CENTRAL VICTORIAN Greenhouse Alliance

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Cool-it Tree Selection

Evaluation of street trees for future climate in the Mallee, Loddon-Campaspe and Central Highlands regions

Prepared by
Dr Cassia Read
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A report by Dr Cassia Read and Dr Meredith Cosgrove
Prepared for Central Victoria Greenhouse Alliance (CVGA)
12th February 2021

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Executive summary

The Cool It project is a partnership between the Central Victorian Greenhouse Alliance (CVGA) and 8 local governments in the region. The project aims to plant trees in locations where social vulnerability and heat exposure overlap, in the shires of Buloke, Pyrenees, Gannawarra, Ararat, Central Goldfields, Macedon Ranges, Hepburn and Mount Alexander. Selection of tree species that are resilient to future climate scenarios is critical for planting success.

The goal of tree selection for the Cool It project was to evaluate and recommend tree species for urban planting, based on their likely resilience to a business as usual, climate scenario in 2050 (i.e. extreme RCP 8.5 emission scenario) in the Mallee, Loddon-Campaspe and Central Highlands regions.

We evaluated 423 species listed on urban tree inventories from towns in Central Victorian and from towns and cities that climate analogues of projected climate (2050) in participating shires. From this list we developed a short list of 100 candidate street and park trees for detailed evaluation of their vulnerability to future climate. This short-list included 50 species currently planted by participating Shires and 50 new experimental species.

Included in this report and the supplied Species Selection Matrix are:

- regional maps that illustrate projected change in mean annual temperature, annual precipitation and maximum temperature of the warmest month in 2050, under extreme climate scenario (RCP 8.5),
- a ranking of all species in terms of their vulnerability to future climate in each region,
- recommended species for each region that are likely to be most resilient to future climate,
- information on attributes and environmental tolerances for 100 species, to aid in tree selection for urban streets and parks, and
- recommendations for increasing the resilience of tree plantings to future climate.

Callistemon viminalis Weeping bottlebrush

Introduction

More than one third of all public trees (35% species) in Australian cities are at high risk from increased temperatures by 2070, in a 'business-as-usual' emissions scenario (Kendal et al., 2017). To maintain and enhance tree cover for urban cooling in regional centers, the current tree stock in parks and streetscapes must be shifted towards a wider diversity of climate resilient species. Sound species selection requires optimising both the benefits from urban trees and their survival under future climate scenarios.

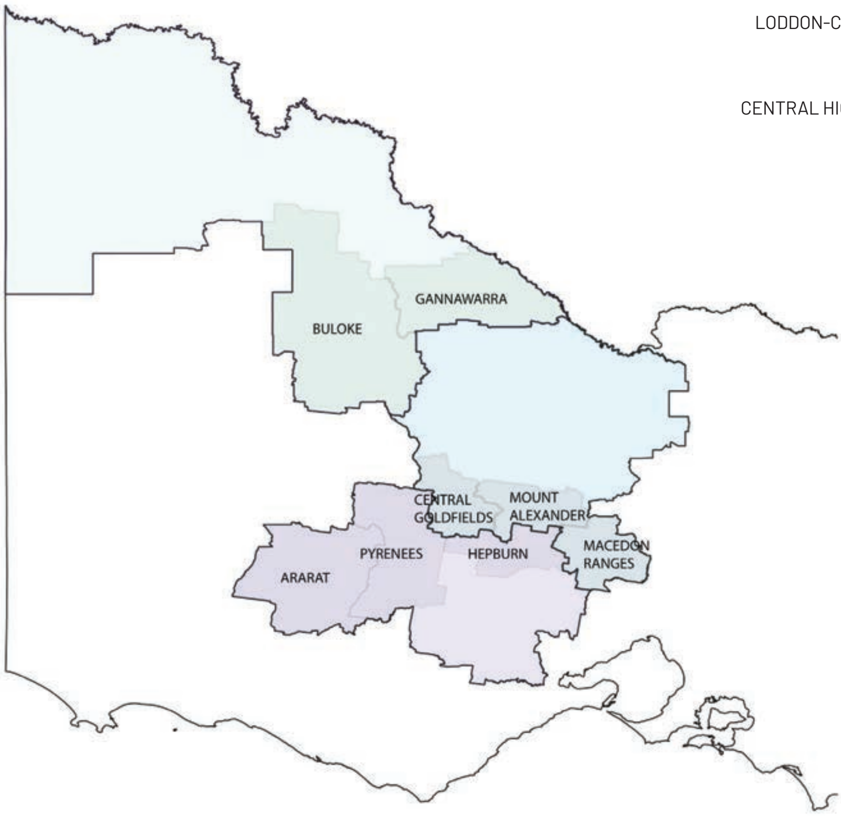
The aim of this report was to evaluate a wide range of urban street and park trees for their likely resilience to future climate in the Mallee, Loddon-Campaspe and Central Highlands regions. These three Victorian Regional Partnership (VRP) regions incorporate eight Shires participating in the Cool It project (Stage 2): Central Goldfields, Macedon Ranges and Mount Alexander Shire Councils in the Loddon-Campaspe region, Gannawarra and Buloke Shire Councils in the Mallee region; and Ararat, Hepburn and Pyrenees Shire Councils in the Central Highlands region (Figure 1). While a number of shires in the regions were not participants in this project (e.g. Mildura, Swan Hill and Loddon Shires), results presented for each region are relevant to all constituent Shires.

