Arboriculture & Urban Forestry 2026. 52(6):621–636
https://doi.org/10.48044/jauf.2026.029

Biodiversity and Climate Vulnerability of Street Tree Species Composition in Old and New Suburbs Along a Climate Gradient

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Abstract. Background: Urban forests may be vulnerable in a changing climate, and a perceived or real lack of biodiversity may exacerbate this vulnerability. Methods: We assessed the biodiversity and climate vulnerability of street trees in 5 local government areas in Greater Melbourne, Australia, along a climate gradient in old (pre-2005) and new suburbs. Results: Despite significant variations in mean annual rainfall and aridity index across the study area, all locations maintained moderate to high biodiversity scores according to both Shannon and Simpson indices. Areas of higher rainfall showed strong genera dominance and a lower taxonomic richness than drier areas, yet they achieved high Simpson diversity scores, suggesting an even distribution among species within dominant genera. Newer suburbs had a lower taxonomic richness of species, genera, and families compared to older suburbs and lower Shannon and Simpson indices; no area complied with the Santamour 10/20/30 rule. Climate vulnerability assessment using climate envelope models indicated that species vulnerability did not differ along the climate gradient and that species in most locations were not very vulnerable under most scenarios. However, trees in new suburbs were less climate vulnerable compared to trees in old suburbs under the 2090 climate scenario. This difference between old and new suburbs indicates that species selection practices may have increased climate resilience, though this comes at the cost of lower overall species diversity. Conclusion: While climate change poses significant challenges, our research demonstrates that considered species selection and management strategies can help create urban forests better adapted to future conditions.

Keywords. Biodiversity; Climate Gradient; Tree Vulnerability; Urban Forest.

INTRODUCTION

Street trees provide numerous benefits to suburban residents such as the mitigation of the urban heat island effect through shade provision and evapotranspiration, pollution interception, noise suppression, and stormwater mitigation (Nowak and Dwyer 2000; Livesley et al. 2016; Nesbitt et al. 2017). However, street trees are also exposed to potential additional stressors in urban centres such as impervious surfaces, more climate extremes, and higher temperatures (Livesley et al. 2016). The health of the urban forest is therefore of concern to urban planners, especially as predicted changes in climate may threaten the provision of the ecosystem services trees provide if existing species are vulnerable to these climate changes.

There are theoretical concepts for the evaluation of the climate resilience or climate vulnerability of street tree species (Ordóñez and Duinker 2014; Steenberg et al. 2017), but there are no perfect predictive tools that have been validated. Climate envelope methods have been popular assessment tools in the last few years, but they have severe limitations given they mainly measure the realised climate niche, which is almost always much narrower than the fundamental climate niche of mature trees (Guerin et al. 2025). However, these methods give some measure of climate vulnerability and will identify species with a large climate niche. The overall resilience of an urban forest is linked to biodiversity indices (Farinha-Marques et al. 2011) by lowering the risk posed by the decline in a dominant vulnerable species type (Alvey 2006; Ordóñez and Duinker 2012; Padoa-Schioppa and Canedoli 2017). Urban forest biodiversity may be assessed using richness scores, a count of the total number of species, genera, or families (Nielsen et al. 2014; Gillespie et al. 2017). Resilience may also be

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calculated as biodiversity indices, which aim to provide numerical measures of biodiversity. Within guiding council documents, general guidelines and rules-of-thumb are frequently cited as biodiversity targets (Kendal et al. 2014; Kendal and Baumann 2016; City of Greater Dandenong 2018; City of Whittlesea 2019). One popular example is the Santamour 10/20/30 biodiversity rule that states that the urban forest should have no more than 10% of any one species, 20% of any genera, and 30% of any family (Santamour 1990). Guidelines such as these have frequently been proposed by researchers in response to urban forest threats (Miller and Miller 1991; Jaenson et al. 1992; Richards 1993). While they are readily adopted into government policy to set quantifiable targets, they also have a number of limitations (Duinker et al. 2026).

Another concern is the climate of a given city itself, as cities in more humid climates may experience different future conditions than cities in more arid climates. This may be challenging for cities that exist along a climate gradient, such as Melbourne, Australia. Melbourne's outer Western suburbs have seen substantial suburban expansion into regions with very low annual precipitation (Melton, 459 mm) when compared to suburbs in Melbourne's east (City of Greater Dandenong, 786 mm)(Table 1). In natural ecosystems, warm, arid regions (drylands) are expected to be particularly vulnerable to the effects of climate change, leading to declines in tree biodiversity (Li et al. 2018; Cartereau et al. 2023). It is unknown whether climate differences across Greater Melbourne have led to differences in urban forest composition and if e.g., suburbs with higher rainfall averages are composed of tree species that may be less vulnerable to future climate change scenarios. Further, it is unknown whether an increased awareness of climate change has led to a recent shift in species selection, leading to changes in the composition and vulnerability of urban forest between old and new suburbs.

Urban forest composition may change with suburb age, with many studies suggesting age as a predictor of biodiversity (Dobbs et al. 2013; Nitoslawski et al. 2016; Threlfall et al. 2022). Street tree composition in older suburbs may exhibit increased species diversity due to factors such as historical development practices; the replacement of failed species and the introduction of new species and cultivars; species trends; and nursery stock availability. Inversely, street tree plantings in new suburban housing developments could feature less species diversity. This may occur due to a range of factors, such as the economical constraints of volume-builder construction practices; a desire for consistent visual homogeneity; and other and supply-related factors. However, street tree species selection practices in new developments remain relatively unknown, depending on location.

Melbourne in Australia was established in 1835, and much of the urban area consisted mainly of grassy vegetation (Boyce 2011). Melbourne's development and growth since the 1830s has had an important influence on the shape and form of the urban forest today (Hartigan et al. 2021); for example, Melbourne had a population of around 3.5 million in 2001 but has grown to over 5.43 million in 2025 (ABS 2026). Over 80,000 new inhabitants are added to Greater Melbourne every year, mainly in new developments in the outer suburbs. Melbourne has 31 local government areas (LGA) which are the primary developers of urban forest strategies (Hartigan et al. 2021). This means there is no overarching urban forest strategy for the entire metropolitan area. New suburbs are mainly created by private developers on the outer urban fringe on previous agricultural land, and these developers are also responsible for the establishment

Table 1. AI and MAP in old and new suburbs in Greater Melbourne, Australia. AI (aridity index); MAP (mean annual precipitation).

Local government area	AI new suburbs	AI old suburbs	MAP new suburbs (mm)	MAP old suburbs (mm)
Melton City	0.36	0.36	459	473
Wyndham City	0.37	0.37	482	514
Hume City	0.47	0.44	588	587
City of Whittlesea	0.55	0.54	658	678
City of Greater Dandenong	0.56	0.64	695	786

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of a new urban forest in the suburbs they develop. It is unknown if the lack of a uniform urban forest strategy and oversight has led to substantial differences in the composition and diversity of the urban forest in new suburbs compared to older suburbs that had much longer timeframes to establish the urban forest.

