(control, T=0,G=0,C=0.2; S9 (T=0,G=50%,C=0.7); S12 (T=5%,G=0,C=0.7) and S18 (T=5%,G=50%,C=0.7)) at A: CBD, B: UP1 and C: UP2

From all selected figures in the paper, we have recreated the above 3 Figures, ii, iii and iv and observed qualitatively similar results and graph patterns as the pre-drawn for smaller resolution and support the ultimate qualitative conclusion of the paper. Since these results are averaging an area of 9 km^2, instead of 1 km^2, wide standard deviations and decreased values are anticipated. It is expected to see averaging of the urban characteristics with a broader domain with uncleared LCZs boundaries. However, we observed with the compared results that the smaller domains are preferable for analysing and resolving issues with UHI as it facilitates sharper results with immediate land-surface changes.

References

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CSIRO. (2020). *CCAM*. Confluence CSIRO. https://confluence.csiro.au/display/CCAM/CCAM

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Chapter 5

"Redesigning urban landscapes with more vegetation and water and implementing passive cooling strategies to improve thermal performance and reduce energy consumption in buildings are key to making cities more resilient to heatwaves".

Jonathan Duwyn *(Head of Cities Unit, UN-Habitat)*

"Trees are the protagonists when it comes to cooling. Creating forests within cities and green corridors are an effective way to shift airmass to cool large areas within a city."

Eleni Myrivili *(Global Chief Heat Officer, UNEP)*

Australian National University

Statement of Contribution

This thesis is submitted as a Thesis by Compilation in accordance with https://policies.anu.edu.au/ppl/document/ANUP_003405

I declare that the research presented in this chapter represents original work that I carried out during my candidature at the Australian National University, except for contributions to multi-author papers incorporated in the thesis where my contributions are specified in this Statement of Contribution.

Title: Does the spatial configuration of urban parks matter in ameliorating extreme heat?

Authors: Prabhasri Herath, Xuemei Bai, Huidong Jin and Marcus Thatcher

Publication outlet: Urban Climate

Current status of paper: Not Yet Submitted/Submitted/Under Revision/Accepted/Published

Contribution to paper: PH conceived the idea, and PH and XB contributed to the conceptualisation and designing of the methodology. MT and HJ assisted with improvements of conceptualisation and methodology. PH performed the simulations, formal analysis, investigation, first draft preparation and visualisation. XB, HJ and MT provided editorial advice and overall supervision.

Senior author or collaborating authors endorsement: Xuemei Bai

Prabhasri Herath
Candidate

Signature

6 November 2023
Date

Endorsed

Primary Supervisor – Xuemei Bai **Signature** **Date**: 7 November 2023

Delegated Authority – ~~Philip Gibbons~~ Joseph Guillaume **Signature** **Date**: 7 November 2023

5. Assess the impact of the spatial configuration of UGI for reducing excess urban heat.

Does the spatial configuration of urban parks matter in ameliorating extreme heat?

Abstract

Extreme heat challenges the liveability of cities. Urban parks are popular as an efficient mitigative solution; however, uncertainties remain regarding whether and how the spatial configuration affects the effectiveness in practice. This paper tackles this issue by comparing the microclimatic amelioration potential of urban parks with the same green ratio in different spatial configurations. The study was conducted using microscale climate simulation in ENVI-met within three highly developed urban settings in Melbourne City, Australia, on 30th January 2009, during one of the most intense heatwave events. Hourly simulated data were extracted from all outdoor grids, encompassing nine heat-related indices, including meteorological variables, thermal comfort variables, and energy balance components. Linear mixed models were used to assess the effect of spatial configuration on improving outdoor thermal conditions. The results highlight a significant influence of spatial configuration in microclimate amelioration, and that these effects were context-specific, and no universally effective design emerged across locations, even within the same city. The findings underscore the necessity of considering other factors, such as surface cover characteristics and building configurations, and emphasise the importance of conducting site-specific simulations when introducing green infrastructure for heat mitigation.

5.1. Introduction

More than half of the world's population resides in cities (United Nations, 2018). Urban areas face risks from hazards amplified by climate change (Dodman et al., 2022). Excessive urban heat is a daunting challenge for cities, which has far-reaching consequences. This not only adversely affects the microclimatic comfort, health and well-being of city residents, but also poses challenges for infrastructure planning, and energy demands (Herath et al., 2021; Romanello et al., 2022). The increasing ageing population in cities adds an extra layer of exposure risk, vulnerability, and the impacts of extreme heat (IPCC, 2022; UN DESA, 2018).

Urbanisation substantially alters land utilisation, resulting in different surface characteristics, urban forms and geometries that alter the urban surface energy balance. Cities claim a decreased latent heat flux with less vegetation and increased anthropogenic heat emissions. Consequently, there are shifts in the energy budget and the corresponding increases in sensible heat fluxes, leading to elevated air and surface temperatures. This interplay gives rise to the urban heat island (UHI) effect, in which cities exhibit higher air and land surface temperatures than nearby rural areas (Oke, 1988).

The severity of urban heat escalates drastically in summer due to UHI intensities exacerbated by extreme heat from heatwaves (Herath et al., 2023; Kueh et al., 2017). In the Australian context, extreme heat events are the most significant natural hazard, and exposure to heat causes the highest mortality than all other natural hazards combined (Coates et al., 2014). Therefore, prioritising heat mitigation and adaptation is crucial for Australian cities and many other cities worldwide. Moreover, climate change predictions indicate a troubling escalation in the frequency, intensity, spatial extent, and duration of extreme heat events (IPCC, 2021). This necessitates immediate attention to heatwaves in research, urban planning, policy, and decision-making.

Nature-based solutions (NbS) have recently gained prominence as an effective means of mitigating excess urban heat. Among NbS, urban green infrastructure (UGI) is recognised for delivering a wide array of ecosystem services (ESS) across environmental, social, and economic domains (European Commission, 2013; Herath & Bai, 2023; MEA, 2005; Sugiyama et al., 2021). Urban heat mitigation is frequently discussed and expected in those ESS (Herath et al., 2021, 2023; Herath & Bai, 2023). Urban greenery provides cooling through mechanisms of evapotranspiration and shading (Taha, 1997; Tran et al., 2006). Evapotranspiration converts the sensible heat to latent heat, while shading reduces the amount of incoming solar radiation intended to be absorbed by urban surfaces (Krayenhoff et al., 2020; Taha, 1997; Winbourne et al., 2020).

This study focuses on the heat mitigation ESS of urban parks, which are open spaces with vegetation and water reserved for public use (Konijnendijk et al., 2013). The effectiveness of urban parks in mitigating urban heat has been well-documented in the literature. Some studies have focused on the dependency of urban heat amelioration on factors such as the size of urban parks (Jiao et al., 2017; Lin & Lin, 2016; Vaz Monteiro et al., 2016), distance from the park (Vaz Monteiro et al., 2016) and the park characteristics (Lin & Lin, 2016; Vaz Monteiro et al., 2016) for urban heat amelioration. The impacts of vegetation or tree coverage type (Duarte et al., 2015), and shape and structure variables (Park et al., 2017; Yu et al., 2018; Zhao et al., 2018) were also studied. Most studies have considered large city parks in terms of size and extent, whereas the thermal benefits of smaller parks have received relatively limited attention. We identified only three studies that discussed small urban parks (Motazedian et al., 2020), either as 'tree patches' or mini-parks' (Jiao et al., 2017; Lin & Lin, 2016). These small urban parks are described in different terms, such as pocket parks (Balai Kerishnan et al., 2020), small public urban green spaces (Peschardt et al., 2012), small green spaces (Park et al., 2017), mini-parks (Zhou et al., 2021), vest pocket parks (Faraci, 1967), street corner parks (Zhou et al., 2021), informal green spaces (Rupprecht et al., 2015), and patch size of trees (Jiao et al., 2017), while a relatively small number of studies have assessed the thermal benefits of mini-parks as 'patches of trees' (Jiao et al., 2017; Lin & Lin, 2016).

With the restrictions and limited accessibility of big central city parks during the recent pandemic, the potential utility of pocket parks in urban planning has received increased attention worldwide (Balai Kerishnan et al., 2020; Liu & Wang, 2021) and particularly in Australia (Berdejo-Espinola et al., 2021; Sugiyama et al., 2021). Prior studies in this domain have focused primarily on the benefits of park usage, visitation, and accessibility. However, none of the existing literature has undertaken a comparative assessment to determine whether pocket parks can provide equivalent or perhaps even superior benefits compared to their more expansive counterparts. Moreover, there are limited assessments of the relative effectiveness of a single larger city park versus several pocket parks for the best thermal performances. Lin and Lin (2016) attempted to identify the thermal behaviour of small, medium, and large park units in Taipei City using finer-scale and neighbourhood-level modelling. However, this case study was limited to one simulation location, and did not maintain the same green ratio across all scenarios (Lin & Lin, 2016). In practice, there is still a lack of clarity, which creates a dilemma in urban planning. This pertains to understanding whether and how the spatial configuration of urban parks with the same green area ratio affects their thermal performance (Herath & Bai, 2023).

Thus, this study aims to compare a single large park with multiple pocket parks to understand how different spatial configurations of the same amount of urban green change the heat-ameliorating capacity in nearby locations instead of a single simulation. Three highly developed urban locations in Melbourne were chosen as experimental sites, including Central Business District (CBD) areas, representing distinct urban settings with varying built-up, and surface cover characteristics associated with Local Climate Zones (LCZs). A series of simulations was performed using ENVI-met, a fluid dynamic, microscale model that captures the influence of micro but distinct urban land-use features on urban microclimate (Bruse & Fleer, 1998). Our experiments maintained the same total green space area and built-cover ratios, under which conditions the heat ameliorating capacities of different spatial arrangements of the green space area, that is, a single large park versus multiple pocket parks, were explored. The indicators explored included meteorological variables, thermal comfort indices, and surface energy balance components for microclimate amelioration.

5.2. Methods

5.2.1. Study area and experimental sites

Our simulation date represents the worst heat conditions during a heatwave day, on 30 January 2009, marking Melbourne's hottest day since the mid-1880s. Temperatures soared to a record-breaking 45.1 °C during a severe southeastern Australia heatwave (mean maximum summer temperature ranges from 24.8 to 27 °C for DJF in Melbourne, records from site 086071 (BoM, 2023)). Melbourne recorded an absolute maximum temperature of 46.4 °C during this heatwave, which persisted from 25 January to 9 February, resulting in 374 fatalities, 2,000 injuries, and the devastating Black Saturday fires on 7 February, causing 173 deaths, 414 injuries, and significant property damage (National Museum of Australia, 2022).

Greater Melbourne, the second-largest city in Australia and Oceania, spans 9,992.5 km^2 with a population of 4.96 million, while the City of Melbourne covers 37.7 km^2 with 184,000 residents (ABS, 2022; City of Melbourne Council, 2020). The CBD's population density reaches 26,420/km^2 within a 1.79 km^2 area. The city has a warm and temperate climate, classified as oceanic temperate climate conditions (Cfb) according to the Köppen climate classification. December to February is the Australian summer with frequently fluctuating hot-dry and cold-wet spells. Melbourne has 19.9 °C and 10.2 °C annual mean maximum and minimum temperatures with 648.3 mm annual mean rainfall (BoM, 2020). The CBD is 2.93 °C hotter than the surrounding rural areas during normal summer heat conditions (modelled 10-year average UHI), proving the existence of UHI in Melbourne (Herath et al., 2023).

The selected locations as experimental sites are situated on the edges of the CBD in Melbourne (–37.811425, 144.972917) characterised by highly developed and dense urban features (see Fig. 5.1). As larger urban parks are not prevalent in the CBD, the experiments focused on urban parks located at the periphery. In terms of land-use classifications, the Melbourne CBD exhibits compact high-rise characteristics (LCZ 1), while the non-CBD zone displays open mid-rise features (LCZ 5) with scattered tree cover (LCZ B), including adjacent urban parks (Stewart & Oke, 2012).

Figure 5.1: Left panels: Locational map for the study area. Right panel: Aerial image of the three study sites (marked with the yellow outline) in Melbourne CBD (Central Business District) and adjacent areas. Olympic Park weather station by the Bureau of Meteorology is shown in red.

5.2.2. Experimental framework

The experiments progressed through three main stages within the ENVI-met platform (see Fig. 5.2): model initialisation, simulation, and analysis. Model initialisation, including database creation, digitisation, and input data, is elaborated in Section 5.2.3, which provides comprehensive parameter configurations. Section 5.2.4, outlines indices and measurements. Model validation, which is essential for verifying the validity and credibility of a climate model, is presented in Section 5.2.5. Following validation, numerical simulations were performed during Melbourne CBD's most severe heatwave, representing a worst-case scenario. The outcomes of Stage 2 were employed in the final analysis stage, which encompassed thermal mapping (using Leonardo), microclimate analysis, and human thermal comfort assessments.

