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Research Note

Mapping the climate risk to urban forests at city scale

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HIGHLIGHTS

- We used an urban tree inventory and high-resolution climate projections to identify species and locations at risk from climate change in Melbourne, Australia.
- The climate safety margin, an indicator of species' climatic tolerance, was used as a metric of climate risk.
- Presently, 218 species (46%) are exceeding their temperature safety margins; this number is predicted to increase to 322 species (68%) by 2050.
- Similarly, 255 species (54%) are exceeding their precipitation safety margins; this number is predicted to increase to 257 species (54%) by 2050.
- Our approach provides spatial information on climate risk at local scales appropriate for management decisions.

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ABSTRACT

Climate change represents a threat to the performance and persistence of urban forests and the multiple benefits they provide to city dwellers. Here, we use a novel approach to identify species and areas at high risk of climate change using the city of Melbourne, Australia, as a case study. We derive a safety margin, calculated based on climatic tolerance to two extreme climate variables (maximum temperature of the warmest month, MTWM; precipitation of the driest quarter, PDQ), for 474 tree species recorded in Melbourne for baseline (average for 2011–2020) and future (2041–2070) climatic conditions. For MTWM, 218 species (46%) are exceeding baseline climatic safety margins; this number is predicted to increase to 322 species (68%) by 2055 under the Shared Socioeconomic Pathway 5–8.5. For PDQ, 255 and 257 species (54%) are identified as at risk for baseline and future climates, respectively. Using georeferenced locations of trees and high-resolution climate data, we map spatial patterns in climate risk, showing high risk areas across the city. We demonstrate how using urban tree inventories and climate risk metrics can aid in the identification of vulnerable species and locations at high climate risk to prioritise areas for monitoring and assist urban planning.

1. Introduction

Urban forests (i.e., all vegetation present in urban areas; sensu Miller et al., 2015) exist within socio-ecological systems and provide multiple ecosystem services to people around the world (Keeler et al., 2019; Livesley et al., 2016). However, the performance and persistence of these forests are threatened by climate change (Esperon-Rodriguez et al., 2022a). In exacerbating the severity and frequency of extreme events, such as drought, heatwaves, storms and wildfires, climate change jeopardises tree physiological function, affects tree growth, and increases the incidence of dieback and mortality (Marchin et al., 2022; Smith et al., 2019; Yan and Yang, 2018).

Identifying vulnerable species and quantifying the risk of tree decline and mortality, therefore, can aid urban forest managers in optimising the use of resources and minimising losses in urban forestry programs (Esperon-Rodriguez et al., 2022a; Hilbert, Roman, Koeser, Vogt, & Van Doorn, 2019). Additionally, planting and preserving urban trees, particularly large-stature trees, can address climate change by cooling the environment via transpiration, shading buildings and paved surfaces to reduce energy usage, and storing carbon with high permanence

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(Nowak and Crane, 2002; Petri et al., 2016; Pregitzer et al., 2022; Sharmin et al., 2023; Zhao et al., 2023). Strategically, given the growth rates of trees and the importance of promoting tree longevity, urban greening via tree canopy cover must be planned years or decades in advance. Furthermore, urban forest planning requires consideration of future climate projections at each locality and in the context of specific site conditions.

Previous studies have assessed the impacts of climate change on urban forests from different perspectives, including climatic and environmental, socio-economic, and cultural (e.g., Brandt et al., 2016; Esperon-Rodriguez et al., 2022a; Lo, Byrne, & Jim, 2017; Ordóñez & Duinker, 2014; Zhang & Brack, 2021; Portoghesi et al., 2023). Although mapping the spatial risk of climate change has previously been done for natural ecosystems and human populations (Fremout et al., 2020; Gizachew and Shimelis, 2014; Scholze et al., 2006) to our knowledge, little effort has been made to develop methods and tools to map the spatial climatic risk of urban forests and there is no published research mapping of such risk. Given the high spatial heterogeneity of urban areas, the small-scale effects of urban trees (i.e., contribution to microclimate), and the species composition of urban forests, comprehensive spatial data at local scales are required (Zhao and Sander, 2018) to assess risk to climate change. However, these data are frequently absent and site-specific differences are overlooked in climate change risk assessments (Brzoska & Spāģe, 2020; Esperon-Rodriguez et al., 2022a; Ordóñez & Duinker, 2014).