In this study we evaluated if the composition of the urban forest in Melbourne changed along the climate gradient and between new and old suburbs using tree biodiversity and climate vulnerability as key variables tested.

MATERIALS AND METHODS

Urban Forest Inventory Data Processing

Georeferenced urban forest inventory data was obtained from 5 Melbourne LGAs in 2020: Melton City, Wyndham City, Hume City, City of Whittlesea, and City of Greater Dandenong. Over 400,000 individual trees were recorded, and the data were analysed using ArcMap (ArcGIS Desktop 10.7.1)(Esri, Redlands, CA, USA) according to the methodology described by Torquato et al. (2024), briefly outlined in the following. Tree height verification was conducted using three-dimensional vegetation raster datasets from CSIRO's Urban Monitor™ (Canberra, Australia) program (Hurley et al. 2019). To establish development timeframes, a Victorian Government project layer showing housing development activity between 2005 and 2016 (DataVic 2026) was used to delineate development boundaries, excluding areas where development commenced after 2016. To isolate street trees within the study area, the dataset was refined using street network boundaries to exclude trees in nonstreet environments such as residential parcels, parks, and gardens. This exclusion was necessary as trees in these settings typically experience different growing conditions. LGA tree inventory point data was then spatially joined to crown polygon features from the 2014 and 2018 layers. For quality control, individual tree points were excluded if they either lacked a corresponding crown polygon within a 2-m radius or were associated with multiple adjacent crown polygons. The remaining trees were grouped by LGA and development type. The decision was made to discard the 90th percentile by species due to a significant number of single-species or erroneous entries. Initial sorting, cleaning, and calculations were made using Rstudio *tidyverse* packages (R Foundation, Vienna, Austria). This was used for all processes except where additional packages were required and are separately cited where appropriate. Entries with incomplete species or genus information (for example, '*Acacia* sp.') were removed. Easily identified taxonomic errors such as *Eucalyptus polyanthemos* occurring as '*Eucalyptus pol*[t]*yanthemos*' were manually corrected where detected. Further, all taxon names were updated to consistent updated scientific nomenclature using the *U.taxonstand* package (Zhang and Qian 2023), which was also used to correct data format and spelling errors and to generate relevant family information.

Location Data

Location data for coordinates of old (established before 2005) and new (established after 2005) suburbs within each LGA was obtained using historical satellite imagery features through Google Earth Pro (Google, Mountain View, CA, USA) and Nearmap (Nearmap Pty Ltd, Sydney, New South Wales, Australia). Here, an approximate visual estimation of new LGA suburbs arising between 2005 and 2016 was made by comparing time-lapsed aerial imagery of previously undeveloped greenfield regions against areas with new construction. Locations of new suburban development were estimated to a central geographical point within each LGA. Old suburb location coordinates were primarily located close to the historical centres of population growth within the LGA. The coordinates are listed in Table S1.

Climate Data

Once coordinates for old and new developments were established, historical climate records and interpolations were obtained through the Long Paddock SILO Project Website (Jeffrey et al. 2001; Queensland Government 2026) which enables specific grid-based data records to be generated. Each grid-point dataset features an area of approximately 5 km^2. This enabled localised results to be generated for the specific development area. Rscript (The R Foundation, Vienna, Austria) was used to calculate mean annual rainfall and aridity index from these records. The aridity index (AI) was calculated as AI = P/PET (Middleton et al. 1992) where P is the average annual precipitation and PET is the potential evapotranspiration. Data from 1976 to 2016 were used to calculate these averages (Table 1), confirming a climate gradient in terms of MAP and AI across the different LGAs.

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Biodiversity

Biodiversity indices were calculated according to Morris et al. (2014). The Shannon index (Shannon 1948) incorporates species richness and abundance; the Simpson index (Simpson 1949) is a measure of statistical probability that two species selected from a sample will belong to the same species (Morris et al. 2014; Roswell et al. 2021). Both indices were calculated using Rstudio ecological tools package *vegan* for each LGA in new and old suburbs (Oksanen 2026).

The Shannon index was calculated as:

$$H' = -\sum_{i=1}^{s} p_i \ln(p_i)$$

The Simpson index was calculated as:

$$D_2 = 1/\sum_{i=1}^{s} p_i^2$$

s being the number of species; *ln* the natural log; and $\sum$ the sum of the species. *P* is calculated from (*n*/*N*), the proportion of individuals of one species (*n*) divided by the total number of individuals (*N*). For ease of comparison, the Simpson index was displayed in the inverse positive form (1 – *D*). Richness (*S* = *N*) data for species, genera, and family taxonomic levels were also generated (Morris et al. 2014), as were relevant percentages of each species, genera, and family exceeding the Santamour 10/20/30 guidelines). The Santamour guidelines have been questioned recently (Duinker et al. 2026) but are frequently referred to in urban forestry strategies. In further calculations, additional Rscript parameter modifications were introduced to entirely exclude the dominant family of Myrtaceae (eucalypts) and the genera and species within. This was processed to evaluate suggestions by Kendal et al. (2014) and others that certain species should be excluded from these calculations.

Similarity in Composition

Species-level compositional similarities in old and new suburbs were calculated between using the Sørensen coefficient similarity index (also called the Sørensen–Dice coefficient, SCSI = 2*M* / [2*M* + *N*]). The Sørensen coefficient is a statistic used to evaluate the similarity between two samples. Higher resulting values indicate higher similarity between groups compared.

Climate Vulnerability

Species climate vulnerability ratings were obtained through the Botanic Gardens Conservation International (BGCI) Climate Assessment Tool website (Climate Change Alliance of Botanic Gardens 2026). This tool was developed at the Royal Botanic Gardens Victoria in conjunction with the Landscape Succession Strategy (Royal Botanic Gardens Victoria 2016). Based on the climate envelope methodology (Pearson and Dawson 2003; Kendal et al. 2017), the tool aims to predict species climate suitability based upon current species distribution information from several plant databases. Predictions using this tool are based on mean annual temperature. Three distinct climate scenarios are calculated: 'Current 2020' represents the current climate; 'Emissions Limited 2050' represents the SSP2/RCP4.5 IPCC emissions limited scenario where emissions are curbed; and the 'Business-as-Usual 2090' scenario represents SSP3/RCP7.0 where emissions have not been limited up to the year 2090. Batch testing was configured using the latitudinal and longitudinal coordinates from Table S1, and corresponding taxon lists for each old or new suburb group were manually uploaded to the portal. Each species was assigned a numeric value between 0 and 11, corresponding to its climate suitability and corresponding database records, where a higher score is generally considered more climate suitable (Table S2). Middle ranges (9 to 11) are classed as optimal, and lower scores are given shoulder (6 to 8), near edge (4 to 5), or not known (0 to 2) scores. Outputs were downloaded via the export function in .csv format and analysed with R.