FIGURE 1 — Map of the eight Local Government Areas (LGAs) that are the focus of tree selection in Cool It Stage 2.

MALLEE REGION
Buloke
Gannawarra

LODDON-CAMPASPE REGION
Central Goldfields
Mount Alexander

CENTRAL HIGHLANDS REGION
Ararat
Pyrenees
Hepburn
Macedon Ranges



We report on evaluations of 100 tree species, including 50 street trees commonly planted in participating Shires and 50 new experimental tree species for councils to consider for use in streetscapes, parks and gardens. Results of species evaluations were used to develop lists of **recommended species for future climate in each region** (presented in this report). Also included in this report are maps that illustrate projected changes in climate in each region and plots that illustrate species climatic range (mean annual temperature and mean annual precipitation) compared to the projected climatic range for each region. Used together these maps and plots will enable Shires to assess the extent of species vulnerability to future climate within each local government area.

The complete results of species evaluations are presented in a searchable excel spreadsheet (**Species Selection Matrix**). In this spreadsheet, each species is ranked in terms of its vulnerability to projected climate for each region (including mean annual temperature, mean annual precipitation and mean maximum temperature in 2050). This matrix also includes information on species attributes and environmental tolerances that enables easy selection of species tolerant to future regional climate and to local conditions and requirements. By filtering on preferred attributes, the spreadsheet can be used to fine-tune tree selection.

This report also includes r**ecommendations for increasing the resilience of street tree plantings**. The methodology used to select climate resilient street trees for urban cooling is briefly outlined below.

Jacaranda mimosifolia Jacaranda

Methodology

Methodologies are summarised in Figure 2 and briefly discussed below.

FIGURE 2 — Process for recommending potential street trees for future climate in 2050 (RCP 8.5)

DATA COLLECTION	Identified best climate models and establish climate projections for participating regions. Collated long-list of tree species for evaluation, including species currently planted in participating Shires (69 species) and species recorded as drought tolerant in climatically analogous regions (total 423 species).
PRELIMINARY ANALYSIS	Filtered long-list by eliminating species inappropriate for public amenity planting, or low tolerance of drought stress, resulting in a short-list of 100 species. Collated data on species attributes and environmental toleranaces for all species on the short-list, from horticultural & ecological literature and databases. Downloaded data on global species distributions from Global Biodiversity Information Facility (GBIF).
FINAL ANALYSIS	Extracted data for recent and future climate based on mean annual temperature, maximum temperature of the warmest month (a mean calculated over years) and mean annual precipitation. Evaluated species vulnerability to future climate in each region, based on species climatic ranges (from historical climatic data) compared to future climate scenarios for each region (based on climatic models). Evaluated species based on their environmental tolerances and attributes.
REPORTING	Provided a searchable matrix of 100 tree species, which can be filtered by species vulnerability to future climate in each region (based on overlap of species current climatic range with regional future-climate projections) and by species attributes. Provided a list of recommended species for future climate in each region. Reported on climate resilient tree selection and planting.

Collating tree lists for evaluation

We collated a long list of 423 potential tree species, including 69 species on tree inventories for seven of the eight participating Shires (we did not obtain a list for Hepburn Shire), and an additional 354 experimental street trees with potential for climate resilient urban plantings.