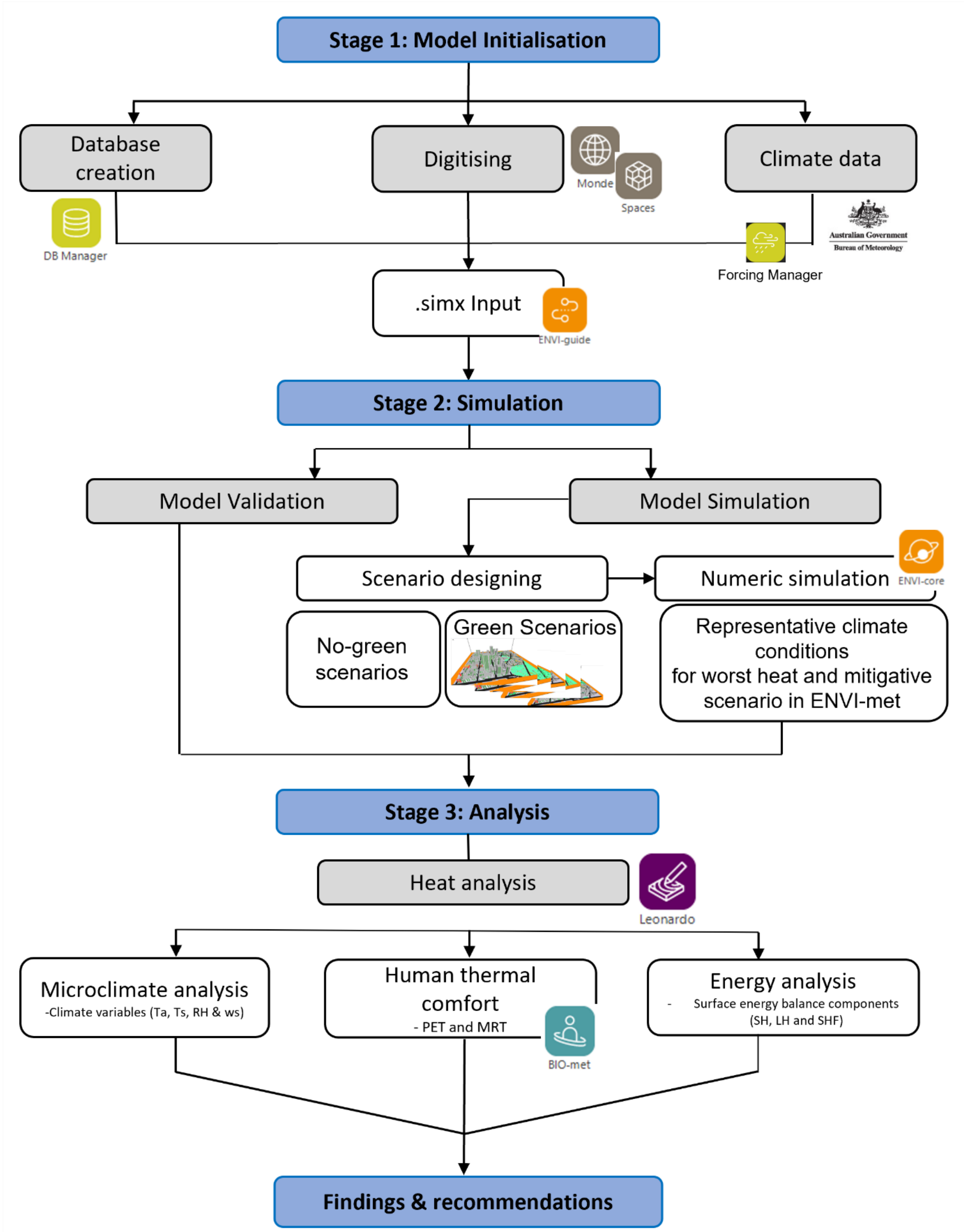


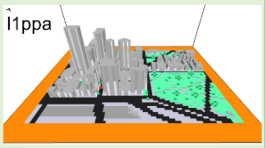
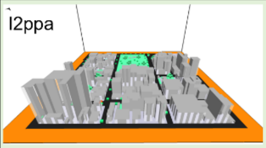
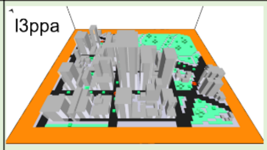
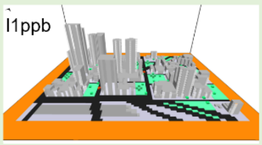
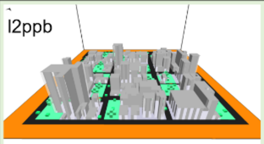
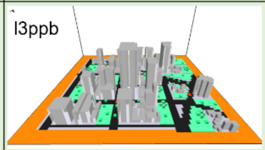
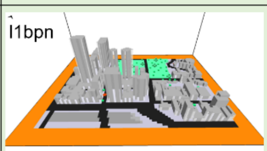
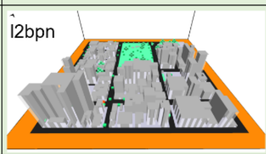
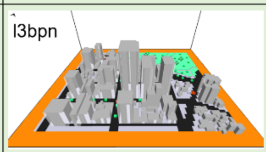
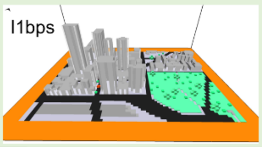
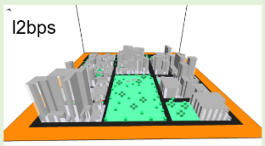
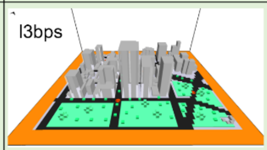
Figure 5.2: Framework for the experimental procedure: Stages 1, 2 and 3 are the main stages, and the rest of the steps are under those three main stages.

5.2.3. Model configuration

This study employed ENVI-met (V5) as a three-dimensional (3D) and non-hydrostatic microclimate model based on computational fluid dynamics (CFD) and thermodynamics. ENVI-met facilitates the simulation of interactions in the urban environments among urban surfaces, soils, vegetation, air, and buildings of varying sizes and forms (Bruse & Fleer, 1998; ENVI-met GmbH, 2022a). It offers a 3D prognostic meteorological model to calculate air temperature, wind flow, humidity, and turbulence at different grid resolutions (ENVI-met GmbH, 2022b). These climate calculations are based on shortwave and longwave radiation fluxes determined by shading, reflection, and re-radiation from the built and natural environments. ENVI-met has demonstrated success in diverse climatic conditions and urban microclimates (ENVI-met GmbH, 2022a), accounting for unique urban canopy characteristics such as shading and drag. Building height, surfaces, and vegetation data were extracted from OpenStreetMap (https://www.openstreetmap.org) using ENVI-met MONDE and shapefiles, with missing building height data supplemented by Butler (2015). The model areas were created in ENVI-met Spaces using those MONDE shapefiles.

Baseline domains without green spaces were created at three selected sites in Melbourne: Locations 1 (L1), 2 (L2), and 3 (L3). These areas feature mixed commercial, residential, and cultural land use. These XY domains measured 800 × 600 m^2 (L1), 750 × 760 m^2 (L2), and 680 × 580 m^2 (L3) and were rotated 20° from the north. Each domain contained 35, 25, or 30 vertical grids, each with a 10 m × 10 m × 10 m of resolution. The model boundary included 6–15 empty grids depending on the neighbouring building heights. A 20% telescoping effect (initiated after 250, 165, and 200 m for L1, L2, and L3, respectively) provides adequate space for the model tops, ranging from the tallest building tops at 265, 165, and 200 m. This was applied to facilitate simulation while maintaining a finer resolution near the ground. The first vertical grid was subdivided into five subgrids to facilitate measurements at the pedestrian level (1 m above the ground).

Table 5-1: Green scenarios description and location characteristics for the study.

	Scenario	Design and specifications			Description
		Location1 (L1)	Location2 (L2)	Location3 (L3)	
Location specs	Coordinates	-37.8135°, 144.9738°	-37.8121°, 144.9552°	-37.8082°, 144.9700°	Grid resolution = 10mx10mx10m
	Area	800 m × 600 m	750 m × 760 m	680 m × 580 m	Telescope factor = 20%
	#z grids	35	25	30	Model rotation = 20°
	Height	250m	165m	200m	Extra x,y grids in each side = 7-15
Scenarios	ppa	I1ppa 	I2ppa 	I3ppa 	Maintained the existing big park in the model site and placed the increased green in pocket parks in available spaces. No building replacements.
	base	No-green Scenario: I1ppa_ng	No-green Scenario: I2ppa_ng	No-green Scenario: I3ppa_ng	
	ppb	I1ppb 	I2ppb 	I3ppb 	Pocket parks in every built-up block. Green spaces distributed in built-up blocks with no big parks. Some buildings are replaced to manage spaces.
	base	No-green Scenario: I1ppb_ng	No-green Scenario: I2ppb_ng	No-green Scenario: I3ppb_ng	
	bpn	I1bpn 	I2bpn 	I3bpn 	With single big park from model north and no small park areas. Maintained the building footprint constant and replaced the removed buildings in available spaces.
	base	No-green Scenario: I1bpn_ng	No-green Scenario: I2bpn_ng	No-green Scenario: I3bpn_ng	
	bps	I1bps 	I2bps 	I3bps 	With single big park from model south and no small park areas. Maintained the building footprint constant and replaced the removed buildings in available spaces.
	base	No-green Scenario: I1bps_ng	No-green Scenario: I2bps_ng	No-green Scenario: I3bps_ng	

Four hypothetical scenarios (see Table 5-1) explored different spatial arrangements of equal urban green (and built-up ratios) within an urban block. The spatial configuration of urban parks was changed across scenarios, such as a single large park and several pocket parks, with different configurations, which require building replacements in some scenarios. The corresponding no-green scenarios allowed the isolation of building configuration effects. The difference between the corresponding no-green baseline and the green scenarios was averaged to represent the total area of the model. A total of 24 simulations were performed: four green and four no-green scenarios per location, each running for 55–120 hours. The scenarios comprised bps and bpn (an individual large park to the south or north), ppa (existing urban morphology with added pocket parks in the available spaces), and ppb (pocket parks distributed in every building grid). While ppa did not involve building replacements but minimal land-cover disturbances in paved open spaces to achieve an increased green ratio, bpn, bps, and ppb involved building replacements as needed. The placement of pocket parks was determined to minimise the need to replace skyscrapers in most building grids. Any removed buildings were relocated without altering their geometries. All green scenarios (bps, bpn, ppa, and ppb) had an equal number of available trees. The total green ratios (grass and trees) were 12, 14, and 18% at locations L1, L2, and L3, respectively. When the additional green spaces were incorporated, these ratios increased and remained at 17, 16, and 21% in the respective locations. The impervious–to–green ratios were 7.3:1, 6.1:1, and 4.6:1 at L1, L2, and L3 locations, respectively. With the inclusion of green spaces, these ratios improved to 4.9:1, 5.3:1, and 3.8:1, respectively.

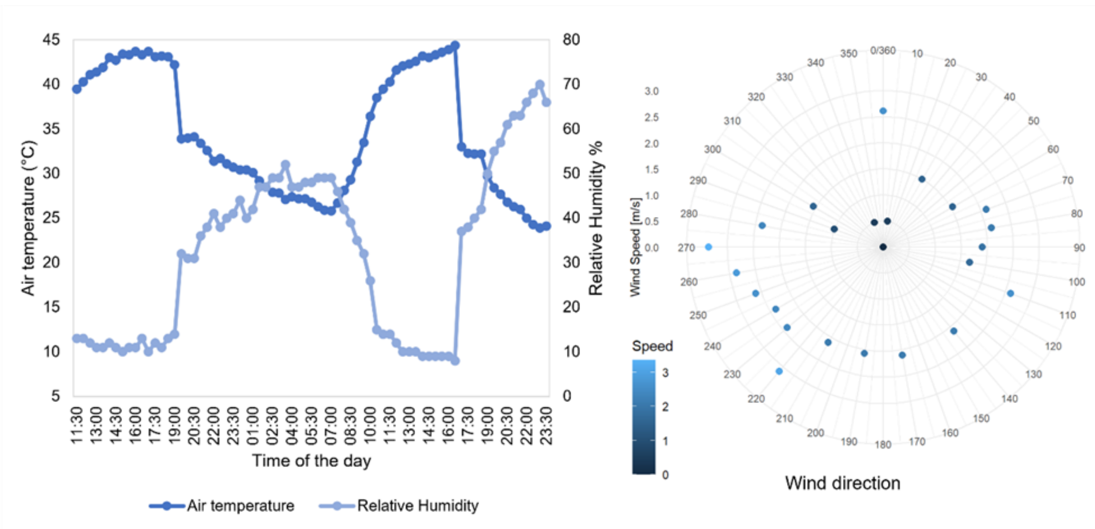


Figure 5.3: Climate data from BoM for 36 hours starting from 11.30 am on 29 January 2009, A) Air temperature and relative humidity; B) Wind speed and Wind direction (multiple speed values during the day towards the same directions have averaged out)

The simulations spanned 36 h, starting from noon on 29 January, to ensure model stability. The irradiation and heat release during the day and night were maintained with this extra 12 h in simulation duration. Data for analysis were extracted from all outdoor grids over a 24-h period. The variables to analyse were extracted from all outdoor grids for 24 hours. Simulations were fully forced with actual synoptic conditions, including air temperature, wind speed, wind direction and relative humidity every 30 min (see Fig.5.3). Weather data were sourced from the Australian Bureau of Meteorology (BoM) from stations in Olympic Park and Essendon (site numbers: 086338: –37.83°, 144.98° and 086038: –37.73°, 144.91°). The Essendon weather station provided boundary conditions due to its location outside the model domain. A roughness length of 0.1 m was assigned for the urban canyon. Table 5-2 details other input data in the configuration file.

Table 5-2: Input data for ENVI-met configuration files for Melbourne.

Input parameters for the configuration file	Initial value
Indoor temperature	20 °C
Albedo of walls	0.5
Albedo of roofs	0.5
Soil Profile	Loamy soil (Agriculture Victoria, 2020; Jamei & Rajagopalan, 2017)
Initial soil temperature upper layer (0–20 cm)	20 °C
Initial soil temperature middle layer (20–50 cm)	20 °C
Initial soil temperature deep layer (50–200 cm)	19 °C
Initial soil temperature bedrock layer (below 200 cm)	19 °C
Soil humidity upper layer (0–20 cm)	30%
Soil humidity middle layer (20–50 cm)	60%
Soil humidity deep layer (50–200 cm)	60%
Soil humidity bedrock layer (below 200 cm)	70%

The model consisted of different impermeable and artificial surfaces, including roads (asphalt roads) and paving (concrete, used/dirty) with permeable surfaces such as grass (newly created in the database) and trees (London planetree/ *Platanus x acerifolia*). Table 5-3 lists the physical and thermal characteristics of the materials used for the buildings and surfaces.