Here, we hypothesised that the risk to climate change will vary spatially given site-specific differences caused by the city's urban configuration and the species composition of the urban forest. We tested this hypothesis by using a novel approach that integrates the climate tolerance of each species (i.e., safety margin, see details below) with urban tree inventory data to identify tree species and locations within the urban landscape at high and low climate risk. This analysis can be used in urban planning and management to guide future species selection and identify areas that require monitoring and where maintenance (e.g., irrigation) will be a priority. We used the city of Melbourne in Victoria, Australia, as a case study. The incidence of extreme climate conditions has increased throughout Australia, with rising extreme temperatures and more frequent severe summer droughts (Cai et al., 2014; Gallagher et al., 2021; Páscoa et al., 2022). As climate in cities, including Melbourne, become more extreme by mid-century, the rapidly changing conditions highlights the importance of identifying vulnerable and resilient tree species as well as high-risk areas in cities.

2. Methods

2.1. Study area

The City of Melbourne (hereafter Melbourne) covers the Melbourne central business district and surrounding inner-city suburbs of the greater metropolitan area of Melbourne. It covers an area of ~ 37.7 km^2 and has an estimated population of 169,860 people (data for 2021 from the Australian Bureau of Statistics <https://www.abs.gov.au>). The city's "The Green Our City Strategic Action Plan" aims to increase tree canopy cover to 40 % on public land by 2040, increase diversity of species and improve vegetation health (CoM, 2018).

Melbourne has a publicly available urban tree inventory (http://melbourneurbanforestvisual.com.au, retrieved March 2023). This inventory includes 76,928 individual georeferenced tree records (hereafter, "locations"). The inventory includes 497 species, subspecies, and varieties, which are both native and exotic to Australia, and includes trees planted in streets (39 % of all records) and parks (61 %); trees in public natural areas or on private property are not recorded. The most abundant species are *Eucalyptus camaldulensis* (8,141 records), *Platanus acerifolia* (5,140 records), *Allocasuarina verticillata* (3,306 records), *Corymbia maculata* (2,965 records), *Eucalyptus melliodora* (2,949 records) and *Ulmus procera* (2,190 records); these six species represent 32 % of the total abundance of trees in the urban tree inventory. In contrast, 262 species have fewer than 10 records. The inventory includes data on planting year (beginning in 1899), planting date, planting setting (i.e., park or street) and geographical coordinates (i.e., latitude and longitude).

2.2. Urban climate data

Baseline climate data for Melbourne were obtained with the UrbClim climate model, forced by ERA-5 reanalysis climate data from the European Centre for Medium Range-Weather Forecasting (Hersbach et al., 2020) and a set of open-source data products (Supplemental Table 1). UrbClim is an urban land surface model that has been specifically developed to obtain high resolution climate information for small-scale areas that typically comprise a city, and includes temperature, humidity, heat fluxes and soil parameters. UrbClim provides detailed temperature, wind, humidity information at a high temporal (hourly) and spatial resolution (100 m). These data discriminate the effect of different land surface types within a city on climate. The model has been validated in cities in Europe and the world (e.g., Lauwaet et al., 2015; Souverijns et al., 2022). A detailed description of the model physics can be found in De Ridder et al. (2015).

We selected two climate variables describing climate extremes: the maximum temperature of the warmest month (MTWM) and the precipitation of the driest quarter (PDQ). Baseline climate represents the average climate conditions during the period 2011–2020, while future climate represents the average of climate conditions during the period 2041–2070 (centred on 2055). Future heat stress data at 100-m resolution were obtained using UrbClim forced by the output of climate simulations obtained with global circulation models (GCMs) participating to the Coupled Model Intercomparison Project (CMIP6) for the grid cell where Melbourne is located. Fourteen CMIP6 GCMs were used in total (i.e., ACCESS-CM2, CMCC-CM2-SR5, CMCC-ESM2, CNRM-CM6-1, CNRM-ESM2-1, IITM-ESM, INM-CM4-8, INM-CM5-0, IPSL-CM6A-LR, KACE-1–0-G, MIROC-ES2L, NESM3, NorESM2-MM, and UKESM1-0-LL) and two Shared Socioeconomic Pathways SSP2-4.5 —this scenario is in the middle part of the full range of emissions scenarios investigated by the IPCC, and SSP5-8.5 —the highest global emissions scenario (Riahi et al., 2017). We used a quantile mapping approach using the climate change signal from the CMIP6 models to obtain future climate results. This approach, as described in Lauwaet et al. (2015), has proven to obtain accurate future climate results. For future scenarios and based on CMIP6 model uncertainty, we used the median across 14 GCMs for the two climate variables for all our analyses. In contrast, future precipitation was obtained directly from CMIP6 models, thus retains the resolution of their native grid (varying between 1°x1° & 2.5°x2.5°among GCMs). The projected changes by 2055 over Melbourne in each scenario are + 2 °C compared to preindustrial levels in SSP2-4.5 (very likely range across GCMs 1.6 °C −2.5 °C) and + 2.4 °C (very likely range 1.9 °C −3.0 °C) for SSP5-8.5 (IPCC, 2021). Future projections are based on the same species composition as present today in the urban forest inventory.