The experimental list was derived from databases and lists of street or park tree species recorded as: tolerant of future climate within the region; i.e. Ballarat, (Kendal et al., 2017), species recorded as drought tolerant in Melbourne (University of Melbourne, 2012), or species recorded as drought tolerant in cities and towns that are climate analogues for future climate in participating Shires, including Tehran in Iran, and Dubbo, Adelaide and Canberra in Australia (Asgarzadeh et al., 2014; Dubbo Regional Council, 2015; Kendal et al., 2017; SA Government, 2020, respectively)

We filtered the experimental Street and Park trees to remove "red-flag" species, inappropriate for public amenity planting due to high potential for becoming invasive, high allergenic properties and high limb-fall risk. We also removed species known to have low or average tolerance of drought stress, low tolerance of cold (minimum temperature >-3° C) and tree species too short to provide value as shade trees (< 5 m maximum height).

Our final short-list of 100 tree species for evaluation included 50 experimental species for evaluation, plus 50 most popular species on Council lists.[1] These species were identified as having a moderate to high likelihood of planting in one or more Shires in 2020-21. These species on the Council lists included 4 species that were rated as moderate to high level of invasiveness (*Celtis australis*, *Schinus molle*, *Leptospermum laevigatum* and *Gleditsia triacanthos*). These were retained in our assessment so we could inform Councils about the likely future of these species under projected climate change. We do not recommend them for future planting. Experimental species were selected to optimise benefits from urban plantings and persistence under future climate scenarios.

1. Previously (January 2020) we evaluated 30 species most likely to be planted by participating Shires in 2020-21 (Appendix I). For consistency, we have reevaluated these species in the current report, using improved modelling methods and data, along with the an additional 20 Council species (included at least once on planting lists of participating Shires and with a moderate likelihood of planting in 2020-21).

Collating species data

For all species on the short list we downloaded data on global species distributions from Global Biodiversity Information Facility (GBIF, https://www.gbif.org, accessed on 1/11/2020). This occurrence data captures species climatic range. Cultivars were included as species, as data on cultivar provenance and climatic suitability are limited.

Species attribute data, for all species on the short-list was collated from plant selection databases, nursery catalogues and scientific papers (listed in Appendix II). Environmental attributes recorded were: tolerance to wind, soil compaction and waterlogging (where 0=sensitive, 1=low tolerance, 2= moderate and 3=high tolerance[2]), light (shade, semi-shade and full sun), soil pH and minimum temperature. Undesirable attributes recorded were: invasive potential, allergenicity, cultivation issues, limb fall risk (where 0=no risk, 1=low risk, 3=high risk). Physical attributes were: height (minimum and maximum), canopy dimensions and seasonality (evergreen/deciduous). We also recorded species family, origin (exotic/native) and whether it was endemic to Victoria (y/n). Because the Burnley Plant Guide (University of Melbourne, 2012) represented the most comprehensive coverage of all species on our final list, for consistency we used this as our primary source of species data, filling in any gaps from other data sources (listed in Appendix II) where required.

Data on species attributes that were beyond the scope of this project to collate, but important for final species selection for urban planting include: aesthetic and cultural value, susceptibility to pests and diseases, and tolerance of conditions particular to high density urban environments (e.g. air pollution, limited root space, and soil contaminants).

Scoring species by their urban cooling benefits was also beyond the scope of this report. Trees provide urban cooling through both transpiration and shade. Transpiration rates were unavailable for most species on our short-list. Further, many species shut-down transpiration (by closing stomata) at high temperatures and low soil moisture values, so cooling provision from transpiration is highly variable trait over the course of a hot day. Estimating shade provision requires knowledge of the leaf area (leaf area index = leaf area per area of ground) and the canopy area. Leaf area index values were also difficult to source for the majority of the trees on our short-list. Councils will need to make their own decisions about canopy properties when selecting trees for urban cooling by visual assessment of tree canopies, either online from photos or on-ground assessment of trees growing in the Shire. We provide further suggestions on species selection and planting for urban cooling in the section "Planting for the future."

2. Species tolerance of an environmental factor is the ability to withstand stress without suffering serious, irreversible damage.

Evaluating species vulnerability to projected climate

We used WorldClim climatic data to evaluate the short-list of street and park trees for resilience to a business as usual, climate scenario in 2050 (i.e. extreme RCP 8.5 emission scenario). Climatic scenarios project the ways that global temperature increases will perturb our current climate into the future. Bioclimatic studies combine climate data and species distribution data to evaluate species vulnerability to future climate, by characterising species climatic range (climate envelopes) and using these ranges to project species potential future distributions under various climate emission scenarios. This method has been used in a wide range of bioclimatic evaluations of tree species, such as: identifying trees likely to be less vulnerable to Melbourne's future climate for the Melbourne Urban Forest Strategy (Kendal et al 2017), assessing probability of finding climatically suitable habitat in each region for urban Australian trees species (Burley et al., 2019) and evaluating candidate forestry species for assisted migration in Manitoba (Park et al., 2018).