RESULTS

Taxonomic Richness and Species Composition of Street Tree Populations

Street tree populations showed consistently higher taxonomic richness in old suburbs (pre-2005) compared to new suburbs (post-2005) across all levels of classification (Figure 1). Species richness in old suburbs ranged from 64 to 95 species compared to 32 to 65 in new suburbs, with the greatest difference observed in Wyndham (95 vs 42 species). On average, old suburbs contained 79.4% more tree species than new suburbs. The greatest LGA internal species richness disparity was observed in Wyndham City (126.2% more species in old suburbs), while Melton City showed the smallest difference (18.5% more species in old suburbs).

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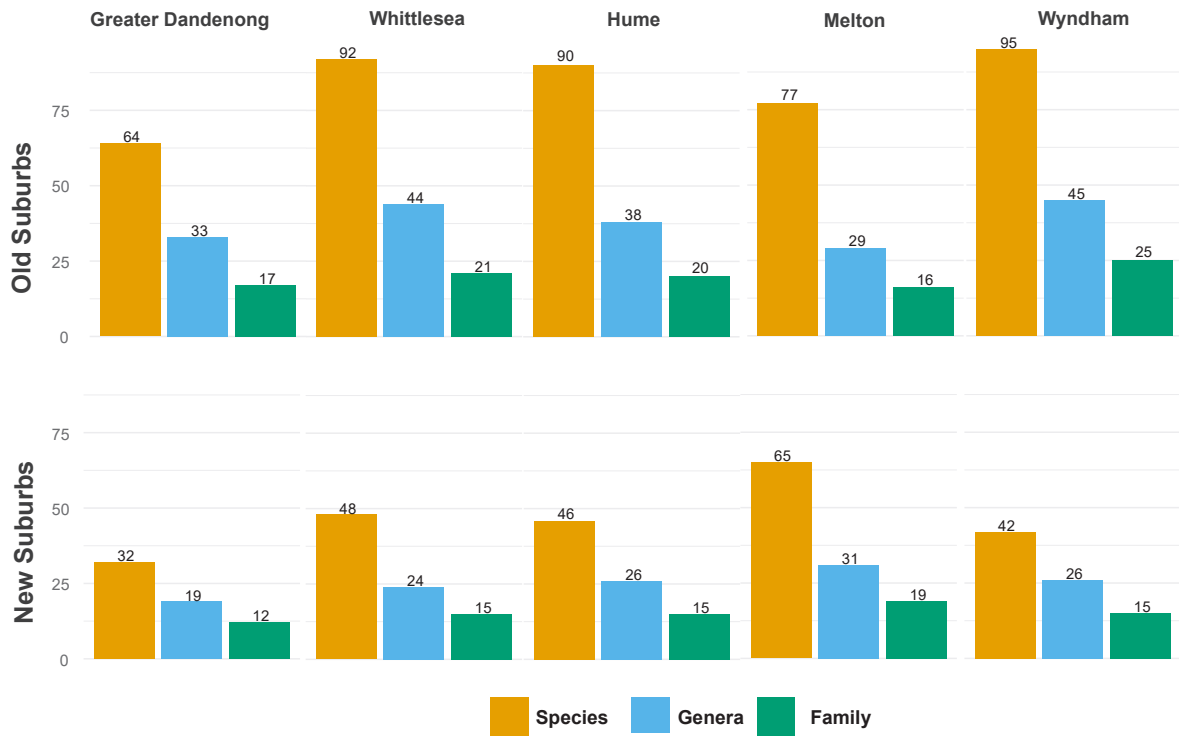

Figure 1. Taxonomic richness in street tree population as defined by species (orange bars), genus (blue bars), and family (green bars) count across 5 Local Government Areas (LGAs) in Greater Melbourne, Australia, in old (pre-2005) and new (post-2005) suburbs.

Similar patterns were evident at the genus level, where old suburbs contained between 33 to 45 genera compared to 19 to 31 in new suburbs. Genus richness in old suburbs (Mean = 37.8, SD = 6.4, Range: 33 to 45) was consistently higher than in new suburbs (Mean = 25.2, SD = 4.4, Range: 19 to 31). On average, old suburbs contained 50.0% more genera than new suburbs. The largest difference in genus richness was observed in Wyndham City (73.1% more genera in old suburbs), while Melton showed the only instance where new suburbs exceeded old suburbs at any taxonomic level with 6.5% fewer genera in old suburbs.

Taxonomic family richness mostly followed the trends seen in species and genus, with old suburbs having between 16 to 25 families compared to 12 to 19 families in new suburbs. Family richness in old suburbs (Mean = 19.8, SD = 3.5, Range: 16 to 25) exceeded that of new suburbs (Mean = 15.2, SD = 2.6, Range: 12 to 19). On average, old suburbs contained 30.3% more families than new suburbs. The greatest LGA family richness disparity was found in Wyndham City (66.7% more families in old suburbs), while the City of Whittlesea showed the smallest difference (40.0% more families in old suburbs).

Differences in overall taxonomic richness between old and new suburbs also showed distinct patterns across the rainfall gradient. In new suburbs, strong negative correlations were observed between both rainfall and taxonomic richness at all levels (families: $r = –0.868$, $P < 0.05$; genera: $r = –0.891$, $P < 0.05$; species: $r = –0.825$, $P < 0.05$) and aridity index (families: $r = –0.873$, $P < 0.05$; genera: $r = –0.896$, $P < 0.05$; species: $r = –0.832$, $P < 0.05$), indicating that new suburbs in drier LGAs had more species, genera, and families than wetter LGAs. In contrast, no significant relationships between climate variables and taxonomic richness were observed in old suburbs, where areas maintained similar levels of richness despite climate differences. For example, Wyndham and Hume maintained similar levels of richness in their old suburbs (95 and 90 species, respectively) despite substantial differences in rainfall.

Dominant Taxa

Analysis of the dominant taxa revealed distinct patterns between old and new suburbs (Figure 2). In new

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suburbs, individual species frequently comprised large proportions of the street tree population, with dominant species representing between 8.1% to 16.2% of all trees. In contrast, dominant species in old suburbs represented smaller proportions, ranging from 4.5% to 8.0% of the total population. *Corymbia maculata* and *E. leucoxylon* were consistently present as dominant species across multiple LGAs, regardless of rainfall conditions. Individual species percentage dominance showed no significant relationship with climate variables in either old or new suburbs. In new suburbs, the percentages of the dominant genera increased significantly with higher rainfall and decreasing aridity (rainfall: $r = 0.892$, $P < 0.05$; aridity: $r = 0.901$, $P < 0.05$). At the family level in old suburbs, urban forest representation by the dominant family Myrtaceae was shown to decrease significantly as rainfall increased and aridity decreased (rainfall: $r = -0.827$, $P < 0.05$; aridity: $r = -0.815$, $P < 0.05$).