2.3. Species climatic tolerance and safety margin

We filtered the urban tree inventory by removing records of duplicate or unknown species, hybrids, and cultivars. We retained 474 species in 72,572 locations (parks = 45,199; streets = 27,373). For each species, we collected global occurrence records (i.e., native ranges and all recorded planted locations) from the Global Biodiversity Information Facility (GBIF.org;1 March 2023, GBIF Occurrence Download https://doi.org/10.15468/dl.4vy9r7) and sPlotOpen, an open-access, global dataset of vegetation plots (Sabatini et al., 2021). Records were cleaned and filtered to remove duplicate and spatially invalid records and locations with errors. We retained only species with more than 20 occurrence records. The average number of occurrence records per species was 4,766 (±12,077, standard deviation), with a maximum of

92,331 occurrences (*Quercus robur*). The taxonomic families with the highest number of species are Myrtaceae (120 species), Fabaceae (37), Fagaceae (36), Sapindaceae (23), and Rosaceae (22). Taxonomy was standardized and verified against GBIF using the *Taxonstand* package (Cayuela et al., 2017) in R (R Core Team, 2022).

Using these records, we estimated the 5th percentile of PDQ and the 95th percentile of MTWM for baseline climate as a proxy of the species' climate tolerance to water limitation and heat, respectively (Esperon-Rodriguez et al., 2022a). These variables are known for their biological relevance and influence on tree physiology, growth and survival (e.g., Field et al., 2014; O'Donnell and Ignizio, 2012). We extracted baseline climate data (95th percentile of MTWM and 5th percentile of PDQ) of each tree location provided in the urban tree inventory (latitude, longitude).

We used the species' safety margin (*S*) as a climate risk metric. The safety margin describes the intrinsic species' sensitivity to climate change and indicates potential tolerance to changing climate conditions (Gallagher et al., 2019). This metric was calculated for baseline (S_{Baseline}) and future (S_{Future}) climates as the difference between a species' climatic tolerance ($Species_{\mathrm{ClimateVariable}}$) and the climatic conditions at each tree location within the city ($City_{\mathrm{ClimateVariable}}$):

$$S_{Baseline} = \begin{cases} Species_{ClimateMTWM} - City_{BaselineClimateMTWM} \\ City_{BaselineClimatePDQ} - Species_{ClimatePDQ} \end{cases} \tag{1}$$

and

$$S_{Future} = \begin{cases} Species_{ClimateMTWM} - City_{FutureClimateMTWM} \\ City_{FutureClimatePDQ} - Species_{ClimatePDQ} \end{cases} \tag{2}$$

For *S*, the climatic tolerance of a species ($\mathrm{Species}_{\mathrm{ClimateVariable}}$) was measured as the 95th (MTWM) and the 5th (PDQ) percentiles of the species' climate range based on its occurrence records for baseline climate. The city's climate ($City_{\mathrm{ClimateVariable}}$) was obtained for each tree location using baseline and future climates from the UrbClim model. A positive safety margin ($S > 0$) indicates that the climatic tolerance of the species exceeds climatic conditions in the focal location (e.g., cooler/wetter and thus "safe"). In contrast, a negative value ($S < 0$) indicates that the species is subject to "unsafe" climatic conditions exceeding its climatic tolerance, which could compromise tree function and survival (Esperon-Rodriguez et al., 2022a). Although the species climatic tolerance remains constant as it is based on global occurrence records, the climate of each tree location varies given spatial variation across Melbourne and, as such, different planting locations may have slightly different climates based on high-resolution (100 m) climate modelling; therefore, the estimation of the safety margin of a given species may differ among individual trees depending on their location.

We used the non-parametric test Kruskal–Wallis to assess significant differences when comparing the safety margins of urban trees planted in parks and streets for baseline and future climates. Across all locations, we compared the climate exposure (i.e., the measure of how much the climate is projected to change and calculated as the difference between future and baseline climate at each location) between streets and parks. All analyses and data visualization were conducted using the statistical software R v.4.2.0 (R Core Team, 2022).