Table 5-3: Some physical properties of the surface and building materials. Absorptivity (α), reflectivity/albedo (ω), emissivity (ε), heat capacity (C), density (δ) and thermal conductivity (λ)

Materials	Rough- -ness length	α (fraction)	ω (fraction)	ε (fraction)	C (J/kg.K)	δ (kg/m³)	λ (W/m.K)
Concrete (walls and roofs)	0.02	0.5	0.5	0.9	850	2,220	1.6
Asphalt (roads)	0.01		0.2	0.9			
Used/dirty concrete (paving)	0.01		0.4	0.4			
Burned bricks (walls)		0.6	0.4	0.9	650	1,500	0.44
Heat-protected glass- one layered (walls)	0.02	0.05	0.05	0.9	750	2,500	1

5.2.4. Indices and measurements

For the analysis, nine variables–meteorology, thermal comfort, and energy budget–were extracted for all outdoor grids from the simulated results. Key meteorological measurements included air temperature (T_a), relative humidity (RH), and wind speed (ws) at a height of 1 m, and land surface temperature (T_s) at 0 m surface level. Surface energy budget components were sensible heat (SH), latent heat (LH), and soil heat flux (SHF). Mean radiant temperature (MRT) and physiological equivalent temperature (PET) were used to assess outdoor thermal comfort (OTC). PET is a universal index designed to determine OTC based on the Munich Energy-balance Model for individuals (MEMI). It rates heat stress on a nine-point numerical scale, from very cold to very hot (Fanger, 1972; Höppe, 1999; Jendritzky & Nübler, 1981; Matzarakis et al., 1999). In this study, 'BIO-met' post-processing application in ENVI-met calculated human thermal comfort using simulated climate data and extra input parameters for a standard 35-year-old male according to ISO 7730, including weight: 75 kg, height: 1.75 m, metabolic rate: 164.49 W (basal rate = 84.49 W + work rate = 80 W for walking at 1.2 m/s speed) and static clothing insulation index: 0.9 clo (ISO, 2005). Threshold levels for comfortable thermal conditions are presented in Table 5-4.

Table 5-4: Threshold levels and physiological stress grades for PET outdoor thermal comfort (OTC) index for a standard person with ISO 7730 standards (according to (Fanger, 1972)), PET: Physiological Equivalent Temperature, internal heat production: 80 W and clothing level: 0.9 clo. Adapted from (Matzarakis et al., 1999).

Thermal perception	Numerical range PET	Physiological stress
Very cold	Below 4	Extreme cold stress
		Very strong cold stress
Cold	4–8	Strong cold stress
Cool	8–13	Moderate cold stress
Slightly cool	13–18	Slight cold stress
Comfortable	18–23	No thermal stress
Slightly warm	23–29	Slight heat stress
Warm	29–35	Moderate heat stress
Hot	35–41	Strong heat stress
Very hot		Very strong heat stress
	above 41	Extreme heat stress

ΔX_{scn} expressed the difference between green (scn) and no-green (ng) scenarios in the corresponding grids for variable X for *i* in the x, y grid location, which calculated as,

$$\Delta X_{scn,\,i} = X_{scn\_ng,\,i} - X_{scn,\,i} \qquad \text{---}[1],$$

where, the measurements from the ng scenario and original scenario are denoted as X_{scn_ng}, and X_{scn}. Hence, ΔX_{scn} represents the measurement change due to the added green amount for each grid. ΔX_{scn} from all outdoor grids across the model domain were averaged out for each hour. Consequently, diurnal averaged delta data (24 values from 12 am to 11 pm) were used to evaluate the effect of spatial arrangement on each variable. Linear mixed models (LMMs) and estimated marginal means (EMMs) were employed to assess the effects and compare the scenarios. LMMs are extensions of linear regression models that describe the relationship between a response variable and other explanatory variables obtained along with the response variable. LMMs can cope with small sample sizes and use explanatory variables as fixed or random factors with different multilevel grouping factors. The simulated data were applied to a statistical model. Therefore, the use of EMM instead of raw means, is mainly for a fairer comparison among different levels of a factor in the model and not solely from the raw data. Tukey's pairwise comparison method for the t-test was used where necessary.

5.2.5. Model validation

Model validation ensures the reliability of model performance. Validation focused on the area around the Olympic Park weather station, using a 24-h simulation on a representative day, 19 January 2022, with normal mid-summer heat. Simulated data were extracted from a receptor point located on the weather station coordinates. Meteorological data from the Essendon weather station (outside the model domain) were used for full-forcing, whereas the field measurements at 30-min intervals (48 data points) for T_a, RH, and ws from the Olympic Park weather station operated by the BoM (within a 2 km radius of all sites) were used for comparisons. Results indicated a high coefficient of determination

(R^2) values for T_a (0.97) and RH (0.98), signifying substantial agreement between ENVI-met simulations and observed station measurements (see Fig.5.4). Comparatively, ws had a lower R^2 value (0.54), indicating a lower agreement than that of T_a and RH.

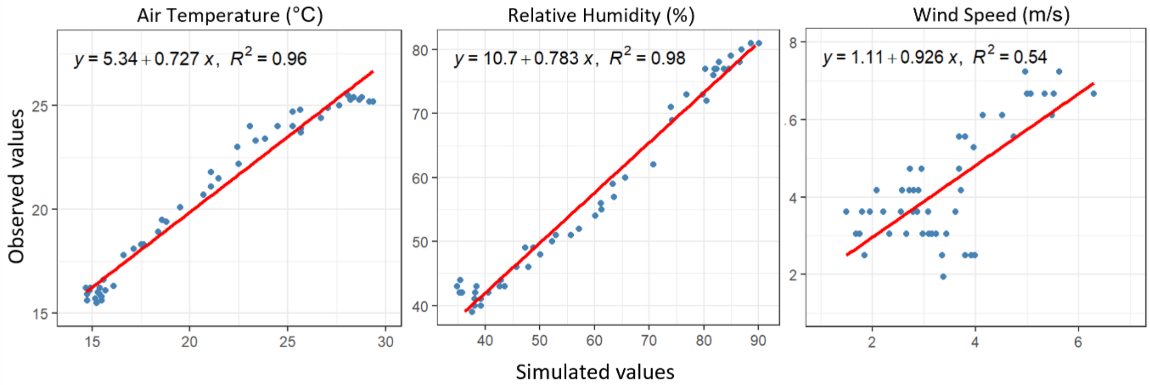


Figure 5.4: Regression of observed versus modelled (a) air temperature, (b) relative humidity and (c) wind speeds.

Table 5-5 shows that ENVI-met slightly overestimated the modelled mean for T_a and RH compared to observed means but underestimated wind speed. The slightly higher averages in simulated results might have been caused by the data acquisition from Essendon airport. This station was purposely selected because it is located around 10 km from the site, to be situated outside the model domain, while the observed data were extracted from the exact validation location. Overall, considering R^2 values, ENVI-met is deemed a reliable model for Melbourne's temperate climate.

Table 5-5: Model validation statistics

Index	**Air Temperature** (°T)	**Relative Humidity** (%)	**Wind speed** (m/s)
R^2 : Coefficient of determination	0.96	0.98	0.54
r : Pearson correlation coefficient	0.98	0.99	0.74
RMSE: Root mean square error	1.61	5.22	1.31
MAE : Mean absolute error	1.2	4.52	1.16
Observed mean	20.58	57.71	4.28
Simulated mean	20.97	60.06	3.42
Bias	0.39	2.35	–0.86

5.3. Results and discussion

5.3.1. Effect of spatial configuration of urban parks on meteorological variables

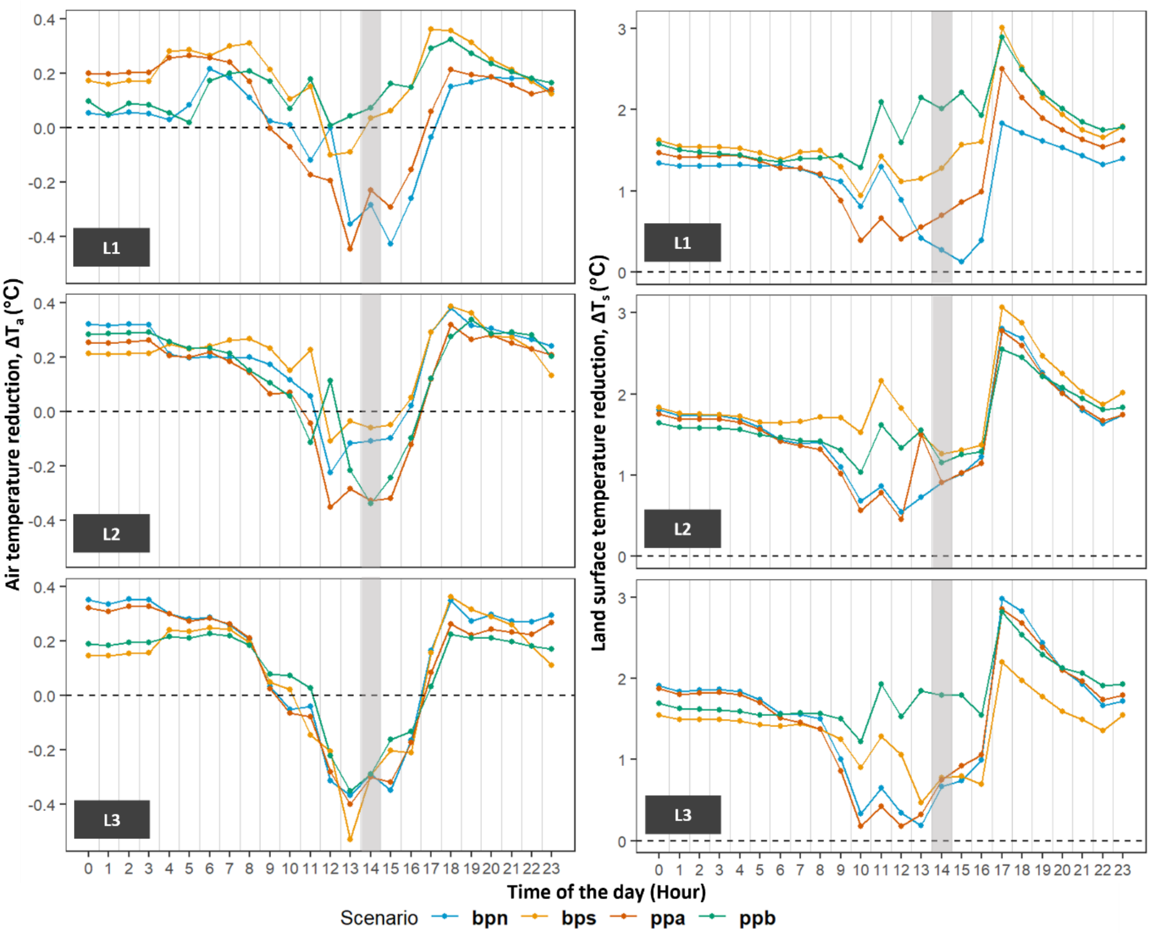


Figure 5.5: Diurnal air temperature (on the left) and surface temperature (on the right) reductions (ΔTa and ΔTs) by each scenario in different locations. Temperature reduction is calculated as the no-green scenario minus the green scenario. Positive values represent temperature reductions, which means the temperature reduction by the applied greenery. The dotted line represents no change between temperatures, while the grey shade represents the hour that records the maximum temperature value. L1, L2 and L3 denote 3 locations, and bpn, bps, ppa and ppb represent the scenarios introduced in Table 1.

Figure 5.5 depicts the diurnal air and land surface temperature reduction (ΔT_a and ΔT_s). Maximum ΔT_a was achieved by bps by 5 to 6 pm across all three locations. However, the scenario achieving the maximum at ΔT_a was not consistently effective in reducing T_a at 2 pm, the hour that reported the maximum T_a. The diurnal cooling efficiency of each scenario varied; ppa increased T_a during daytime (from 10 am to 4 pm) but demonstrated considerable reductions at night. In contrast, bps remained effective during most hours, with some transient increases than the no-green condition at noon. For ΔT_s, all green scenarios consistently reduced surface temperatures throughout the day, highlighting the cooling potential of urban parks. Urban green, in the form of grass and trees, reduces the interception of incoming solar radiation by shading and covering the floor instead of heat-absorbing concrete surfaces, which directly leads to low T_s. The maximum T_s reductions were achieved by bps in L1 and L2, while bpn was effective at L3 at 5 pm. In summary, it is assumable that any green arrangement effectively reduced average T_s in an urban area, but the T_a reduction potential relied on the scenario and location.

Effect sizes were evaluated for each variable to test the effectiveness of the results further. Table 5-6 presents the model effects, with F-statistics and p-values for four meteorological variables: T_a, T_s, ws and RH. The analysis evaluated the fixed main effects of the location of the model in the city (L1, L2 and L3), spatial configuration scenarios, and their interactions (location × scenario), while including the random effects due to the time of day. The linear mixed models (LMM) were arranged as follows,

ΔT_a ~ Scenario*Location + (1 | Hour)

which means the fixed relationship between ΔT_a and Hour may vary from one observation to another.

Table 5-6: Statistical summary of the Linear Mixed Models (LMMs) to estimate the effects between the variables and scenarios at the 0.95 confidence level. Statistical significance represents with * 0.05; ** 0.01; *** 0.001 next to the p-value. The overall effect size of the model parameters next to the value in the Effect size column as + small effect (0.01 – 0.06); ++ medium effect (0.06 – 0.14); +++ large effect (0.14 - ∞) and no + means negligible effect (<0.01).