Biodiversity Indices

The Shannon diversity index values ranged from 2.22 to 2.93 across all locations (Table 2). Old suburbs generally had higher Shannon diversity (2.51 to 2.93) compared to new suburbs (2.22 to 2.70). The highest and lowest values were recorded in the City of Whittlesea's old and new suburbs (2.93 and 2.22, respectively). No clear relationship was observed between

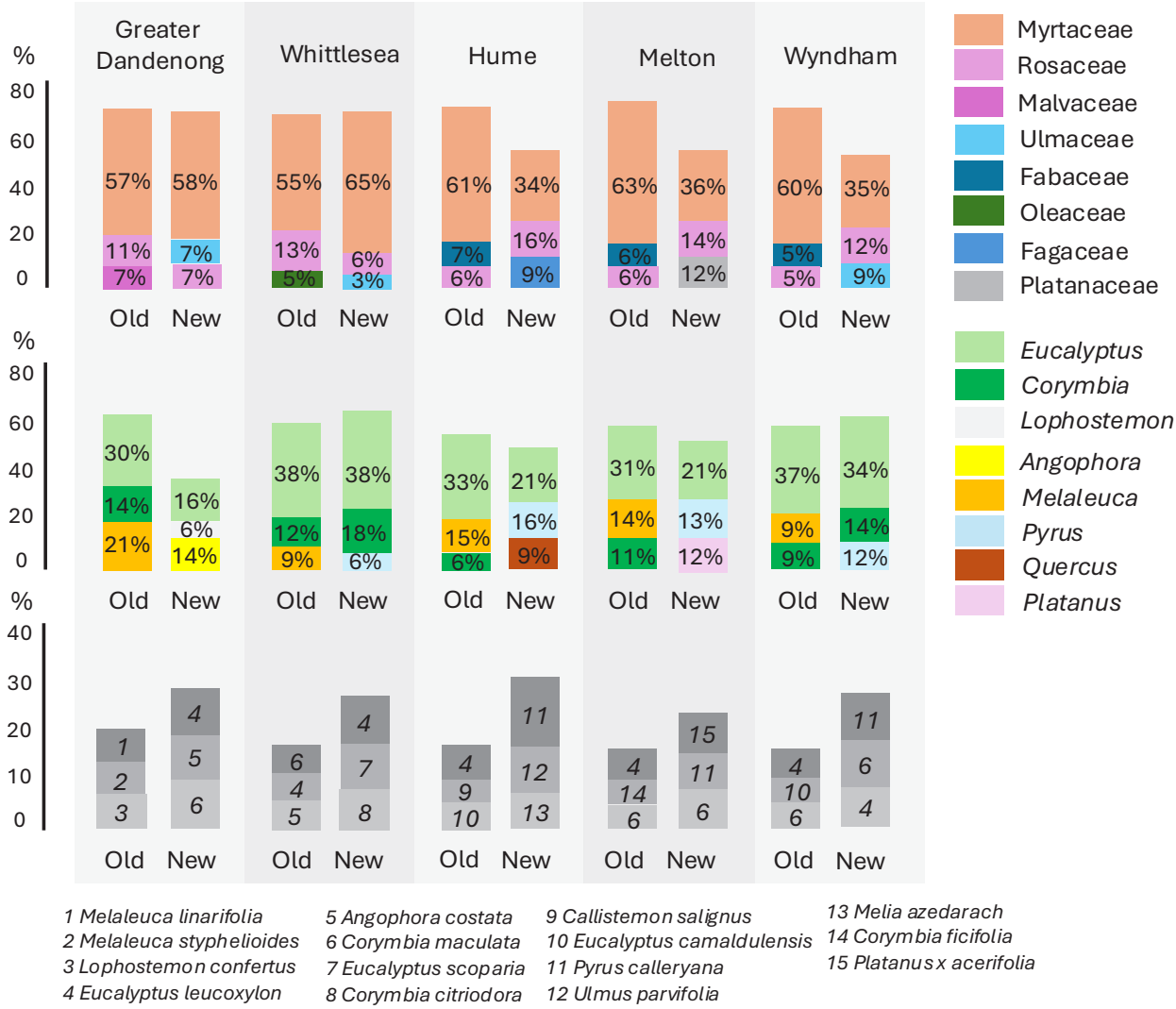

Figure 2. Percentage of the 3 most abundant street tree families (top), genera (middle), and species (bottom) in old (before 2005) and new (after 2005) suburbs of 5 Local Government Areas (LGAs) across Greater Melbourne, Australia.

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Shannon diversity values and position along the rainfall gradient.

Simpson diversity index (1 – D) values were consistently high across all locations, ranging from 0.80 to 0.91. Like the Shannon index, old suburbs typically displayed slightly higher Simpson diversity values (0.84 to 0.91) than new suburbs (0.80 to 0.90). The City of Greater Dandenong's old suburbs recorded the highest Simpson index (0.91), while the lowest value was found in the City of Whittlesea's new suburbs (0.80).

Compositional Similarity

The Sørensen similarity coefficient revealed distinct patterns in species composition among suburb types (Figure 3). Old suburbs had the highest internal similarity (0.529 ± 0.086 SD), followed closely by new suburbs (0.503 ± 0.085 SD). Cross-comparisons between old and new suburbs showed markedly lower similarity (0.374 ± 0.077 SD). The greatest species overlap was observed between Hume and Wyndham old suburbs (0.724), while Greater Dandenong new suburbs and Melton old suburbs showed the least similarity (0.294). Old suburbs demonstrated a higher similarity (15.6%) to each other compared to cross-age comparisons.

Biodiversity Targets

Assessment against Santamour's 10/20/30 rule revealed that no LGA met all diversity targets (Table S3). For the 10% species threshold, 4 of 5 new suburbs exceeded this limit, with highest exceedance in Hume new suburbs (16.2%). Old suburbs generally performed better, with only one location exceeding the species threshold. The 20% genus threshold was exceeded in all locations, ranging from 20.7% to 38.3%. All locations substantially exceeded the 30% family threshold, with values ranging from 34.3% to 64.7%.

When Myrtaceae were excluded from analysis, more family thresholds were met, but variations between old and new suburbs became more pronounced. New suburbs showed increased species-level percentages, with the highest single species representation reaching 27.7% in Wyndham. Genus-level percentages improved substantially, with 6 locations falling within the 20% threshold. Family-level diversity met the 30% threshold in 8 of 10 locations.

Climate Vulnerability Score

The BGCI Climate Assessment Tool scored species positions within their known ranges across the 3 climate scenarios (2020, 2050, 2090). Scores were produced by the Climate Assessment Tool between 0 to 11 (maximum possible). Within the current 2020 scenario, species mostly occurred within the middle of their ranges (92.49% = scores 9 to 11), with weighted average scores between 9.43 and 10.11 across both old and new suburbs in all LGAs (Figure 4). New suburbs had a slightly higher proportion of species in the middle of their ranges (mean = 9.73; range: 9.47 to 10.11) compared to old suburbs (mean = 9.66; range: 9.43 to 10.08).