3. Results

Across all species and tree locations (i.e., parks and streets), for the 2041–2070 period compared to baseline conditions, the average increase in future MTWM was 1.2 °C ± 0.01 (SSP2-4.5) and 1.9 °C ± 0.02 (SSP5-8.5), while the average change in PDQ was 3.1 mm ± 0.02 (SSP2-4.5) and −0.7 ± 0.01 mm (SSP5-8.5). We did not find significant differences when we compared the exposure between streets and parks ($P > 0.05$). Average MTWM exposure of park and street locations was 1.15 and 1.16 °C, respectively for SSP2-4.5, and 1.85 and 1.86 °C, respectively for SSP5-8.5. For PDQ, there were no differences in exposure between parks and streets ($P > 0.05$).

For MTWM baseline (2011–2020) and future (2041–2070) climates, street trees had significantly higher safety margins compared to trees planted in parks (Table 1). Across all locations, for MTWM baseline climate, we identified 218 tree species (46 %) in 37,320 locations (51 %) exceeding their climatic tolerance. The number of species and locations are predicted to increase in the future under both SSP5-8.5 and SSP2-4.5. For baseline and future conditions, park locations had far higher numbers of species at risk compared to street locations (Table 2).

In contrast, for PDQ, trees in parks had significantly higher safety margins compared to street trees for both baseline and future climates (Table 1). Across all locations, a greater number of species exceeding their safety margins were identified for PDQ baseline conditions: 255 species (54 %) in 46,508 locations (64 %). Future PDQ under SSP5-8.5 represent a high risk to 257 species; however, under SSP2-4.5, the number of tree species and locations at risk is predicted to decrease marginally. For both baseline and future conditions, park locations had far higher numbers of species at risk compared to streets (Table 2).

Across all locations and species, the average baseline MTWM safety margin was 0.4 °C ± 2.3, while future MTWM safety margins were −1.4 °C ± 2.3 (SSP5-8.5) and −0.7 °C ± 2.2 (SSP2-4.5), reflecting increasing risk with further global warming (Fig. 1). The number of plant families at risk from changes in MTWM was predicted to increase from 38 (baseline) to 48 by 2055 for SSP5-8.5 and to 45 for SSP2-4.5, where Myrtaceae, Fabaceae and Proteaceae had higher proportional increases in the number of species exceeding their safety margins. For baseline climate, 189 species (40 %) exceeded their MTWM safety margin in all locations (100 %) where they are planted, while 256 species (54 %) were identified as "safe" (i.e., within their safety margins) in all locations. By 2055, 304 (64 %) and 189 (40 %) species were predicted to exceed their MTWM safety margins in all locations where they are planted for SSP5-8.5 and SSP2-4.5, respectively; 152 (32 %) and 256 (54 %) species were predicted to remain safe in all their locations for SSP5-8.5 and SSP2-4.5, respectively. The five species at highest risk under both SSP2-4.5 and SSP5-8.5 for MTWM were *Eucalyptus pulchella, Nothofagus cunninghamii, E. brookeriana, E. pulchella,* and *Ulmus glabra*. In contrast, some of the most abundant species in Melbourne, like the native *E. camaldulensis* and the exotic *Platanus acerifolia*, were predicted to be within their safety margin in all locations where they are planted for baseline and future climates (Supplemental Tables S2-S4; Supplemental Data).

For PDQ, the average baseline safety margin was −8.2 mm ± 42 and average future safety margins were −8.9 mm ± 43 (SSP5-8.5) and −5.2 mm ± 41 (SSP2-4.5) (Fig. 1). Forty-six families were predicted to be at risk for baseline and future climate under SSP2-4.5, while 47 families were predicted at risk under SSP5-8.5. Baseline safety margins of 255 species (54 %) were exceeded in all locations (100 %) where these species are planted, while 219 species (46 %) were safe in all locations.

Table 1
Kruskal Wallis test results (H = Kruskal-Wallis statistic) comparing park and street tree average safety margins of baseline (2011–2020) and future (2041–2070) for the maximum temperature of the warmest month (MTWM) and the precipitation of the driest quarter (PDQ) across all tree species (n = 474) and locations (n = 72,572: parks = 45,199; streets = 27,373) in Melbourne, Australia.