Parameter	Scenario				Location				Scenario: Location			
outcome	**F value**	**p-value**	**Effect size**	**95% CI**	**F value**	**p-value**	**Effect size**	**95% CI**	**F value**	**p-value**	**Effect size**	**95% CI**
∆Ta	6.358	3.6×10^{-4} ***	0.070^{++}	[0.02, 0.13]	9.341	1.22 × 10-4 ***	0.070^{++}	[0.02, 0.13]	9.214	3.93×10^{-9} ***	0.180^{++}	[0.09, 0.25]
∆Ts	26.111	9.51×10^{-15} ***	0.240^{+++}	[0.15, 0.32]	26.111	5.41×10^{-5} ***	0.070^{++}	[0.02, 0.14]	11.491	2.30×10^{-11} ***	0.210^{+++}	[0.12, 0.29]
∆RH	9.119	9.42×10^{-6} ***	0.100^{++}	[0.03, 0.17]	9.119	1.50×10^{-5} ***	0.080^{++}	[0.03, 0.15]	19.083	< 2.2e-16 ***	0.310^{+++}	[0.21, 0.39]
∆ws	10.657	1.27×10^{-6} ***	0.110^{++}	[0.04, 0.18]	10.657	1.49×10^{-5} ***	0.080^{++}	[0.03, 0.15]	4.778	1.24×10^{-4} ***	0.100^{++}	[0.03, 0.16]
∆MRT	16.189	1.17×10^{-9} ***	0.160^{+++}	[0.08, 0.24]	16.189	9.92×10^{-15} ***	0.230^{+++}	[0.14, 0.31]	12.182	4.96×10^{-12} ***	0.220^{+++}	[0.13, 0.30]
∆PET	14.652	7.92×10^{-9} ***	0.150^{+++}	[0.07, 0.22]	14.652	2.84×10^{-13} ***	0.200^{+++}	[0.12, 0.29]	12.290	3.91×10^{-12} ***	0.230^{+++}	[0.13, 0.30]
∆SH	7.467	8.26×10^{-5} ***	0.080^{++}	[0.02, 0.15]	7.467	9.76×10^{-3} **	0.040^{+}	[0.00, 0.09]	1.622	0.1413	0.040^{+}	[0.00, 0.07]
∆LH	15.186	4.07×10^{-9} ***	0.150^{+++}	[0.07, 0.23]	15.186	0.756	0.002	[0.00, 0.02]	3.139	5.50×10^{-3} **	0.070^{++}	[0.01, 0.12]
∆SHF	0.367	0.78	0.004	[0.00, 0.02]	0.367	0.570	0.004	[0.00, 0.03]	0.596	0.733	0.010^{+}	[0.00, 0.03]

Table 5.7: Estimated marginal mean (EMM) difference of difference from pairwise comparisons (using Tukey pairwise comparison) between scenarios in each location. Negative values in cells represent ΔEMM of the first scenario < ΔEMM of the second scenario in the pair, which implies a comparatively higher average reduction by the second scenario. Thus, – or + sign is to decide the scenario with the better performance, and the cell value represents the reduced or increased mean of each measurement during the changing of scenarios. The method is similar for each variable, but the decision varies for wind speed and latent heat (LH). During the low wind conditions in the heatwave, mitigation scenarios are expected to increase the wind speed, and latent should be increased by vegetation to lose sensible heat (SH) via evapotranspiration. Values with * are statistically significant with p-values < 0.05. Shaded cells are statistically significant and effectively reduced the outcome than the first scenario (or increased for only ws & LH).

Variable	Location	Δbpn – Δbps	Δbpn – Δppa	Δbpn – Δppb	Δbps – Δppa	Δbps – Δppb	Δppa – Δppb
T_a	L1	–0.169*	–0.047	–0.130*	0.122*	0.039	–0.083*
	L2	–0.012	0.077*	0.037	0.089*	0.049	–0.04
	L3	0.049	0.023	0.043	–0.026	–0.006	0.02
T_s	L1	–0.458*	–0.125	–0.621*	0.333*	–0.163	–0.496*
	L2	–0.341*	0.007	–0.111	0.348*	0.230*	–0.118
	L3	0.164	0.037	–0.290*	–0.127	–0.454*	–0.327*
RH	L1	0.244*	0.588*	–0.046	0.344*	–0.290*	–0.634*
	L2	0.004	0.144	0.630*	0.14	0.627*	0.486*
	L3	–0.069	–0.054	–0.028	0.015	0.041	0.026
ws	L1	0.100*	0.075*	0.110*	–0.025	0.01	0.035
	L2	0.008	0.041	0.028	0.034	0.02	–0.014
	L3	–0.008	0.013	0.02	0.021	0.028	0.007
MRT	L1	–5.112*	–4.710*	–4.911*	0.402	0.201	–0.201
	L2	–0.094	0.138	–3.866*	0.232	–3.772*	–4.004*
	L3	0.424	0.202	0.384	–0.222	–0.04	0.181
PET	L1	–1.766*	–1.566*	–1.668*	0.201	0.098	–0.102
	L2	0.04	0.077	–1.239*	0.037	–1.279*	–1.316*
	L3	0.21	0.083	0.169	–0.127	–0.041	0.086
SH	L1	–2.846	1.021	–4.566	3.867	–1.72	–5.587*
	L2	–4.741*	1.195	–0.913	5.936*	3.828	–2.108
	L3	–0.025	1.485	–3.465	1.51	–3.44	–4.950*
LH	L1	–3.363	–4.775	1.756	–1.411	5.119	6.531*
	L2	8.692*	–0.237	7.210*	–8.929*	–1.482	7.447*
	L3	4.559	–0.167	9.093*	–4.725	4.535	9.260*
SHF	L1	–1.566	–0.813	–1.23	0.753	0.336	–0.417
	L2	–1.401	–1.646	–0.229	–0.245	1.172	1.417
	L3	1.287	–0.114	–0.229	–1.401	–1.516	–0.116

All meteorological variables in the total model area exhibited statistically significant effects in the implemented scenarios. Scenarios with different spatial arrangements have significantly driven meteorological factors in the model area, demonstrating the heat mitigation potential of urban parks. Location, as a main effect, had a statistically significant influence on all meteorological variables (the collective impact of built-up and surface cover characteristics), and its effect size was smaller than that of the scenario. The combined impact (location × scenario interaction) between the location and scenario drove all meteorological variables, with large effect sizes.

The pairwise comparisons in Table 5-7 reveal the comparative effectiveness of the scenarios. Negative ∆EMMs (the difference of the difference) indicate that the second scenario in a pair achieved a larger average reduction, which is valid for all variables except for ws and LH. Statistically significant cells marked with * indicate the significance; however, it is essential to consider whether they represent a reduction or increase, depending on the variable. For instance, increasing ΔT_a and ΔT_s means reducing the existing temperature by using a scenario as mitigation; however, reductions are meaningful for ∆ws and ∆LH since high wind speeds promote heat distribution, while extremely high wind speeds again become disadvantageous. Wind speeds are expected to increase because the observed speeds from the existing urban conditions were extremely low (close to zero), which causes heat stagnation in the urban canyon. However, not all the comparisons were statistically significant. Figure 5-6 illustrates the scenario comparisons per location for all meteorological variables. Positive values on the y-axis indicate that the green scenario yields lower means than the respective no-green scenario, which is favourable for ΔT_a, ΔT_s and RH, except for ws.

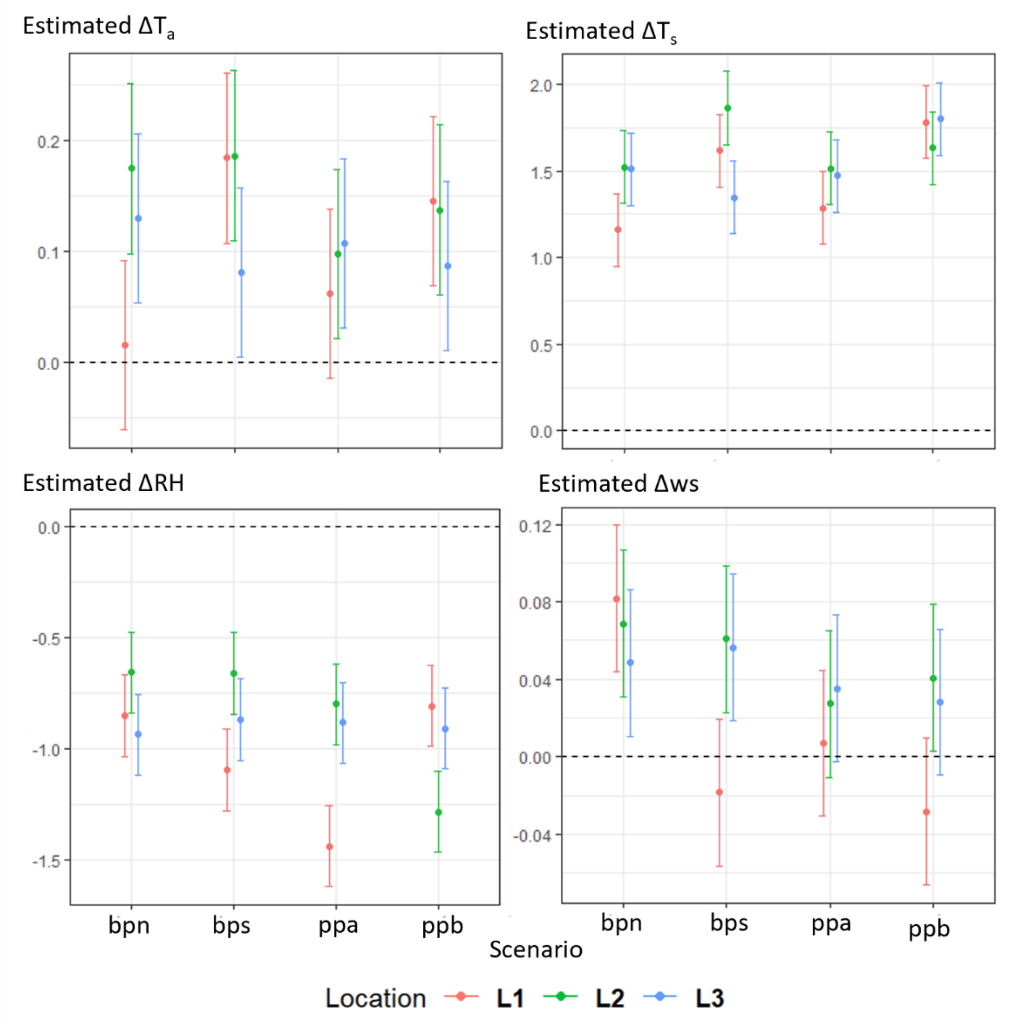


Figure 5.6: Delta Estimated marginal means (EMMs) of scenarios for each location presented in the effects plot for four meteorological variables. L1, L2 and L3 denote 3 locations, and bpn, bps, ppa, and ppb represent the scenarios introduced in Table 1. Δ values represent the differences between the EMMs for existing condition and scenarios for air temperature (Ta), land surface temperature (Ts), relative humidity (RH) and wind speed (ws).

Urban geometry significantly shapes the urban microclimate. The urban fabric with different geometric, orientation and configurational features drives the heat absorption from the sun (primary input of urban thermodynamic system), heat storage and heat exchange in the built environment (Bernabé et al., 2015). Complex heat exchange between building materials and adjacent air layers determines the intensity and airflow patterns in urban canyons (Soltani & Sharifi, 2017). Heat is primarily generated by impervious surfaces, lack of greenery, and urban metabolism, such as energy consumption and transportation, contributing to excess heat and the urban heat island (UHI) effect. Excess heat and UHI occur due to these factors and their interactions. Mitigation scenarios introduce vegetation into the model area, which can modify this excess heat.

Human thermal comfort is closely related to RH because heat dissipation through sweating depends on the air moisture content. Humidity is one of the six fundamental factors influencing thermal comfort, along with air temperature, radiant temperature, wind speed, clothing insulation, and metabolic heat. RH within the range of 40–70% has a minimal impact on thermal comfort (HSE Executive, 2022). Our results demonstrate that RH reductions in the model area showed statistically significant changes in both L1 and L2, although the effectiveness varied (e.g., the most effective ppb in L1 became the least at L2). For the overall pairwise comparisons, large parks proved to be better at improving RH in both L2 and L3 than pocket parks.

Wind speed, a key factor in thermal comfort, facilitates heat loss via convection. Dense CBD building structures increase surface roughness, causing drags on winds to impede air velocity (HSE Executive, 2022; Xia et al., 2022). Stagnant air within the urban canyon contributed to reduced turbulent mixing and weakened SH flux, resulting in significant differences in the T_s and T_a. Determining the optimal wind speeds to dissipate excess heat is debatable, and the mitigation potential varies with locations. Scenario ppb performed the best for L1 and L3, whereas ppa improved the wind conditions for L2. These mitigation scenarios are expected to increase the observed low wind speeds during heatwaves and disperse stagnant heat. Considering this pattern, we can imagine that distributing urban green as pocket parks in model areas acts supportively to improve wind conditions.

5.3.2. Effect of spatial configuration of urban parks on thermal comfort

Heat stress is a result of interactions among six key factors: ambient temperature, radiant temperature, humidity, air movement (environmental factors), metabolic rate, and clothing (behavioural factors) (Epstein & Moran, 2006). The modelling area was highly uncomfortable during the heatwave with extreme ambient and radiant temperatures and low wind speeds.

Thermal comfort is a subjective sensation defined as 'a condition of mind that expresses satisfaction with the thermal environment' (ASHRAE, 2017). Various indices, including the PET, MRT, universal thermal climate index (UTCI), predicted mean vote (PMV) and standard effective temperature (SET), can be used to assess thermal comfort. In our study (as discussed in Section 2.3), we used PET and MRT as thermophysiological indices to evaluate the OTC in Melbourne. MRT is a human energy balance governing parameter directly influencing air temperature, RH and wind speed, all of which are critical for assessing human thermal comfort (Höppe, 1999). From the established trade-offs, a change of 1 °C in MRT can be offset by 1 °C in air temperature (Epstein & Moran, 2006).