Table 2. Shannon and Simpson biodiversity index scores of 5 LGAs in new and old suburbs in Greater Melbourne, Australia. LGA (local government area).

LGA	Suburb type	Shannon biodiversity index	Simpson biodiversity index
Melton City	New	2.7	0.9
Melton City	Old	2.51	0.86
Wyndham City	New	2.35	0.83
Wyndham City	Old	2.7	0.84
Hume City	New	2.62	0.9
Hume City	Old	2.64	0.85
City of Whittlesea	New	2.22	0.8
City of Whittlesea	Old	2.93	0.9
City of Greater Dandenong	New	2.42	0.86
City of Greater Dandenong	Old	2.87	0.91

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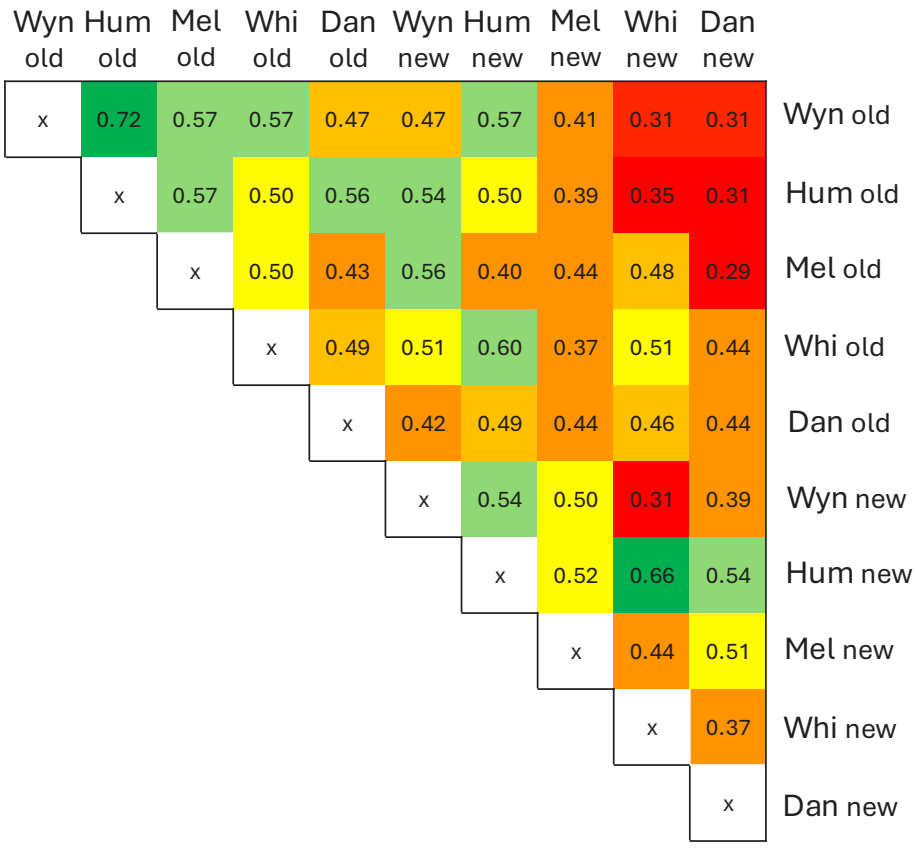
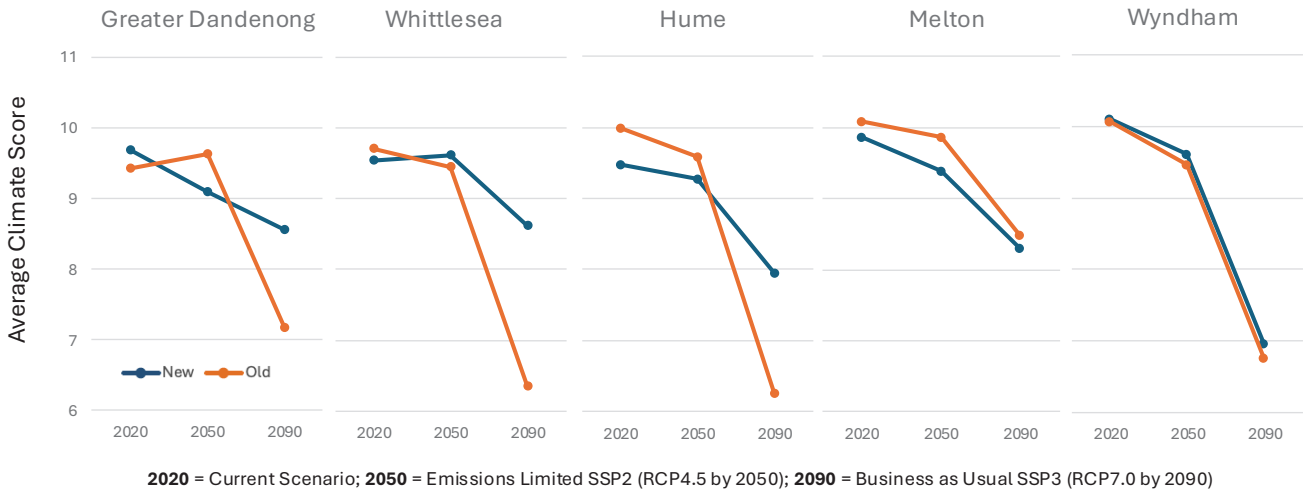


Figure 3. Urban forest species list similarity in old and new suburbs in 5 Local Government Areas (LGAs) of Greater Melbourne, Australia. The Sørensen similarity coefficient shows comparisons between old and new suburbs in high growth areas (0–1). The higher the number, the higher the similarity between two species lists.



2020 = Current Scenario; **2050** = Emissions Limited SSP2 (RCP4.5 by 2050); **2090** = Business as Usual SSP3 (RCP7.0 by 2090)

Figure 4. Differences in weighted mean climate score of urban forest species in old (orange line) and new (blue line) suburbs in 5 Local Government Areas (LGAs) of Greater Melbourne, Australia, under 3 potential climate change scenarios from https://cat.bgci.org.

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The 2050 emissions-limited scenario was very similar to the 2020 baseline (mean change –3.1%, SD = ±2.9%), with 82.4% of all species continuing to fall within middle range categories (scores 9 to 11). Seven of ten locations showed some progression toward range edges, while two locations improved their overall range positions: old suburbs within the City of Greater Dandenong (+2.1%) and new suburbs within the City of Whittlesea (+0.9%). Old suburbs in Wyndham City showed the greatest shift toward range edges (–5.9%).