Location	MTWM Baseline	MTWM Future SSP2-4.5	MTWM Future SSP5-8.5	PDQ Baseline	PDQ Future SSP2-4.5	PDQ Future SSP5-8.5
Park	0.1 °C	−1.1 °C	−1.8 °C	3.4 mm	6.4 mm	2.6 mm
Street	1.0 °C	−0.1 °C	−0.8 °C	−27.3 mm	−24.3 mm	−28.1 mm
Statistic						
H	3598.7	3596.6	3591.4	8519.7	8504.7	8522.7
P value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Table 2
Number (and percentages) of tree species and locations in Melbourne, Australia, exceeding their safety margins of the maximum temperature of the warmest month (MTWM) and the precipitation of the driest quarter (PDQ) under baseline (2011–2020) and future (2041–2070) climate conditions under two Shared Socioeconomic Pathway (SSP2-4.5 and SSP5-8.5). Total tree species is 474 and total tree locations is 72,572 (parks = 45,199; streets = 27,373).

		MTWM Baseline	Future SSP2-4.5	Future SSP5-8.5	PDQ Baseline	Future SSP2-4.5	Future SSP5-8.5
Species	Total	218 (46 %)	280 (59 %)	322 (68 %)	255 (54 %)	245 (52 %)	257 (54 %)
	Parks & Street	122 (26 %)	147 (31 %)	179 (38 %)	150 (32 %)	142 (30 %)	151 (32 %)
	Parks	86 (19 %)	120 (25 %)	128 (27 %)	90 (19 %)	88 (19 %)	91 (19 %)
	Street	10 (2 %)	13 (3 %)	15 (3 %)	15 (3 %)	15 (3 %)	15 (3 %)
Locations	Total	37,320 (51 %)	43,053 (59 %)	50,170 (69 %)	46,508 (64 %)	42,408 (58 %)	46,642 (64 %)
	Parks	25,960 (36 %)	29,234 (39 %)	33,131 (45 %)	25,735 (35 %)	22,353 (31 %)	25,790 (36 %)
	Street	11,360 (16 %)	13,819 (19 %)	17,039 (23 %)	20,773 (29 %)	20,055 (28 %)	20,852 (29 %)