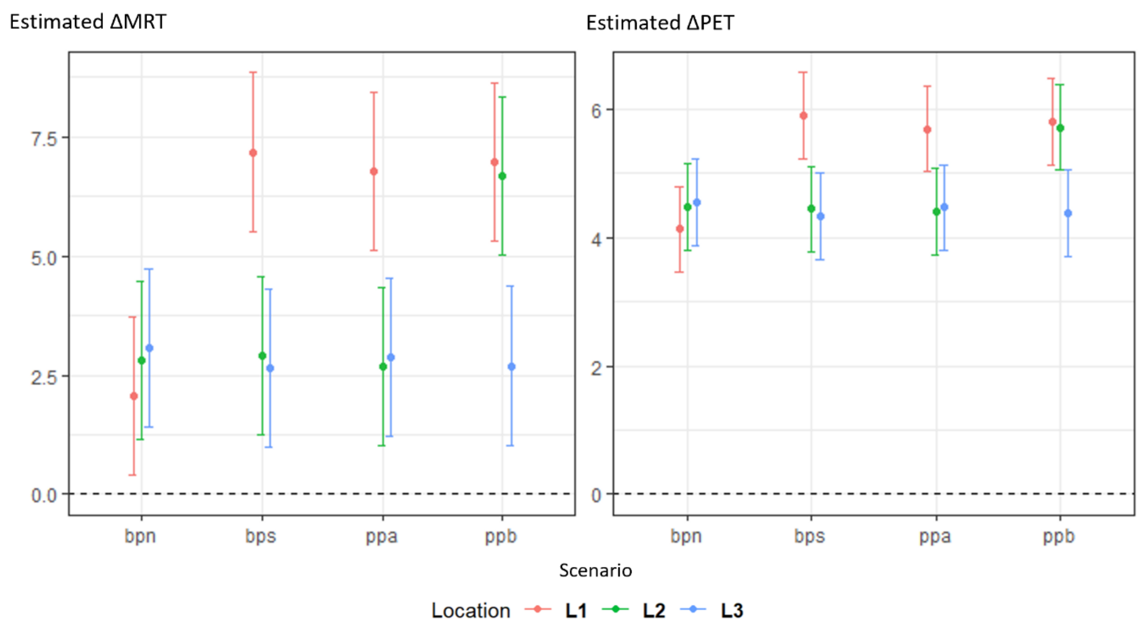


Figure 5.7: Effects plots for EMMs (estimated marginal means) of ∆MRT and ∆PET for each location. L1, L2 and L3 denote 3 locations, and bpn, bps, ppa, and ppb represent the scenarios introduced in Table 5-1. Δ values represent the differences between the EMMs for existing condition and scenarios for mean radiant temperature (MRT) and physiological equivalent temperature (PET).

Table 5-6 shows that TCIs, MRT, and PET have substantial effect sizes across all main and interaction parameters, and these indices are highly statistically significant ($p < 0.001$) for all model components. Notably, PET and MRT exhibited similar patterns of performance in L1 and L3, where big parks are effective. In contrast, L2 showed differing performance, with ppb being the most effective in reducing PET and MRT (see Fig. 5.7).

Figure 5.8 shows the MRT and PET values with similar trends. On 30th January, the heatwave day, daytime PET values fell in the range of slight heat stress to extreme heat stress (−23 to 41). In L1, bpn appeared to be less effective and could exacerbate thermal discomfort during heatwaves. L2 benefited from ppb, lowered the PET values, and even shifted them to comfortable ranges for some hours. In L3, all scenarios showed similar behaviours but did not reach the thermally comfortable zone, which is consistent with the extreme heat scenario. Overall, large parks proved to be more effective than pocket parks in enhancing thermal comfort in the model area.

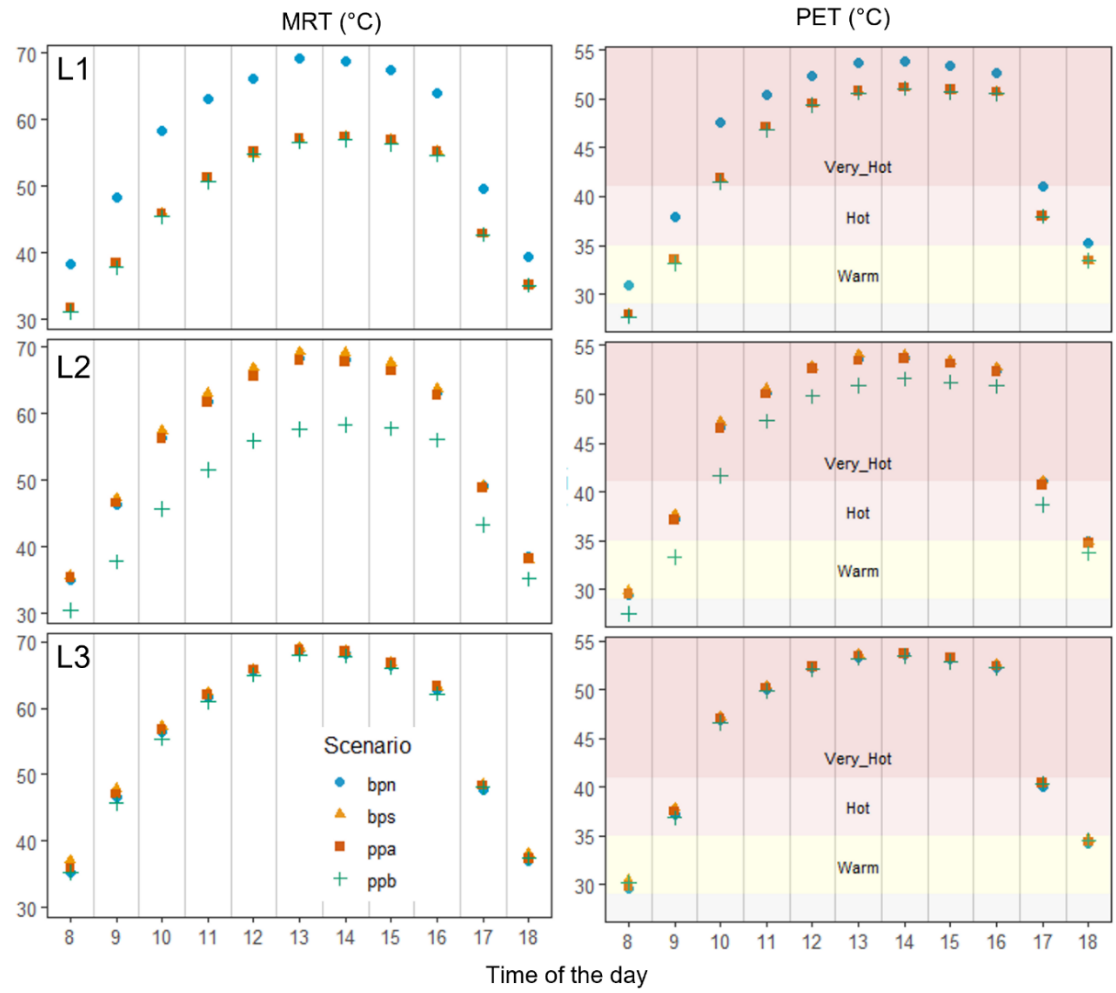


Figure 5.8: MRT and PET values for bpn, bps, ppa and ppb green scenarios during daytime: MRT values (left panel) and PET values (right panel). L1, L2 and L3 denote 3 locations, and bpn, bps, ppa and ppb represent the scenarios introduced in Table 5-1.

5.3.3. Effect of spatial configuration of urban parks on the surface energy balance

Solar radiation is the Earth's primary energy source. Approximately two-thirds of the incoming solar radiation is absorbed by land, water, and ice surfaces, whereas the remainder is reflected into the atmosphere. The absorbed heat is then emitted as longwave thermal radiation. However, human interventions, including the greenhouse effect, have disrupted this natural balance, which leads to trapping the excess heat (Met Office, 2022). This excess energy results in imbalanced energy flows, which are typically in equilibrium,

$$R_N = H_S + H_L + H_G$$

where H_S is the upward surface sensible heat flux (SH in this study), H_L = LE is upward latent heat flux owing to evaporation at rate E (LH in this study), H_G is the downward ground heat flux, and is the downward net radiative heat flux (SHF in this study) (Arnfield, 2003; Oke, 1987). In urban areas, R_N balances downward shortwave and longwave radiation minus upward reflected/emitted radiation. LH represents the energy generated via evapotranspiration, which can be significantly low because of limited vegetative surfaces (Papangelis et al., 2012). SH is released into the air, whereas soil heat fluxes are transferred into the soil or surface. Urban lands with dense building materials absorb heat substantially during the day, store it as SHF, and re-emit it at night, creating significant changes in urban microclimate (the UHI effect).

When cities are planned with vegetation through land-use mixing, the vegetative portion reduces heat trapping and enhances terrestrial radiation release compared with built-up areas (Herath et al., 2023; Papangelis et al., 2012). Under average thermal conditions, UGI, including urban parks, green roofs, green walls and wetlands, can reduce urban heat and improve thermal comfort in cities (Herath et al., 2018a, 2018b, 2021; Li & Norford, 2016; Papangelis et al., 2012). These interventions can alleviate urban heat and enhance thermal comfort even during heatwaves (Imran et al., 2018, 2019). This section uses a detailed microclimate model to examine how different spatial arrangements of urban parks impact thermal conditions in Melbourne CBD.

Table 5-6 presents ANOVA statistics for LMMs of three primary surface energy balance components: SH, LH, and SHF. Scenario significantly drove SH and LH, respectively, with medium to large effect sizes. Location mainly affected SH but not LH, suggesting that the spatial configuration of the same amount of green matters for LH, but not where that green is placed. Scenario–location interactions have small to medium effects on all components, rendering their effects statistically significant ($p < 0.001$), except for SHF.

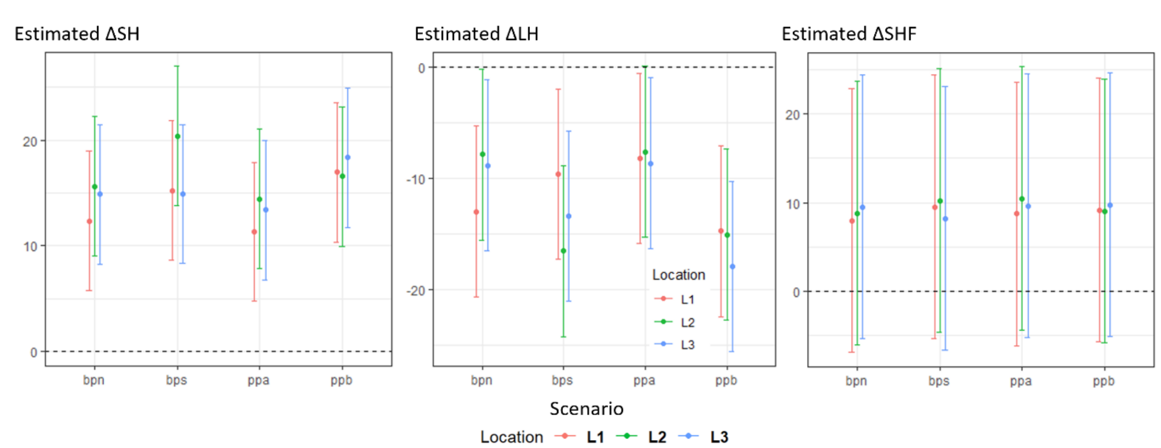


Figure 5.9: Effects plots for EMMs (estimated marginal means) of ΔSH, ΔLH and ΔSHF for each location. L1, L2 and L3 denote 3 locations, and bpn, bps, ppa and ppb represent the scenarios introduced in Table 5-1. Δ values represent the differences between the EMMs for existing condition and scenarios for sensible heat flux (SH), latent heat flux (LH), and soil heat flux (SHF).

Among the scenarios, ppb proved most effective for L1 and L3, with an average reduction in surface SH of 16.93 and 18.34 Wm^{-2}, respectively. Distributing pocket parks as ppa was the least effective for every location. L2 performed best with bps, reducing SH (average 20.37 Wm^{-2}) and improving LH (average –16.57 Wm^{-2}). All scenarios showed significant SH reduction after 5 pm (see Fig. 5.9). L1 and L3 experienced increased daytime SH (11 am – 1 pm) with bpn and ppa scenarios. In L2, all scenarios provided all-day SH reduction. The presence of green always increases the LH, which drew all negative values in the graph, while ppb recorded the highest values for increased LH in L3 as 17.94 Wm^{-2}.

In general, ΔSH and LH patterns were similar in L2 and L3. We observed that the scenarios showing a (significant or non-significant) reduction in SH reduce the EMMs for T_s. Following the above observations, the mitigation potential varied between scenarios in separate locations. When heat-absorbing urban materials were replaced by mitigative surfaces, it enhanced moisture availability, increased LH and decreased SH (Papangelis et al., 2012). Our results show that SHF did not indicate a significant change, while LH increased to use in evapotranspiration and balances with decreased SH. These rebalances led to T_s reduction and, eventually, the T_a in the area.

Although SHF changes were not statistically significant in pairwise comparisons, some contrasts showed reduced SHF at all three locations. This can be explained by the fact that the same amount of green coverage avoids consuming built-up areas, thus maintaining soil heat storage across scenarios. Low wind speeds reduce the turbulent heat exchange (SH flux) between the urban surface and the atmosphere, resulting in higher urban surface temperatures. Higher surface temperatures, in turn, further hinder heat exchange, resulting in a feedback loop that amplifies the temperature increase. Overall, it is evident that the surface energy budget is influenced by low wind speeds, as indicated by the higher temperatures. During extreme heatwaves, the tested mitigation scenarios were less effective in mitigating the UHI or improving nighttime thermal comfort, as the reduction in SHF for all three locations was not statistically significant, ensuring that these scenarios would not exacerbate UHI.