The 2090 business-as-usual climate scenario showed substantial shifts in species positions relative to their natural ranges, with only 31.3% of species being recorded within middle ranges (9 to 11). In old suburbs, considerably more species were scored at range edges (score 3 to 5, mean change = –29.0%, range: –34.6% to –24.0%) when compared to new suburbs (mean change = –16.8%, range: –31.1% to –9.7%). Species in Hume old suburbs (–37.4%) and Whittlesea old suburbs (–34.6%) showed the largest overall shifts from middle to edge positions within their ranges, while Whittlesea new suburbs (–9.7%) maintained more central range positions.

DISCUSSION

Changes in Species Taxonomic Composition and Biodiversity Across Climate Gradients

Our analysis revealed complex relationships between street tree biodiversity and climate patterns across Greater Melbourne's rainfall gradient. Despite significant variations in mean annual rainfall (459 mm to 785 mm) and aridity index (0.36 to 0.64) across the study area, all locations maintained moderate to high biodiversity scores according to both Shannon (2.22 to 2.93) and Simpson (0.80 to 0.91) indices. However, as measures of biodiversity, these indices present a contradiction with the taxonomic dominance patterns. Areas of higher rainfall showed strong genera dominance (up to 60.2% of species were in the top 3 genera) and negative correlations between climate variables and taxonomic richness, yet they still achieved high Simpson diversity scores (up to 0.90), suggesting an even distribution among species within dominant genera. The family Myrtaceae showed significant negative correlations with both rainfall ($r = –0.827$, $P < 0.05$) and aridity ($r = –0.815$, $P < 0.05$), indicating decreased family-level dominance in areas of higher rainfall. We note that urban forest composition is mainly influenced by management decisions of councils and urban foresters and likely not influenced by climate directly. These findings have implications for urban forest planning across Melbourne's climate gradient. The stability of biodiversity indices across rainfall gradients suggests that current management practices may effectively buffer street trees against natural rainfall limitations. However, the contradictory strong relationships between climate variables and taxonomic patterns indicate that achieving balanced biodiversity scores may require different approaches in different climates, particularly those with higher rainfall favouring fewer, dominant genera.

Similarity Analysis

The analysis of compositional similarity revealed unexpected patterns that challenge assumptions about species selection in newer developments. Despite having lower species richness, new suburbs showed only marginally lower internal similarity (0.503 ± 0.085 SD) than old suburbs (0.529 ± 0.086 SD). This appears counterintuitive given the presumably more standardized planning controls, similar development timelines (2005 to 2016), restricted species palettes, and developer-driven tree selection processes in new suburbs. While new suburbs generally showed strong genera dominance that might suggest homogeneity across these suburbs (the 3 most popular genera making up to 60% of the urban forest), the moderate similarity values between new suburbs indicate a broader species selection from within these genera. This finding has implications for urban forest planning, indicating that even within standardized planning frameworks, local decision making may be influencing species selection more than previously recognized.

Climate Vulnerability

The greater climate resilience of trees in new suburbs further supports the idea that future-climate adaptation is possibly considered more than expected, and this should be confirmed with practitioners in future studies. The Climate Assessment Tool revealed that on average, urban forest species scores remained stable within the 2050 climate scenario (mean change –3.07%, SD = ±2.91%). However, these scores differed substantially between old and new suburbs into the 2090 scenario (old = –28.91%, SD = ±1.54%; new = –20.8%, SD = ±0.86). This methodology suggests that the tree species being selected for new

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suburbs have some measure of increased future climate suitability, regardless of the driving factors behind the selection process. Inversely, significant declines in climate vulnerability scores occurred in regions of higher levels of biodiversity within older suburbs. While higher biodiversity scores can account for a broader range of species, our findings show that these suburbs contain a contingent of more climate vulnerable species, at least according to the classification of the tool.

However, this result presents an interesting paradox: while new suburbs show better climate vulnerability scores overall, new suburbs also display lower diversity and a greater dominance of individual species. The complexity of this pattern may, as previously discussed, be further indicative of a conservative approach to species selection, whereby a limited palette of "safe" climate-adapted species is being repeatedly deployed. This practice may have the effect of reducing the immediate risks associated with climate vulnerability and potentially create other vulnerabilities through a lack of diversity. This result contrasts with studies of natural ecosystems, where trees in more arid environments are expected to have lower diversity due to increased vulnerability to climate change (Li et al. 2018; Cartereau et al. 2023).

Biodiversity Targets

The Santamour 10/20/30 rule, still widely referenced in urban forest policies, proved problematic when applied to our study areas. No single location met all thresholds, and this raises questions about the practical utility of these guidelines, particularly in the Australian context where certain families (notably Myrtaceae) dominate urban forests. When the family Myrtaceae was removed from both equations, old Hume and old Wyndham suburbs achieved compliance under the Santamour rule, but these were exceptions. Because the Myrtaceae family constitutes between 58% and 60% of the urban forest in all but two areas (new suburbs in Melton 36% and Hume 34%), the overall usefulness of these rules and their consistent reappearance in policy documents needs to be questioned. Melbourne suburbs are certainly not unique in failing to come close to achieving these benchmarks: an international study of urban forest inventories found that only 2 of the 151 cities fell within the Santamour thresholds (Kendal et al. 2014). This highlights a potential difficulty for policymakers, as systematic inclusion of unattainable targets may have broader implications for urban forest management. Rather than serving as effective guidance, the Santamour 10/20/30 guidelines may risk undermining policy credibility and potentially discourage innovative, context-appropriate approaches to urban forest diversity. Future policy development might benefit from a tiered system of targets that includes both aspirational long-term goals, achievable intermediate benchmarks, and frequent revision intervals. We concur with the view put forward that rule-based approaches offer valuable insights into some of the concepts underlying sustainable urban forest management but that there is a risk that their convincing appeal might substitute for careful consideration of feasibility, ecological grounding, and local context (Duinker et al. 2026).

Limitations and Methodological Considerations

Several limitations should be considered when considering the findings of this study. Firstly, the binary classification of suburb age (pre/post-2005) simplifies what is a continuous variable. Similarly, the single coordinates for old or new suburbs within an LGA were applied as representative of a broad spectrum within a region. Some LGA's, such as the City of Whittlesea, have wider ranging climate within their geographical boundaries, and both old and new developments may occur in a variety of these locations.