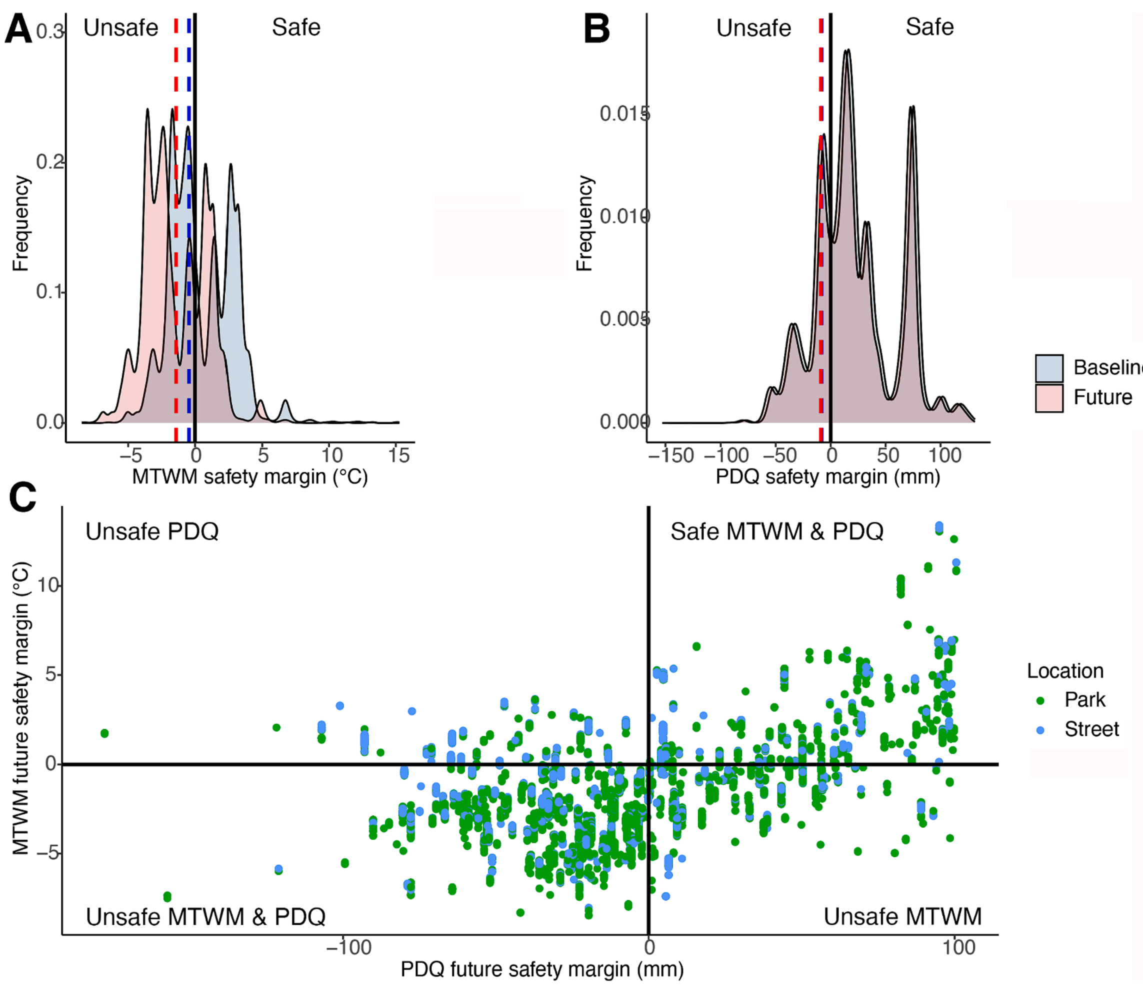

Fig. 1. Safety margins (S) for tolerance to heat and water limitation of urban trees in Melbourne, Australia, under baseline and future climate conditions. Probability density of the 95th percentile of the maximum temperature of the warmest month (MTWM; **A**) and the 5th percentile of the precipitation of the driest quarter (PDQ; **B**) for baseline and future safety margins across 72,572 locations of 474 species in Melbourne, Australia. Blue and red dotted lines indicate the mean across all tree locations for baseline and future climates, respectively. Black solid lines indicate the zero; a positive safety margin ($S > 0$) indicates trees with a climatic tolerance limit greater than that of climatic conditions at each location and thus "safe"; a negative value ($S < 0$) indicates trees predicted to be under "unsafe" climatic conditions (i.e., exceeding their safety margins). Note that y-axes of (**A**) and (**B**) are not in the same scale. Distribution of safety margin gradients indicating areas of risk for each climate variable for trees planted in parks (n = 45,199) and streets (n = 27,373) (**C**). Baseline climate represents the average of 2011–2020 and future climate represents the average of 2041–2070 and the median across 14 global circulation models from CMIP6 and the Shared Socioeconomic Pathway SSP5-8.5. Note that each point represents a location as individual trees of a given species can have a different safety margin depending on the locations where it is planted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Future PDQ safety margins of 257 (54 %; SSP5-8.5) and 245 (52 %; SSP2-4.5) species were exceeded in all locations, but 217 (46 %; SSP5-8.5) and 229 (48 %; SSP2-4.5) species were safe in all locations where they are planted. *Prunus blireana, Agathis australis, Vitex lucens*, *Quercus michauxii* and *Q. phellos* were at most risk for low PDQ under both SSPs. *Eucalyptus camaldulensis, Casuarina cunninghamiana* and *E. leucoxylon*, some of the most abundant species, were predicted to be safe in all their locations they are planted for baseline and future climates (Supplemental Tables S2-S4; Supplemental Data).

Trees at risk were located across the entire geographic area of

Melbourne for both climate variables. MTWM climate risk was higher in some areas in the north and west of the city; in contrast, areas of low climate risk clustered in the city centre and southeast. We highlight that this is for currently planted trees and species; therefore, these findings should not be perceived as a green light to plant any tree in these locations because future risk depends upon the combined effects of climate change and individual species tolerance. The climate hazard will increase, but it may not put the species planted in those locations at risk. For future climate, risk expanded throughout the entire city, with some areas with low risk on the west coast and north of the city. Compared to MTWM, the risk was lower for PDQ for baseline climate, with some areas in the north of the city at higher risk. In the future, the PDQ climate risk will increase throughout the entire city, with similar patterns to those found for MTWM (Fig. 2).

4. Discussion

Using urban tree inventory data to calculate climate risk metrics can aid in the identification of vulnerable trees and areas at climate risk at city scale. Our approach expands previous research using urban tree inventory data to evaluate climate risk to urban trees (e.g., Brandt et al., 2016; Brandt, Johnson, North, Faje, & Rutledge, 2021; Esperon-Rodriguez et al., 2022a; Esperon-Rodriguez, Ordoñez, van Doorn, Hirons, & Messier, 2022c; Liu, Zhang, Pietzarka, & Roloff, 2021; Woodall, Nowak, Liknes, & Westfall, 2010; Zhang & Brack, 2021) and incorporates species tolerance metrics (i.e., safety margin) to map species risk across the urban landscape. This approach can be used to prioritise species and areas for monitoring, especially where tree dieback or decline may already be evident. Importantly, climate risk should inform species selection to avoid planting failures. Furthermore, knowing tree species' vulnerability to local climatic conditions can help inform species choice in municipalities considering future climate change (Esperon-Rodriguez et al., 2022b).