5.3.4. Selecting the best mitigation scenario

The nine indices examined in this study contribute directly and indirectly contributed to the thermal conditions of the city. As discussed herein, the energy balance components determine the surface temperature. The balance between incoming shortwave radiation and outgoing longwave radiation, known as net radiation, generates radiant energy that either heats or cools the surface. During the daytime when the sun is present, the net radiation becomes positive, resulting in more incoming solar radiation than outgoing longwave radiation, which leads to surface warming and higher surface temperatures. At night, as the surface radiates longwave energy into space, the net radiation becomes negative, thereby reducing surface temperature. T_a represents the ambient temperature in the area where city residents live and generally follows a similar trend to surface temperature. The net radiation depends on SH, LH, and SHF, and directly affects the thermal state of the city. MRT is derived from T_s and T_a and strongly influences PET (Fanger, 1972). The interconnected relationships among these indices underscore their significance in this study. The thermal comfort of cities during heatwaves and average heat conditions can be enhanced by reducing Ta, Ts, RH, MRT, PET, SH and SHF, while simultaneously improving ws and LH through different spatial arrangements of urban parks. Therefore, choosing appropriate scenarios to optimise all these indices is crucial for urban planning.

a

	L1							L2							L3						
ΔTa	bpn	<	ppa	<	ppb	<	bps	ppa	<	ppb	<	bpn	<	bps	bps	<	ppb	<	ppa	<	bpn
ΔTs	bpn	<	ppa	<	bps	<	ppb	ppa	<	bpn	<	ppb	<	bps	bps	<	ppa	<	bpn	<	ppb
ΔRH	ppa	<	bps	<	bpn	<	ppb	ppb	<	ppa	<	bps	<	bpn	bpn	<	ppb	<	ppa	<	bps
Δws	bpn	<	ppa	<	bps	<	ppb	bpn	<	bps	<	ppb	<	ppa	bps	<	bpn	<	ppa	<	ppb
ΔMRT	bpn	<	ppa	<	ppb	<	bps	ppa	<	bpn	<	bps	<	ppb	bps	<	ppb	<	ppa	<	bpn
ΔPET	bpn	<	ppa	<	ppb	<	bps	ppa	<	bps	<	bpn	<	ppb	bps	<	ppb	<	ppa	<	bpn
ΔSH	ppa	<	bpn	<	bps	<	ppb	ppa	<	bpn	<	ppb	<	bps	ppa	<	bpn	<	bps	<	ppb
ΔLH	ppa	<	bps	<	bpn	<	ppb	ppa	<	bpn	<	ppb	<	bps	ppa	<	bpn	<	bps	<	ppb

b

ΔTa	1	<	2	<	3	<	4	1	<	2	<	3	<	4	1	<	2	<	3	<	4
ΔTs	1	<	2	<	3	<	4	1	<	2	<	3	<	4	1	<	2	<	3	<	4
ΔRH	1	<	2	<	3	<	4	1	<	2	<	3	<	4	1	<	2	<	3	<	4
Δws	1	<	2	<	3	<	4	1	<	2	<	3	<	4	1	<	2	<	3	<	4
ΔMRT	1	<	2	<	3	<	4	1	<	2	<	3	<	4	1	<	2	<	3	<	4
ΔPET	1	<	2	<	3	<	4	1	<	2	<	3	<	4	1	<	2	<	3	<	4
ΔSH	1	<	2	<	3	<	4	1	<	2	<	3	<	4	1	<	2	<	3	<	4
ΔLH	1	<	2	<	3	<	4	1	<	2	<	3	<	4	1	<	2	<	3	<	4
overall	13		13		25		29	12		19		23		26	15		19		22		24
score	bpn	=	ppa	<	bps	<	ppb	ppa	<	bpn	<	ppb	<	bps	bps	<	ppa	<	bpn	<	ppb

Figure 5.10: Comparison of scenarios: a) arranged according to the order of performance based on higher reduction/increase based on the variable, b) scoring method, organised to give higher scores indicate better performance. Scores are rated as 1= lowest to 4 = highest in performance for ameliorating the index. L1, L2 and L3 denote 3 locations, and bpn, bps, ppa and ppb represent the scenarios introduced in Table 5-1.

Based on the values from the pairwise comparison in Table 5-7, Fig. 5.10a shows the performance of scenarios and their behaviour in each location. To compare and select the optimal scenario, a scoring method was employed, assigning rankings from 1 to 4 to reflect the performance from the poorest to the highest (see Fig. 5.10b). Because the SHF did not exhibit a statistically significant effect on any model component, it was omitted from consideration, leaving eight indices for scoring. Consequently, the maximum possible score for a scenario was 32, whereas the minimum score was 8. However, it is essential to note that this scoring system represents only one of several possible approaches and does not establish a standardised measure.

By incorporating different indices, this scoring method offered a practical approach for assessing the overall effectiveness of urban parks from their spatial arrangement as big parks or pocket parks. The scores obtained for L1, L2, and L3 indicated that ppb, bps, and ppb are the best scenarios for each respective location. None of the indices behaved similarly for all three locations. However, some general observations can be made. For instance, big parks outperformed in reducing average air temperature, while distributing park areas across the location led to better surface temperature reduction. Strategically placing urban parks throughout the urban area to enhance wind conditions proved advantageous. In an overall assessment across all locations, ppb emerged as the most effective scenario in two of the three locations, while in L2, ppb was the second best. Considering these findings, it can be inferred that distributing several pocket parks across the model area could be comparatively effective.

This method assessed the overall performance using eight different indices, removing any bias caused by considering only one variable. To select the most suitable urban park design for a specific location, this scoring method provided a flexible decision-making system for urban planners, decision-makers, and practitioners. In practical urban planning, the selection of mitigation scenarios is often based on the implementation costs. A ranking method that incorporates performance data can facilitate the decision-making process. For example, although ppb may not be a realistic solution for an established city, these scores assist planners in eliminating it as an option and selecting the next-best alternative based on the functionality of meteorological benefits. When designing new cities or suburbs with various options available, employing this approach allows the optimal selection of green plans tailored to the needs of specific areas.

Importantly, this study demonstrates that the suitability and performance of the best scenario were not uniform across all locations. This observation holds true even for locations in the same neighbourhood or city. This underscores the notion that a standardised optimal green space design cannot be recommended for an entire city based solely on simulation results from one location. The thermal performance of a large park or several pocket parks differed according to location. Various LCZ characteristics have been incorporated into this location term, including surface cover (vegetation cover or built-up area), structural elements (building heights, configurations, and materials), and street orientations. These factors are significant and unique as urban microclimatic characteristics that must be considered in heat mitigation planning. There is no universally superior design for effective heat mitigation because of this unique location dependency, which requires context-specific designs.

People visit urban parks for their physical and psychological well-being benefits. Historically, urban parks have primarily been considered recreational and public facilities during urban planning, focusing on economic development (Lin & Lin, 2016). However, the COVID-19 pandemic and associated restrictions on mobility and social distancing have highlighted the practical challenges of maintaining large public parks in city centres (Fernandez & Hart, 2020; Slater et al., 2020). These restrictions have led to severe consequences for the mental and physical health of urban population (Yu et al., 2018). Despite these restrictions, some studies revealed improved park usage in certain countries during the pandemic (Berdejo-Espinola et al., 2021; Venter et al., 2020). Green spaces served as 'safe havens' during COVID-19 (Herath & Bai, 2023), enabling citizens to use some outdoor areas in proximity (e.g., within 1 km or 1 mile) for physical exercise (Berdejo-Espinola et al., 2021; Sugiyama et al., 2021). Pocket parks have emerged as a viable solution for individuals who wish to avoid the health risks associated with crowded public parks (Berdejo-Espinola et al., 2021; Herath & Bai, 2023). In addition, pocket parks offer various benefits, such as fostering community interaction, improving social bonds and cohesion, enhancing recreational opportunities, and contributing to citizens' mental and physical well-being, all while promoting sustainability (Berdejo-Espinola et al., 2021; Liu & Wang, 2021; Zhou et al., 2021). This study expands on the thermal benefits and performance of different park arrangements.

The location of a park is primarily based on the availability of space during historic urban planning. The results of this study emphasise that location, built-cover and land-cover characteristics play significant roles in delivering the benefits of urban parks. Hence, when planning new cities and suburbs, the spatial arrangement and allocation of parks should be carefully considered. A broader implication of these findings is that evaluating and simulating a specific planning area is always advisable as a standard practice in urban planning. In terms of green mitigation plans, what works well in one city may not be applicable to others or even to separate locations within the same city. The unique microclimate and local climate conditions play a critical role, making context-specific simulations a crucial step in planning and decision-making, emphasising that no 'one-size-fits-all' solution exists for heat mitigation plans using urban parks.

5.4. Conclusion

We investigated the spatial configuration of urban parks to identify the optimal strategies for ameliorating outdoor microclimates. Four scenarios for each of the three selected experimental locations were evaluated, ranging from placing a single large park (in the north and south) to strategically dispersing pocket parks (within the available spaces and distributed in each building block) in the existing urban fabric with the same green-to-built-up ratio. Implementing pocket parks in available spaces is a scenario, which did not change the current building configurations, whereas all other scenarios redistributed the building configuration to create hypothetical spatial differences. By rigorously scrutinising these scenarios against a baseline devoid of green spaces with the same building configurations, we discerned notable variances in their effectiveness across nine heat-related indices, including meteorological, thermal comfort, and energy balance components. Our investigation, conducted at three nearby locations in Melbourne CBD during one of the worst heatwave events, yielded valuable insights and actionable recommendations for urban planners and policymakers grappling with the urgent need for sustainable urban development.

The findings of this study underscore the substantial influence of the spatial arrangement of urban parks on OTC. However, the impact of each scenario varied from one location to another, even within close proximity, demonstrating that there is no one-size-fits-all solution for green planning for heat mitigation. This diversity can be attributed to the unique location-specific microclimatic attributes (local climate zone - LCZ characteristics) prevalent in each area, including surface cover, built-up infrastructure, materials, and street orientations. There is no universal panacea for urban heat mitigation; instead, the success of these mitigation strategies depends on careful consideration of the local context. This study emphasises the pivotal role of context-specific green mitigation planning, which is supported by detailed site-specific evaluations and simulations during planning and decision-making. By carefully tailoring the unique location-specific characteristics, spatial arrangements, and holistic sets of climate indices, urban planners can unlock the full heat mitigation potential of a given amount of urban greenery. This approach maximises the effectiveness and ensures that limited resources are allocated judiciously.

While this study offers valuable insights, it is essential to acknowledge its limitations. The utilisation of ENVI-met, while powerful, consumed longer modelling time and entailed high computational demands that constrained downscaling for finer resolutions, such as

1−5 m, in complex urban areas. Due to time limitations, this project had to limit the study's scope to a reasonably high resolution (10 m) and assess the case during the worst-case scenario. In the scenario design phase, limitations stemming from the constrained space availability in an established, pre-planned, and densely built city compelled us to restrict the introduction of additional green, reflecting practical constraints in real-world urban planning contexts. In addition, extending the scope to encompass average heat conditions would provide a more comprehensive understanding of the efficacy of these mitigation strategies across diverse climatic contexts for future research.

These findings emphasise that a nuanced understanding of urban microclimates is essential for implementing effective park planning. We propose an integrated approach that considers the specific needs and attributes of each urban location. As cities face challenges posed by urbanisation and climate change, the role of urban green in mitigating these issues has become increasingly critical. By embracing innovative, context-specific strategies, urban planners can foster greener, cooler, more liveable, resilient, and sustainable urban environments.

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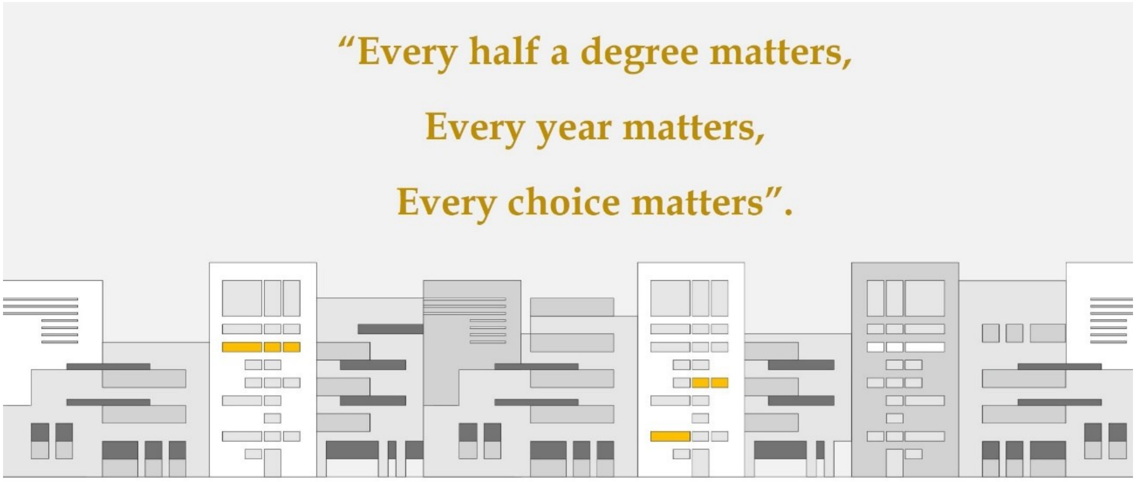
Chapter 6



Howden & Colvin (2018)

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6. Conclusions

6.1. Summary

Meteorological and local climate issues in cities are a major global concern in the changing climate context. As discussed in urban climatology, cities experience urban heat due to their complex urban systems, resulting in elevated temperatures (Masson et al., 2020). When compared to rural areas, this heat difference is described as the urban heat island (UHI) effect (Oke, 1973). Summer heatwaves exacerbate the already elevated heat (Rogers et al., 2019), leading to excess urban heat conditions. With predictions of more frequent and severe extreme heatwaves due to current and future climate change and global warming, extreme urban heat presents an additional challenge requiring immediate attention. Extreme urban heat poses a significant threat to cities, adversely affecting social, economic and environmental sectors. Furthermore, it heightens the risks, exposure and vulnerabilities of heat-related fatalities and illnesses within urban populations, particularly among individuals with varying socio-economic backgrounds, ages, and medical conditions. Consequently, urban planners for future cities must prioritise climate-resilient urban planning, which includes, most importantly, effective heat mitigation and adaptation strategies.