Secondly, the BGCI Climate assessment tool, while useful for comparison, has numerous limitations. Many of these are associated with problems arising from the climate envelope methodology (Hanley et al. 2021; Guerin et al. 2025). These methods model the suitability of a tree species in a future climate by identifying the range of current climatic conditions (like temperature and precipitation) where the species naturally occurs, then projecting this "envelope" onto future climate. Thus, these methods are excellent in identifying species with large climate envelopes, but they measure the 'realised climate niche' that is shaped by many biological processes such as flowering, seed setting, seed distribution, germination, establishment, disturbances, etc. The 'fundamental climate niche' of most species is much larger than observed occurrences suggest, and thus species with a narrow realised niche can grow and thrive in climates outside the realised climate niche. A species with a low number of occurrence records

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does not equate to a lack of species suitability. While the output number score system (0 to 11) attempts to quantify a measure of reliability based on database type, the tool provides no real confidence interval. One example of this bias effect can be seen in *E. camaldulensis* (4.57% of urban forest), a species with a broad local and international distribution dataset which remained in the middle of its natural range (11) across all scenarios in almost all locations. Thus, the climate vulnerability data presented here should be used with utmost caution and were conducted merely to allow a comparison of the urban forests of new and old suburbs along the gradient.

Thirdly, the data used in this study excluded the 90th percentile of species according to cumulative percentage due to data quality concerns, which may affect diversity calculations. When considered against the smaller, less diverse urban forest inventory datasets in new suburbs, this may have led to exaggerated results. Although it is unlikely that single-entry species contribute to the broader ecosystem diversity, this effect was not measured. Similarly, sample size of the urban forest inventory may be a limiting factor to the reliability of results. Melton had an urban forest inventory of under 10,000 trees, whereas Wyndham had over 100,000.

Lastly, the study's temporal scope of data until 2016 means recent changes in planting practices are not captured, particularly where the influence of new species lists, council policies, and updated diversity targets are concerned.

CONCLUSION

We examined urban forest composition across Melbourne's climate gradient in old and new suburbs, challenging our assumptions about the relationship between climate, biodiversity, and urban forest resilience. Biodiversity metrics remained relatively stable across the climate gradient. However, our analysis revealed differences between areas of varying climate in new suburbs, where strong negative correlations emerged between rainfall and taxonomic richness at all levels. This suggests that while climate differences may have influenced urban forest composition, the relationship is complex and appears to be mediated by development age and management practices.

Our findings also revealed that contrary to expectations, trees in new suburbs, particularly those in more arid areas, demonstrated greater resilience under future climate scenarios compared to those in older, higher-rainfall suburbs. Further, our study provides clear evidence that suburbs with higher rainfall averages are not necessarily composed of species more suited to a future climate. This difference between old and new suburbs shows a shift in species selection practices that may have increased climate resilience, though this comes at the cost of lower overall species diversity. However, the moderate dissimilarity between new suburb species compositions also suggests that, overall, a broad range of species are being selected.

While the Santamour biodiversity guidelines remain widely cited in urban forest policies, none of the surveyed areas in Melbourne met all thresholds, suggesting these targets require fundamental reconsideration for practical application in Australian cities where species of the Myrtaceae family are prevalent. Moving forward, urban forest management strategies must evolve beyond rigid diversity guidelines to create frameworks that balance climate resilience with biodiversity objectives. This could be achieved through context-specific diversity targets, standardized monitoring protocols, and evidence-based policies that reflect local environmental conditions. While climate change poses significant challenges, our research demonstrates that considered species selection and management strategies can help create urban forests better adapted to future conditions.

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ACKNOWLEDGEMENTS

We thank Patricia Torquato for assistance with access to the data and all relevant councils for the provision of their urban tree inventories, namely the City of Melton, City of Wyndham, City of Hume, City of Whittlesea, and City of Greater Dandenong. Rainer Doecke received support from the Frank Keenan and Madeleine Selwey-Smith Memorial scholarships.

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Conflicts of Interest: The authors reported no conflicts of interest.

Résumé. Contexte: Les forêts urbaines peuvent être vulnérables face aux changements climatiques et un manque de biodiversité, qu'il soit perçu ou réel, peut aggraver cette vulnérabilité. Méthodes: Nous avons analysé la biodiversité et la vulnérabilité climatique des arbres de rue dans cinq collectivités locales de l'agglomération de Melbourne, en Australie, le long d'un gradient climatique dans des banlieues plus âgées (antérieures à 2005) et des banlieues récentes. Résultats: Malgré des variations significatives quant aux précipitations annuelles moyennes et à l'indice d'aridité dans la zone d'étude, tous les sites ont maintenu des cotes de biodiversité modérées à élevées, selon les indices de Shannon et de Simpson. Les zones à forte pluviométrie présentaient une forte dominance des genres et une richesse taxonomique inférieure à celle des zones plus sèches; elles affichaient toutefois des indices de diversité de Simpson élevés, suggérant une répartition homogène entre les espèces au sein des genres dominants. Les banlieues plus récentes présentaient une richesse taxonomique (espèces, genres et familles) inférieure à celle des banlieues plus vieilles, ainsi que des indices de Shannon et de Simpson plus faibles; aucune zone ne se conformait à la règle de Santamour 10/20/30. L'évaluation de la vulnérabilité climatique à l'aide de modèles d'enveloppe climatique a montré que la vulnérabilité des espèces ne variait pas le long du gradient climatique et que, pour la plupart des sites, les espèces n'étaient pas très vulnérables sous la plupart des scénarios. Toutefois, selon le scénario climatique de 2090, les arbres des banlieues récentes se sont révélés moins vulnérables aux impacts des changements climatiques que ceux des banlieues plus âgées. Ce différentiel entre les banlieues récentes et celles plus vieilles suggère que les pratiques de sélection des espèces ont possiblement renforcé la résilience face aux changements climatiques, même si cela s'accompagne d'une diminution de la diversité globale des espèces. Conclusion: Bien que les changements climatiques posent des défis importants, nos recherches montrent qu'une sélection des espèces et

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des stratégies de gestion bien réfléchies peuvent contribuer à créer des forêts urbaines mieux adaptées aux conditions futures.

Zusammenfassung. Hintergrund: Stadtwälder können in einem sich wandelnden Klima anfällig sein, und ein wahrgenommener oder tatsächlicher Mangel an Biodiversität kann diese Anfälligkeit noch verstärken. Methoden: Wir untersuchten die Biodiversität und die Klimaanfälligkeit von Straßenbäumen in fünf Kommunalbezirken im Großraum Melbourne, Australien, entlang eines Klimagradienten in alten (vor 2005 entstandenen) und neuen Vororten. Ergebnisse: Trotz erheblicher Schwankungen bei der mittleren jährlichen Niederschlagsmenge und dem Ariditätsindex im gesamten Untersuchungsgebiet wiesen alle Standorte gemäß den Shannon- und Simpson-Indizes moderate bis hohe Biodiversitätswerte auf. Gebiete mit höheren Niederschlagsmengen zeigten eine starke Gattungsdominanz und einen geringeren taxonomischen Reichtum als trockenere Gebiete, erreichten jedoch hohe Simpson-Diversitätswerte, was auf eine gleichmäßige Verteilung der Arten innerhalb der dominanten Gattungen hindeutet. Neuere Vororte wiesen im Vergleich zu älteren Vororten eine geringere taxonomische Arten-, Gattungs- und Familienvielfalt sowie niedrigere Shannon- und Simpson-Indizes auf; kein Gebiet erfüllte die Santamour-10/20/30-Regel. Die Bewertung der Klimavulnerabilität mithilfe von Klimahüllmodellen ergab, dass sich die Vulnerabilität der Arten entlang des Klimagradienten nicht unterschied und dass die Arten an den meisten Standorten unter den meisten Szenarien nicht sehr vulnerabel waren. Allerdings waren Bäume in neuen Vororten im Vergleich zu Bäumen in alten Vororten unter dem Klimaszenario für 2090 weniger klimavulnerabel. Dieser Unterschied zwischen alten und neuen Vororten deutet darauf hin, dass Praktiken der Artenauswahl die Klimaresilienz möglicherweise erhöht haben, auch wenn dies auf Kosten einer geringeren Gesamtartenvielfalt geht. Fazit: Während der Klimawandel erhebliche Herausforderungen mit sich bringt, zeigt unsere Forschung, dass eine durchdachte Artenauswahl und Bewirtschaftungsstrategien dazu beitragen können, Stadtwälder zu schaffen, die besser an zukünftige Bedingungen angepasst sind.