Predicted increases in MTWM will exacerbate the climate risk of Melbourne's urban forests. We found high MTWM risk associated with species from the Myrtaceae family, notably *Eucalyptus* species, which aligns with previous work showing that some *Eucalyptus* species are vulnerable to climate change (Booth, 2013; Hughes et al., 1996). However, functional traits and climate niche breath can facilitate survival of *Eucalyptus* species in cities (Esperon-Rodriguez et al., 2024). For PDQ, small increases in risk (e.g., 5–20 mm) may be comparatively benign, particularly for mesic origin species. Nonetheless, high risk was associated with exotic species, such as *Prunus blireana* and *Quercus* spp., indicating that climatic conditions in Australia might represent a particular risk to introduced species. However, deciduous species might not be as sensitive to water limitations during their leafless period. We also found two native gymnosperms (*A. australis* and *N. cunninghamii*) exceeding their safety margins. These species have xylem conduit morphology suited to cooler conditions (Zanne et al., 2014), which might be driving their risk under warming projections for Melbourne. We acknowledge, however, that our approach did not consider additional factors that might facilitate the presence of species in cities, such as human management (e.g., irrigation) and species' adaptive capacity. Urban trees can adapt, in part, to different climatic conditions via trait plasticity or as a response of human interventions (Esperon-Rodriguez et al., 2020; Hanley et al., 2021; Ibsen et al., 2023).

Interestingly, we found a higher number of trees exceeding their MTWM safety margins planted in parks than in streets, which likely

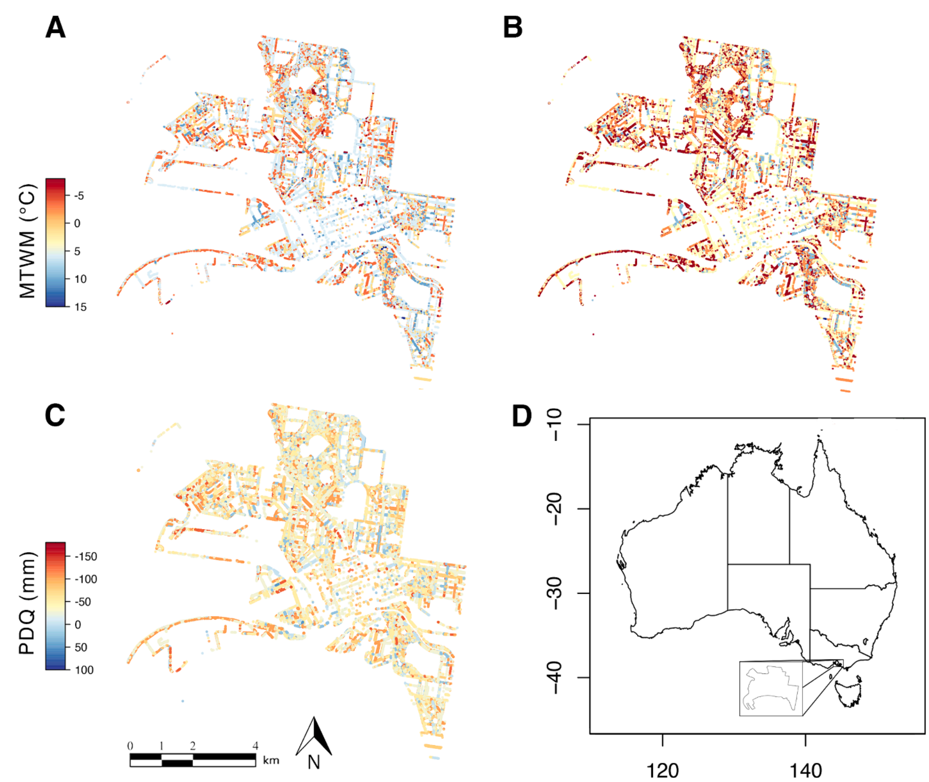

Fig. 2. Spatial distribution of climate risk for heat and water limitation for urban trees in Melbourne, Australia, under baseline (average climate conditions during the period 2011–2020) and future climate conditions (average of 2041–2070 and the median across 14 global circulation models from CMIP6 and the Shared Socioeconomic Pathway SSP5-8.5) at 100-m spatial resolution. Spatial distribution of urban street and park trees exceeding their safety margins (predicted to be under "unsafe" climatic conditions) for the maximum temperature of the warmest month (MTWM) for baseline (**A**) and future (**B**) climatic conditions, and for urban street and park trees exceeding their safety margins for the precipitation of the driest quarter (PDQ) for future climatic conditions (**C**). A positive safety margin ($S > 0$) indicates trees of species with a climatic tolerance limit greater than that of climatic conditions at each location; a negative value ($S < 0$) indicates trees of species predicted to be under "unsafe" climatic conditions (i.e., exceeding their safety margins). Inset map shows the location of the City of Melbourne within Victoria, Australia (**D**).