Climate data were used to compare the recent historical climate (1970-2000) to the newest generation of future climate projections (2041-2060), under a high carbon emissions scenario (RCP 8.5, https://worldclim.org/). This scenario is the current global trajectory, unless fast and drastic global action is taken. Climate projections values were extracted from one of the CMIP6 suite of global future scenarios.[3]

Mean annual temperature and mean annual precipitation are recognised as being highly correlated with plant species climate vulnerability across species ranges (Gallagher et al., 2019) and were selected as the primary variables for species climate vulnerability ranking in the current project. We also used mean temperature of the warmest month to capture the effect of heat stress during more extreme weather events. Climate variables were extracted from Bioclim rasters.[4]

3. The global climate model used was BCC-CSM2-MR_ssp585_2041-2060. While downscaled high-resolution climate change simulations are available for Victoria, from CSIRO's Climate Science Centre, we could not use these, as we required congruence with global species distribution data. We chose the recently updated CMIP6 global model BCC-CSM2-MR_ssp585_2041-2060 because it provides average results compared to the other climate models available and it more closely matches the Australian climate. CMIP6 global models predict slightly hotter temperatures than the downscaled Victorian models.

4. Global bioclimatic variables from WorldClim are derived from the monthly temperature and precipitation values in order to generate more biologically meaningful variables. These are often used in species distribution modeling and related ecological modeling techniques. The bioclimatic variables represent annual trends.

By taking the current climatic range of a species[5] and comparing it to the future climate in the Mallee, Loddon Campaspe and the Central Highlands we were able to estimate how much climatic overlap there was between species current climatic range and the future climatic ranges of the three regions, where 0% = no overlap and 100% = total overlap. For scores of 100, the overlap was either because the species range was broader than the regional range, or the reverse, the regional range was broader than the species range.

Each species' likely vulnerability to the future climate in each region was ranked, based on these estimates of percentage overlap. Percentage overlap for mean annual temperature and mean annual precipitation was calculated, summed and standardised for each region, to give a standardised "vulnerability" score that could be used to rank all species (0= very high vulnerability, 100 = very low vulnerability).

Species with "*low vulnerability*" to future climate were those with an overall, non-zero standardised overlap score (but may have zero score for either mean annual temperature or mean annual precipitation). Species with "*very low vulnerability*" to future climate were those with a non-zero overlap in both mean annual temperature and mean annual precipitation. Species with "lowest vulnerability" to future climate were those with non-zero overlap in all three climate variables in each region, including maximum temperature of the warmest month.

Tree species ranked as "*very low*" and "*lowest vulnerability*", indicate species that may require little or no support as they mature in hotter, drying climates. While species vulnerable to future climate can still be planted and trialled in the regions, they should only be considered for planting in sites with amenable microclimates and soils and with supportive horticultural practices such as irrigation and soil improvement.

Results are presented in the searchable Species Selection Matrix for Shires to use in tree selection, where species can be screened by their vulnerability to future climate, environmental tolerances and general attributes. These results are the basis of recommended species for each region.

5. Four steps were involved in calculating the overlap between the current climatic range of 100 species with the future climatic ranges of the three regions: 1) estimate species mean annual temperature and mean annual precipitation, from global species distribution records in the Global Biodiversity Information Facility (GBIF) database; 2) Calculate a conservative species 'window' for each climate variable, calculated as ± one standard deviation from the mean. This 'window' was a conservative estimate of species climatic range, as it contains 68% of species records; 3) Calculate a 'window' for the projected climate in each region as ± one standard deviation from mean annual temperature and mean annual precipitation for each region; 4) Calculate percent overlap between the window for each species with the regional window for each climate variable, and standarise to a score between 0-1.