A lack of comprehensive knowledge about the effective use of operationalisable heat mitigation planning impedes the ability of planners and policymakers to manage this challenge. Therefore, this thesis evaluated the effectiveness of urban green infrastructural solutions to mitigate and adapt to excess urban heat during average summer and extreme heatwave conditions. The contribution of different types of urban green infrastructure (UGI) towards the average and extreme summer heat was evaluated in a temperate city using mesoscale and microscale climate models, The Air Pollution Modell (TAPM) (Hurley, 2008) and ENVI-met (Bruse & Fleer, 1998), respectively. This thesis advanced knowledge in urban planning using Melbourne as the case study city and provided empirical evidence related to existing research gaps. The main objective of this thesis was to evaluate the effectiveness of urban green infrastructural solutions as heat mitigation and adaptation strategies during extreme and average urban heat conditions in Melbourne, Australia. This primary aim was examined through four research questions (mentioned and discussed below in Section 6.2), which played the role of building blocks of each chapter.

6.2. Major findings

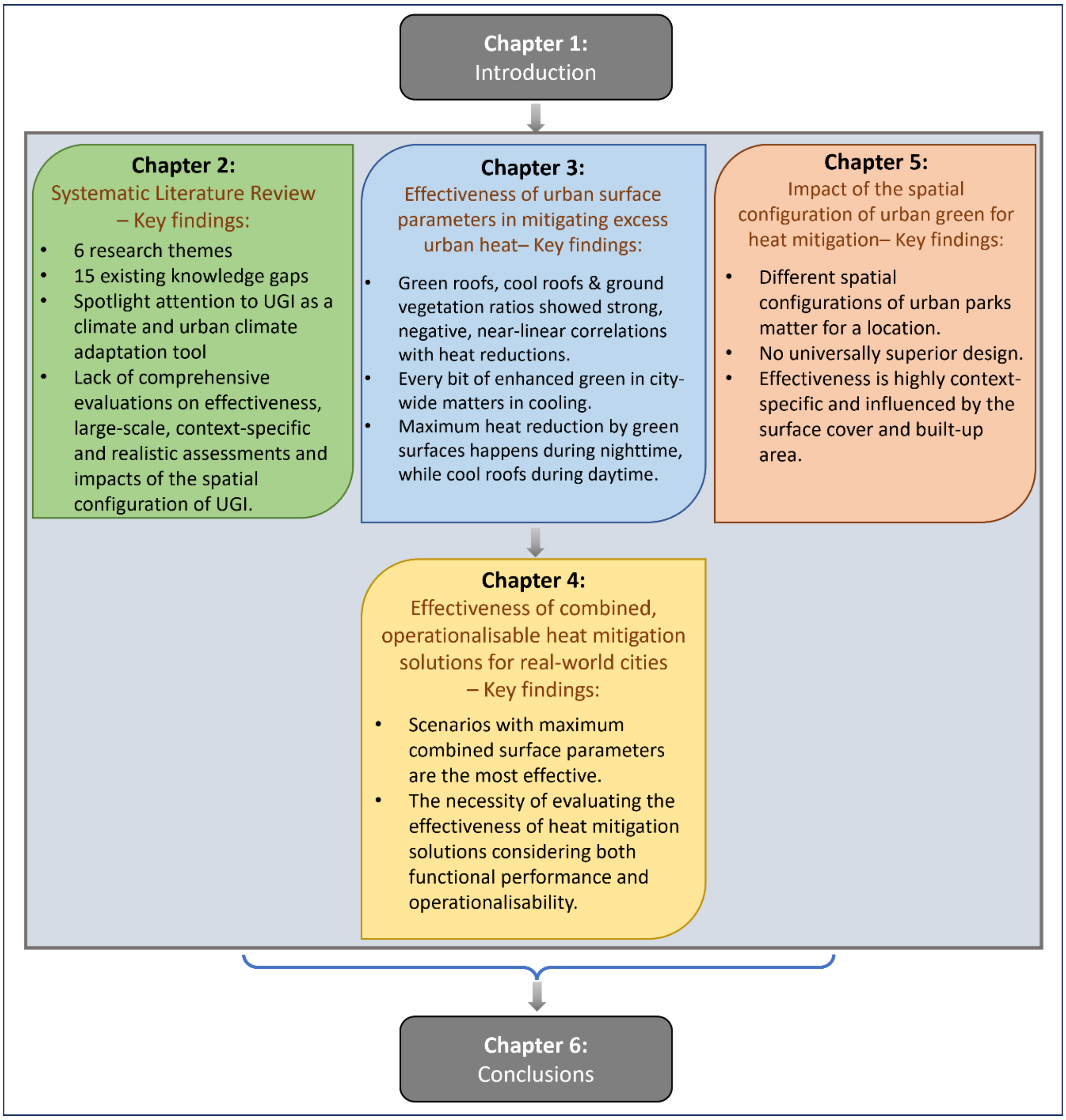

Figure 6.1: Key findings from Chapters 2 to 5

6.2.1. Research question 1: What is the role of green infrastructure for sustainable cities, and what are the gaps in the current literature regarding UGI solutions?

A systematic literature review of urban green infrastructure (UGI) was presented in Chapter 2, which shed light on urban ecosystem services (UES). By employing mapping and clustering techniques on selected empirical case studies, this chapter extracted contextual, methodological, geographic and temporal information about existing knowledge that helped to identify the current understanding of benefits and co-benefits of UGI through discussion trends, timely research focuses and links between research clusters. Based on the frequency of appearance in the network visualisation of keywords, six themes of current trends were identified, namely, 1) benefits of UGI as UES; 2) mitigating climate and urban climate impacts by UGI; 3) UGI contribution to sustainable development goals; 4) reconceptualising greenspaces as 'safe havens'; 5) public acknowledgement and supportive governance for UGI, and 6) rethinking the operationalisability of UGI. The first two themes represent the existing focus on categories of ecosystem services, the next two encompass broader emerging co-benefits and the last two focus on how to operationalise UGI and support widespread adoption and implementation. During the narrative discussion of each theme, fifteen existing research gaps were identified, and some of these gaps were needed to structure this thesis. The following paragraphs summarise these six themes while listing the existing knowledge gaps.

The literature was reviewed through a three-tier screening process representing a spectrum of research areas, demonstrating the diverse functionality and applicability of UGI in every domain (environmental, economic and social). Regarding the spatial distribution of publications, two-thirds of studies represent the Global North, emphasising the biases in urban research. Under the first theme, benefits of UGI as UES, the recognition of green infrastructure is highlighted as an integral component of a liveable and sustainable city by categorising the benefits of UGI as UES into the four traditional categories from Millennium

Ecosystem Assessment (MEA): regulating, provisioning, supporting and cultural ecosystem service (MEA, 2005). Regulating UES has become the most frequently discussed category (77.5%) while supporting, provisioning and cultural UES have appeared in relatively fewer percentages, 7.8%, 7.4% and 7.4%, respectively, of the total cases. This helped recognise the first research gap: (i) an uneven coverage of UES categories in the literature, meaning some benefits are underexplored and undervalued.

Throughout the literature, UGI is extensively identified as a climate and urban climate adaptation tool since the highest ratio of evidence was available for regulating climate and urban climate impacts among all other regulating UES. Hence, the second theme discussed is UGI for mitigating climate and urban climate changes. The expectations of using urban greenery are mainly focused on regulating urban temperature to control thermal comfort and air quality, and further extending towards other climate benefits of stormwater regulation, water storage, GHG mitigation, carbon storage and sequestration. However, heat regulatory service dominates other climate benefits as the most discussed service in the existing literature. Based on the discussion on this theme, the following further research gaps were identified: (ii) the diverse effectiveness of UGI plans over different climate zones; (iii) the availability of evidence-based measurements due to the lack of real-ground implemented evidence; (iv) the existing research primarily remains in the experimental or modelling stages.; (v) the lack of large-scale assessments of UGI for climate adaptation and overall effectiveness; (vi) insufficiency of multi-year analysis studies in the literature; (vii) inadequacy of assessments focusing on the co-benefits approach; and (viii) the limited investigations of UGI performance during extreme heat conditions.

Functional green spaces provide several co-benefits to the urban ecosystem by accommodating the 11th Sustainable Development Goal (SDG), sustainable cities and communities. Hence, the third theme was recognised as UGI contribution to sustainable development goals. Due to the interlinked and multidisciplinary nature of UES, cities can apply the co-benefits concept during sustainability planning with UGI to maximise effectiveness. Within the discourse of this theme, (ix) the Limited understanding of mechanisms for investing in UGI plans while addressing existing inequalities was identified as a substantial research gap.

During the COVID-19 pandemic, an increased connection between people and natural public spaces in urban areas was observed, recognised as theme four: reconceptualising green spaces as 'safe havens'. However, (xi) potential misuse of public green spaces beyond idealistic uses is still a significant grey area in the literature.

With the observed positive perception and high acceptance from the public and institutional and policy support, theme four was identified as public acknowledgement and supportive governance for UGI. Most city plans from European countries, USA and Australia have policy support for the mainstream green infrastructure plan. However, (x) the lack of clear pathways towards financing green infrastructure was identified as a research gap under this theme.

Possible limitations often disturb the translation of UGI planning to larger-scale implementations; hence, the sixth theme was introduced, rethinking the operationalisability of UGI. Green-blue-grey hybrid infrastructure can effectively deliver a spectrum of benefits and co-benefits; however, (xii) insufficient broader empirical basis for understanding the effectiveness and co-benefits brought by hybrid infrastructure solutions remains a research gap. The definition of effectiveness should account for operationalisability as a key consideration, but (xiii) the lack of comprehensive evaluation and assessment of the UGI effectiveness is noticeable in the existing literature. There is (xiv) insufficient exploration of the spatial configurational efficiency of UGI, which was identified as another research gap. This chapter confirmed (xv) the necessity of more research on context-specific, multi-year analyses in different climatic regions to inform city-level practice. Some of the findings from Chapter 2 were used as research gaps to address throughout this thesis.

6.2.2. Research question 2: How effective are the different urban surface parameters in mitigating excess urban heat?

Chapter 3 aimed to bridge the existing gap in context-specific heat mitigation planning by evaluating the effectiveness of urban surface parameters (USPs) in mitigating urban heat. This gap is addressed by simulating the heat performance of various USPs on a large spatial scale. Urban areas exhibit diverse surface characteristics due to extensive changes in land cover and land use, contributing to excessive urban heat. Factors such as reduced vegetation, the aerodynamics of urban materials, and limited water bodies influence the urban energy budget (Masson et al., 2020; Rizwan et al., 2008). Therefore, understanding the thermal behaviour of different USPs at large spatial scales is essential for strategic heat mitigation. Hence, Chapter 3 evaluates the correlation between urban heat and individual USPs, including vegetation type, built–cover ratio, green and cool roofs and building heights using different scenarios according to changing USP ratios. This case study was conducted in Melbourne, Australia, with a temperate oceanic climate, using a mesoscale climate model, TAPM, which is dynamically coupled with the Urban Climate and Energy Model (UCLEM) for urban parameterisation. The experiments are based on one-at-a-time (OAT) approach, and 52 simulation studies conducted for the austral summer (DJF) in 2019 were included in this sensitivity analysis.

The first phase of the study assessed the heat reduction potential of each scenario using different heat indices. According to the results, when natural vegetation of grasslands, shrublands and forests covered 100% land area, those scenarios achieved the best mean summer daily minimum temperature ($\Delta\overline{T}_{min}$) and attest to the cooling potential of natural vegetation in the absence of built-up characteristics. However, these unrealistic conditions do not apply to mitigating urban heat. When considering more realistic urban scenarios, increasing the roof reflectance helped to reduce the mean summer daily maximum temperature ($\Delta\overline{T}_{max}$) by 1.29 °C when the roof albedo is increased to 0.85 in the central business district (CBD). When the experiment area is occupied with 100% green roofs,

$\Delta\bar{T}_{min}$ reached the maximum reduction of 1.15 °C. Changing surface parameters had an impact on the number of hot days, HDs (>35 °C), and very hot days VHDs (>40 °C). Changing roof albedos in buildings situated only inside CBD reduced the number of HDs by 23%, while when the change was made in both CBD and the generic urban (UG) areas, the HDs reduced by 50%. By converting the total roof area (100%) to green roofs, hot nights – HNs (>20 °C) – were reduced by 43%, which creates a direct impact on reducing the UHI effect. In reality, no city can establish 100% cool roofs or green roofs as a part of their mitigation plans due to many practical limitations. Hence, the second phase of the experiment performed a correlation analysis to identify the relationship between the ratios of the parameters and the heat reduction variance. A negative linear correlation (r) of ~ –1 was observed between the urban vegetation ratio in CBD and $\Delta\bar{T}_{min}$. When applied green roof scenarios in both CBD and UG, $\Delta\bar{T}_{max}$ and $\Delta\bar{T}_{min}$ demonstrated strong, near-linear negative relationships (r=–0.99). Moreover, cool roofs in CBD and UG also exhibited a strong, near-linear negative relationship with $\bar{T}_{max}$. For Melbourne CBD, building heights did not show a statistically significant relationship with the temperature change.

This paragraph summarises the outcomes of Chapter 3. Most importantly, the heat reduction variations differed according to the time of the day. Green surfaces are the most effective option for heat mitigation at night, while cool roofs appear most effective in the daytime, which signifies that the effectiveness of heat mitigation strategies needs to be assessed with the concerns of diurnal variations. Consequently, green surfaces can be a more effective strategy for reducing the worst UHI magnitudes, while cool roofs are effective as an urban heat mitigation strategy when cities experience peak temperatures (Martilli et al., 2020). This diurnal variation indicated the potential for maximum diurnal cooling effectiveness by combining different surface parameters as mitigation strategies, as assessed in Chapter 4.