reflects differences in tree species composition. This may nevertheless not directly lead to higher overall stress or dieback for trees in parks, as parks represent more benign environments or comparatively resource-rich environments and thus can accommodate a higher-risk portfolio of tree species. At the city level, trees planted in parks may be planted in deeper soils and have greater access to water and nutrients compared to street trees. In contrast, street trees, in general, are chosen for their hardiness and planted in more challenging conditions, such as limited soil volume and nutrients and low water availability (Brandt et al., 2021; Smith et al., 2019). This is also reflected in findings of a higher proportion of species exceeding their PDQ safety margins in streets compared to parks. It is worth noting that the future change in climate risk strongly depends on the assessed climate variables and projected changes in climate. For MTWM, the proportion of species at risk was predicted to increase from 46 % to 59 % (SSP2-4.5) or 68 % (SSP5-8.5) by 2055, while the climate risk of PDQ exhibited little change from 54 % to 52 % (SSP2-4.5) or 55 % (SSP5-8.5). These findings provide evidence of Melbourne's tree species hardiness and water stress tolerance, but lower heat tolerance under climate change.

We highlight some caveats of our approach. First, the species safety margin is only a proxy of species tolerance and does not necessarily reflect risk of dieback or mortality. A tree exceeding its safety margin in a given location may not be at risk of dieback and mortality but can be subjected to stressful conditions (based on the species safety margin) that could jeopardise physiological function, health and growth. This is reflected in the number of species identified as exceeding their current baseline safety margins, where baseline climate conditions may represent warmer (or drier) conditions exceeding the tolerance of some species that have been historically planted in Melbourne. Indeed, 22,753 trees (31 %) were planted before 2011. However, we estimated species tolerances based on global occurrence records that included plantings outside native distributions but may nonetheless be incomplete and therefore not fully representative of the species fundamental niche and climatic tolerance. Second, we only used two climate variables to assess risk, yet other factors can increase the vulnerability of urban trees, such as susceptibility to pests and disease, and ability to withstand flooding, extreme storms and long-term drought (e.g., Dale and Frank, 2017; Foran et al., 2015; Marchin et al., 2022; Yan and Yang, 2018). Our results also showed limited change in PDQ in the future. However, projections indicate a decrease in moderate and increase in extreme precipitation events, compensating for each other (Bao et al., 2017), potentially affecting tree water availability. Finally, by selecting different and equally plausible GCMs and two SSPs, we aimed to account for the variation among different models in terms of projected temperature and precipitation trends. Nevertheless, we acknowledge that different climate scenarios can produce different results, in particular, increases in temperatures and temperature extremes are expected for scenarios leading to greater warming, while the trend for precipitation over Melbourne is less clear. Furthermore, the precipitation data from UrbClim is obtained from its forcing data (ERA-5 reanalysis data for the present-day and CMIP6 for the future). Both have a resolution of at least ~ 25 km resolution, resulting in a comparatively low spatial variation in precipitation over Melbourne. In contrast, UrbClim provides considerable spatial detail (100-m resolution) in MTWM by considering detailed urban landscape features.

The long-term stability of urban forests is unavoidably dependent on the identification of species and cultivars that are resilient to climate change in a given location. To maintain healthy urban forests in a changing climate, it will likely be necessary to prioritise management in establishing and maintaining urban plantings. Filling the knowledge gaps in appropriate species and site selection for changing climatic conditions is a crucial complement to local knowledge and practice. Our approach demonstrates that the use of an urban tree inventory and climate change projections provides information on climate risk at city scale appropriate for informing management decisions and presents a path forward to prioritise tree species and areas for monitoring.

CRediT authorship contribution statement

Manuel Esperon-Rodriguez: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Rachael V. Gallagher:** Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – review & editing. **Niels Souverijns:** Data curation, Formal analysis, Methodology, Resources, Software, Writing – review & editing. **Quentin Lejeune:** Data curation, Formal analysis, Methodology, Resources, Software, Writing – review & editing. **Carl-Friedrich Schleussner:** Formal analysis, Methodology, Resources, Writing – review & editing. **Mark G. Tjoelker:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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