Resumen. Antecedentes: Los bosques urbanos pueden ser vulnerables ante un clima cambiante, y la falta de biodiversidad—ya sea real o percibida—puede agravar dicha vulnerabilidad. Métodos: Evaluamos la biodiversidad y la vulnerabilidad climática del arbolado en vía pública en cinco áreas del gobierno local del Gran Melbourne (Australia), a lo largo de un gradiente climático que abarcaba tanto barrios antiguos (anteriores a 2005) como nuevos. Resultados: A pesar de las variaciones significativas en la precipitación media anual y el índice de aridez en toda el área de estudio, todas las ubicaciones mantuvieron niveles de biodiversidad de moderados a altos según los índices de Shannon y Simpson. Las zonas con mayores precipitaciones mostraron un marcado predominio de ciertos géneros y una menor riqueza taxonómica que las zonas más secas; no obstante, alcanzaron puntuaciones elevadas en el índice de Simpson, lo que sugiere una distribución equilibrada de las especies dentro de los géneros dominantes. Los barrios más recientes presentaron una menor riqueza taxonómica de especies, géneros y familias en comparación con los antiguos, así como índices de Shannon y Simpson más bajos; ninguna zona cumplía con la regla de diversidad 10/20/30 de Santamour. La evaluación de la vulnerabilidad climática mediante modelos de nicho climático indicó que la vulnerabilidad de las especies no variaba a lo largo del gradiente climático y que, en la mayoría de las ubicaciones, las especies no presentaban una vulnerabilidad elevada bajo la mayoría de los escenarios. Sin embargo, los árboles de los barrios nuevos resultaron menos vulnerables al clima que los de los barrios antiguos bajo el escenario climático previsto para el año 2090. Esta diferencia entre barrios antiguos y nuevos sugiere que las prácticas de selección de especies podrían haber aumentado la resiliencia climática, aunque a costa de una menor diversidad general de especies. Conclusión: Si bien el cambio climático plantea desafíos importantes, nuestra investigación demuestra que una selección de especies y unas estrategias de gestión bien planificadas pueden contribuir a crear bosques urbanos mejor adaptados a las condiciones futuras.

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Appendix.

Table S1. Reference coordinates for new and old suburb locations. LGA (local government area).

New suburbs			Old suburbs		
LGA	**Latitude**	**Longitude**	**LGA**	**Latitude**	**Longitude**
Melton City	–37.694847	144.544757	Melton City	–37.684285	144.577759
Wyndham City	–37.831874	144.671935	Wyndham City	–37.901576	144.663459
Hume City	–37.590724	144.919436	Hume City	–37.690395	144.920684
City of Whittlesea	–37.669633	145.041141	City of Whittlesea	–37.669633	145.041141
City of Greater Dandenong	–38.00279	145.169687	City of Greater Dandenong	–37.960644	145.180884

Table S2. Climate Assessment Tool output categories scored from 0 to 11 with corresponding database and range information. Adapted from https://cat.bgci.org.

Value	Description
11	Middle of natural range
10	Middle of urban range
9	Middle of BG range
8	Shoulder of natural range
7	Shoulder of urban range
6	Shoulder of BG range
5	Near edge of natural range
4	Near edge of urban range
3	Near edge of BG range
2	Not known but likely
1	Not known but possible
0	Not known and not likely

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Table S3. Santamour 10/20/30 rule street tree diversity evaluation of 5 LGAs in old and new suburbs in Greater Melbourne, Australia. The lower table excludes data from Myrtaceae. LGA (local government area).

Santamour 10/20/30 rule									
LGA	**Suburb type**	**Number of species exceeding rule**	**Highest species %**	**Number of genera exceeding rule**	**Highest genus %**	**Number of families exceeding rule**	**Highest family %**	**Additional trees required to meet rule**	**Increase required %**
Greater Dandenong	New	1	11.49	1	30.11	1	58.02	6,434	93
Greater Dandenong	Old	0	6.57	1	21.4	1	57.1	44,302	90
Hume	New	1	16.2	1	21.28	1	34.29	8,950	62
Hume	Old	0	8.04	1	32.92	1	60.53	58,124	102
Melton	New	1	10.09	1	20.69	1	36.32	1,184	21
Melton	Old	0	6.27	1	31.11	1	63.4	3,697	111
Whittlesea	New	0	5.16	1	23.69	1	55.15	52,917	116
Whittlesea	Old	0	8.31	1	38.26	1	64.73	43,333	84
Wyndham	New	1	11.62	1	34.26	1	58.06	40,186	94
Wyndham	Old	0	9.03	1	37.08	1	60.33	61,441	101
Santamour 10/20/30 rule excluding Myrtaceae									
LGA	**Suburb type**	**Number of species exceeding rule**	**Highest species %**	**Number of genera exceeding rule**	**Highest genus %**	**Number of families exceeding rule**	**Highest family %**	**Additional trees required to meet rule**	**Increase required %**
Greater Dandenong	New	2	15.01	0	15.6	0	17.61	1,450	50.2
Greater Dandenong	Old	1	11.64	0	12.58	0	25.44	3,375	16.4
Hume	New	3	24.66	1	24.66	0	24.66	13,898	146.6
Hume	Old	0	8.56	0	13.1	0	17.43	0	0
Melton	New	2	15.85	1	20.52	0	21.3	2,093	58.5
Melton	Old	1	13.83	0	14.98	0	16.54	465	38.3
Whittlesea	New	2	19.27	1	20.56	0	20.56	12,044	92.7
Whittlesea	Old	0	9.89	0	18	1	30.4	298	1.4
Wyndham	New	3	27.71	1	27.71	0	27.71	31,927	177.1
Wyndham	Old	0	8.61	0	8.61	0	13.21	0	0

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