The results indicated that increased ground-level vegetation or cool roofs city-wide would provide a proportional benefit to cooling the microclimate with their level of area cover, which implies that all these three parameters contribute positively towards urban heat reduction. Ground-level vegetation is more effective at cooling a city when placed in parks rather than limited by proximity to walls and roads (street canyon). Urban trees offer higher cooling effectiveness when distributed in both canyon and urban parks than only planted in the street canyon; however, a more detailed analysis of how vegetation is parameterised will be required. It is essential to consider improving the surface characteristics in the overall city regardless of the generic urban area or the CBD for maximum thermal performance.

These findings highlight the significance of USPs for heat mitigation, which can inform strategic urban planning by incorporating green infrastructure. The simulation study helped to overcome limitations in translating neighbourhood-scale mitigation plans to larger scales and vice versa. The outcomes offer empirical evidence to identify effective strategies for heat mitigation at a city level on the basis that any change made can affect the unique urban microclimate. This mesoscale study enables the assessment of changes at the urban level to observe the impact at the microclimatic level and allows the usage of the identified successful USPs for finer-scale urban design in the next steps of our research.

6.2.3. Research question 3: How different heat mitigation solutions can be combined to deliver operationalisable strategies with maximum effectiveness in real-world cities?

In the existing practice, several strategic efforts on microclimatic heat mitigation are achieved through manipulating the above USPs with urban planning and design measures. Chapter 4 goes beyond the individual USPs from the previous chapter and considers the different efficacies of mitigation potentials and diurnal variabilities of different UPSs. Therefore, Chapter 4 was based on the hypothesis that the combined USPs may maximise the overall effectiveness and aimed to assess the effectiveness and operationalisability of different USPs for urban heat mitigation. Since each city has a unique microclimate, there are no one-size-fits-all planning solution, and each city needs to identify their context-specific green plan for urban heat adaptation and mitigation; Chapter 4 sought an operationalisable and effective heat mitigation strategy for the case of Melbourne, Australia.

Ground-level vegetation (urban trees), green roofs and cool roofs that proved effective in Chapter 3 were selectively used in Chapter 4. Melbourne city climate was simulated using TAPM mesoscale climate model with 1 km × 1 km spatial resolution for a 25 km × 25 km area. The simulations were conducted for 10 years to achieve a much larger sample size over a longer period than prior simulation studies. The heat variation was observed in both average and extreme summer conditions. The outcome emphasises the necessity of defining the effectiveness of UGI-based heat mitigation scenarios through functional performance and operationalisability. During the scenario design, the operationalisability of mitigation scenarios was considered in choosing realistic ratios; hence, urban trees to cover 20% of the total area, green roofs to cover 50% of the total roof area, and cool roofs with a 0.7 albedo to cover the rest of roofs were selected as the reasonable maximum ratios. The heat reduction potential was observed against different heat indices, including seasonal averages, maximum and minimum temperatures, and extreme temperatures during heatwaves and UHI. During a widespread heatwave event, some of the tested scenarios with combined surface parameters could reduce the extreme values of the energy budget components – sensible heat flux, latent heat flux and change in heat stored – up to seasonal averages compared to the existing urban conditions in Melbourne. The results demonstrate different heat reduction benefits, limitations and effectiveness levels across the scenarios with different heat indices. The scenario with combined parameters, with the highest ground-level vegetation, green roofs and cool roofs, could reduce air temperatures up to 2.4 °C, which suggested that the strategies with combined parameters of vegetative and high-albedo surfaces would deliver higher effectiveness with maximum cooling benefits for cities with the most realistic implementation (operationalisability) than mitigation strategies that use individual parameters.

The findings highlighted the cooling capacity of thoughtfully designed surface parameters, including increased tree coverage, creating urban parks, and promoting green and cool roofs within a city. The results emphasised the effectiveness of strategic planning that combines multiple urban surface strategies, surpassing the impact of a single approach for cities. These results agree with the findings from Jacobs et al. (2018) on using cool roofs and vegetation for urban heat mitigation. Moreover, the results effectively address a prominent confusion in the current urban heat and UHI mitigation literature. Martilli et al. (2020) highlight the need for distinct mitigation measures concerning urban heat and UHI magnitude. UHI mitigation strategies must prioritise nighttime effectiveness, as the strongest UHI magnitude occurs during evening or nighttime. Conversely, urban heat mitigation strategies should focus on their impact on absolute temperature, where the worst thermal stress and peak building cooling energy consumption are prevalent during the daytime (Martilli et al., 2020). Hence, combined mitigation strategies provide the highest effectiveness with this diurnal cooling and act as a mitigation strategy for both urban heat and UHI. Future cities need thoughtful urban planning to achieve the ultimate goal of enhancing their liveability. Chapter 4 concludes that this urban planning should consider strategies that improve diurnal thermal performance with fewer limitations on practicality and costs during implementation.

6.2.4. Research question 4: Does spatial configuration of UGI matter in reducing excess urban heat and improving human thermal comfort?

The heat mitigation potential of urban parks has been proven in previous literature; however, some areas related to their spatial configuration are yet underexplored. Considering mitigation strategies from both regional and neighbourhood levels is essential when planning healthier, sustainable and liveable cities. However, to observe impacts at the spatial configuration level, studies need to be downscaled to the neighbourhood level, and these finer-scale results have the potential to inform urban planning. Therefore, this thesis aimed to understand the influence of different spatial configurations of urban green on the effectiveness of microclimatic amelioration.

To investigate the effects of various spatial configurations of urban green spaces on the urban microclimate, four hypothetical scenarios were created, each representing the same amount of urban green. One big park or several pocket parks were placed in different urban locations to represent different spatial distributions. Each scenario has a no-green baseline to mitigate for the effects of building replacements, which enabled the analysis of the delta value between no-green and green scenarios. Diurnal data (24 hours) were extracted from all outdoor grids for four meteorological variables (air temperature [T_a], surface temperatures [T_s], relative humidity [RH] and wind speed [ws]), three energy budget indices (sensible heat [SH], latent heat [LH] and soil heat [SHF] fluxes) and two thermal comfort indices (mean radiant temperature [MRT] and physiological equivalent temperature [PET]) on 30 January 2009 (the middle day of the south-eastern Australian heatwave) to represent the extreme heat conditions. The use of three urban locations in Melbourne CBD with different built-up and surface cover characteristics, such as different building heights, green distribution and canyon orientations, which are related to different local climate zone (LCZ) conditions, supported an understanding of the impact of a particular location. All simulations were conducted in ENVI-met V5, a microclimate model, in 10 m x 10 m x 10 m resolution for 24-hour model time with an extra 12-hour spin-up time.

Simulation results reveal the significant impacts of meteorological variables and thermal comfort indices for all model components considered for scenario, location and the scenario–location interaction, proving those indices are driven by the impact of green and the built and surface cover characteristics. However, SHF was not statistically significant for any model component. LH did not have a statistically significant impact on location, while SH was for the location–scenario interaction. Results from pairwise comparisons and a scoring method indicated the most efficient scenario for each location. The arrangement when pocket parks distributed in each building block in the model location gave maximum scores in two locations out of three. None of the indices behaved similarly for all three locations, but the results indicated an effective way to include green spaces for a specific location. Although the locations are close to each other and within the same neighbourhood, the performance of various factors differed, which shows there are no universally superior designs for heat mitigation and that case-by-case assessments are required. The study proved that the overall suitability depends on the location or the combined LCZ characteristics based on each location's built and surface cover parameters. Therefore, this thesis emphasises that the effective performance of heat mitigation plans is highly context-specific, and there is no 'one-size-fits-all' solution for all urban locations.

6.3. Key conclusions and implications

The implications of the research in this thesis should be highly applicable to real-world cities. Since the simulation results proved the significant impact of built and surface cover parameters on the urban microclimate, mesoscale climate modelling studies could be used to identify the most influencing USPs in any city with any climate or geography. Changing and manipulating those USPs can bring a substantial cooling impact on cities. Meanwhile, city planners should try to increase their green surface cover. Due to the spectrum of ecosystem services that green infrastructure can provide, including urban heat regulation, urban planners, practitioners and decision-makers must try to enhance the UGI in cities to improve urban sustainability and liveability. In cities facing practical constraints like limited water and space for urban green, adopting a combined heat mitigation planning approach offers a realistic solution while ensuring optimal cooling effectiveness. The most influential USPs for a specific urban area can be strategically combined in practical and feasible ratios, with a focus on maximising urban greenery. However, it is crucial to consider each city's unique characteristics and context when increasing urban greenery, as poorly designed configurations can adversely affect the microclimate. A close investigation of the finer spatial scales is necessary to determine the influence of spatial configuration. Ground-level vegetation exhibits its highest cooling potential when evenly distributed throughout both the street canyon and urban parks. Planning urban parks requires a case-by-case evaluation, considering factors such as park configuration, whether they are large parks or pocket parks, and their specific location within the area. These considerations play a crucial role in shaping the thermal conditions of the surrounding environment. If a city needs to evaluate the best possible way to reduce its excess heat, it is advisable to perform context-specific simulations before planning and decision-making. This would be highly useful when planning new cities and suburbs, as' prevention is always better than cure'.

6.4. Limitations and future research directions

This paragraph summarises the limitations associated with the case study modelling to support highlighting potential avenues for future research. The urban surface parametric data required for TAPM mesoscale climate model was adopted from a previous study conducted in Melbourne by Coutts et al. in 2007. Despite the data being somewhat dated, they were used in the study with an acknowledgement due to their reliability as Melbourne's most recent available dataset. TAPM is coupled with some submodels for urban parameterisation. Although the main model was validated against real meteorological data during the model validation, the green roof sub-model was not validated separately using actual measurements from an urban green roof. Using a shorter duration (one summer) could introduce issues with climate variability. Although Chapter 3 used summer months in 2019, Chapter 4 extended the simulation to multiple years, providing a more comprehensive understanding and addressing possible flaws in the outcomes. Another possible limitation is that this thesis primarily assessed heat conditions during the summer. However, a year-round assessment to incorporate seasonal variations and extreme and average conditions is necessary for a complete understanding of the effectiveness of mitigation strategies. Finally, during the ENVI-met simulations, the scope was constrained to a reasonable resolution (10 m) due to the considerable computational demands and extended modeling times required for downscaling to finer resolutions (1-5 m).

To address the limitations identified above and enhance the accuracy of modeling efforts, we propose future research directions to conclude the thesis. This thesis has focused on how to improve the effectiveness of heat mitigation strategies with the highest levels of operationalisability. An essential avenue for future research is to explore the co-benefits of UGI plans in conjunction with their heat mitigation potential. Integrating these co-benefits into a comprehensive cost–benefit analysis is a crucial research task in future investigations. Our body of knowledge must be broadened both spatially and temporally to leverage co-benefits while adopting a comprehensive system framework. Additionally, it is essential to establish clear and consistent definitions of the term 'effectiveness' within the context of this research.

From a different perspective, our observations on the cooling benefits of green roofs are most pronounced when they possess sufficient soil depth, effective irrigation, and robust vegetation. However, green roofs have limited direct impacts on enhancing thermal comfort at the pedestrian level, which can be improved through developing green walls. Green infrastructural mitigation solutions in Australian cities face an extra challenge with irrigation due to their limited water resources. As an alternative approach, it is advisable to prioritise using cool roofs, while redirecting harvested water from roofs to support the development of green walls to improve the thermal comfort at the pedestrian level. Further comprehensive studies would be necessary to test and validate these insights rigorously.

Urban models serve as a valuable tool to approximate reality, but they are not flawless. They may not fully encompass all the necessary effects for a comprehensive assessment and can exhibit biases. Continuous refinement and upgrades are essential in striving for up-to-date and accurate information. As such, ongoing efforts in the realm of climate modelling are focused on improvement and innovation. For example, expanding the grid domain to capture urban–rural interactions and complex climate variabilities require more advanced climate models with increased computational power and resources. Future studies can expand on capturing these urban–rural interactions, including the impacts of advection induced by mesoscale circulations such as sea breezes or mountain-valley flow (as proposed by Martilli et al., 2020). This can be achieved by employing more robust regional climate models like the Conformal Cubic Atmospheric Model (CCAM) (CSIRO, 2020). While the main climate model validates against realistic urban conditions, there is a need for more extensive validation of the green roof model with actual measurements. Future studies should aim to evaluate the modelling ability of green roofs within TAPM with a real-city configuration more extensively.

The changes made in generic urban areas can create an effect on the climate within CBDs, and vice versa. Therefore, efforts to enhance thermal performance should incorporate comprehensive strategies within the broader context of city design rather than focusing solely on specific areas. Building upon this understanding, future research can explore the distances over which the CBD is influenced by the surrounding urban area, while emphasising the advantages of incorporating a more intricate three-dimensional model of the atmosphere (e.g., using CCAM (Chapman et al., 2018) or WRF (Jacobs et al., 2018)).

In addition, our findings from Chapters 4 and 5 suggest that the arrangement of trees in a city has a significant impact on the thermal conditions of the canyon. Parameterising vegetation with strong coupling to the urban canyon reduces the cooling efficacy of vegetation in cities. Our findings suggested that distributing urban trees equally in both street canyons and urban parks can enhance thermal performance when all vegetation is not placed in limited proximity to walls and roads. This conclusion requires further evidence, and future work, conducted at a regional and finer-scale level, could help validate and solidify this finding.

This thesis has concentrated on simulations of summer heat mitigation specifically for Melbourne, primarily due to constraints on computational power and time. A valuable avenue for future research would involve expanding the study to encompass a year-round analysis to provide a more comprehensive understanding of the functionality and effectiveness of the chosen mitigation scenarios across different seasons. Further, it would be intriguing to examine the microclimatic impacts of these selected scenarios under the evolving diverse climatic contexts in the near future. This thesis used case studies for current and past experiences (2009–2022), and as identified in Chapter 2, there is a research gap in evaluating future climate. Experiments could be conducted to see predictions for future cities in predicted high heat conditions with IPCC emission scenarios (e.g., the over 2 ºC warming scenario by IPCC) to evaluate the effectiveness of proposed combined mitigative scenarios from this study.

6.5. References

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