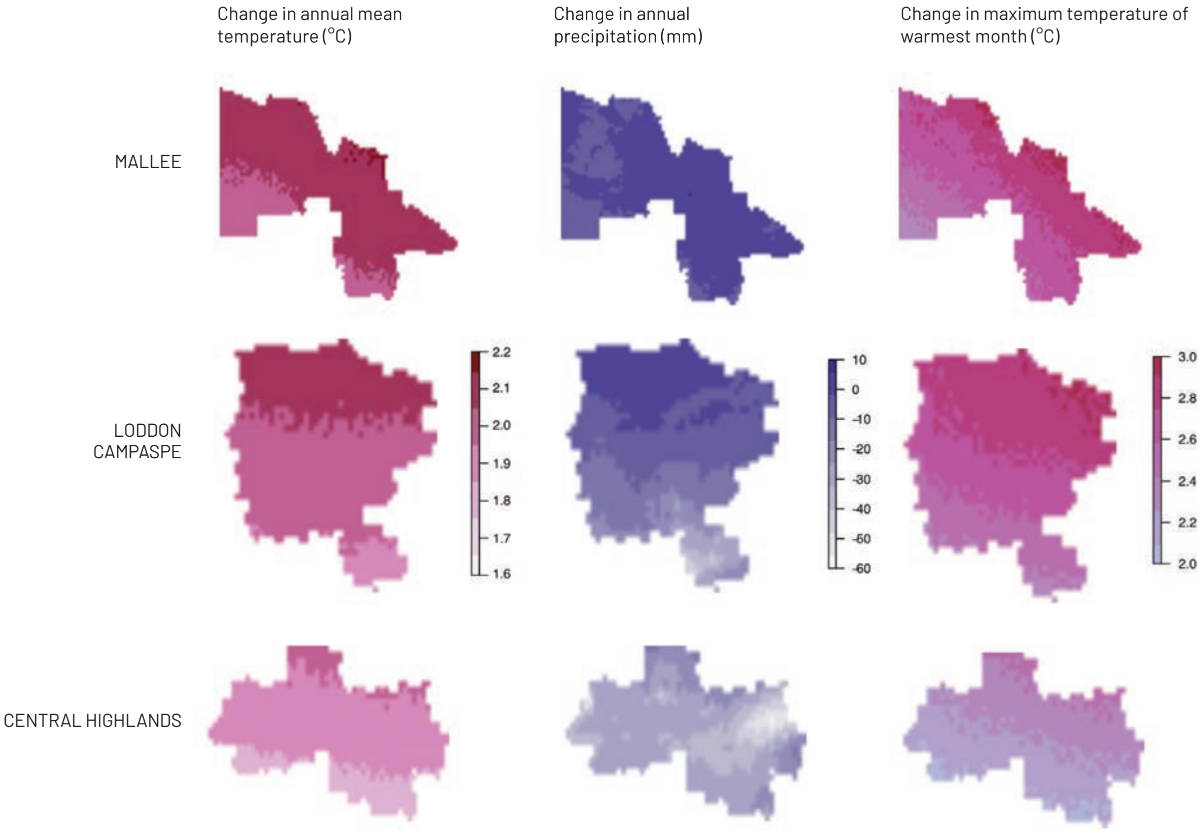
Regional climate change projections

Understanding variation in regional climate trends is important for appropriate tree selection within each region. Average values for three climate variables (mean annual temperature, annual precipitation and maximum monthly temperature) are provided in Table 1. Average climate values are good at picking up general trends, but they fail to identify how much variation there is at a local scale. In Victoria, temperatures are predicted to rise but these will happen at varying intensities across the different regions. Variation in projected changes in climate variables is illustrated in (Figure 3). Before following recommendations trees for future climate in each region, it is important to be aware of regional variation.

TABLE 1 — Mean projected average climate values for three regions in 2041-2060 (under extreme climate change, RCP 8.5)

		Average 1970-2000	Average 2050	**Average change**	Standard deviation change
Annual mean temperature (°C)	Mallee	16.4	18.5	**2.1**	0.04
	Loddon	14.6	16.6	**2.0**	0.04
	Highlands	12.8	14.7	**1.9**	0.05
Maximum temperature of warmest month (°C)	Mallee	31.7	34.5	**2.67**	0.04
	Loddon	29.4	32.1	**2.70**	0.15
	Highlands	26.2	28.5	**2.25**	0.11
Annual recipitation (mm)	Mallee	339	340	**0.2**	2.4
	Loddon	535	527	**-8.7**	9.8
	Highlands	675	644	**-30.8**	6.6
Precipitation of driest quarter (mm)	Mallee	64	67	**2.7**	2.3
	Loddon	97	99	**1.5**	2.2
	Highlands	117	120	**2.6**	4.9

FIGURE 3 — Projected changes in climate in the three regions (mean annual temperature, mean precipitation and mean maximum temperature) in 2050, under extreme climate scenario (RCP 8.5)



Gingko baloba Gingko

Recommended trees

Recommended trees for Mallee region

A total of forty-five species were identified as having "low vulnerability" to future climate in the Mallee region, estimated from a standardised ranking of both mean annual temperature and mean annual precipitation (Table 2). But only three species were identified as having "lowest vulnerability" to all three climatic variables, including maximum temperatures of the warmest month (species marked ** on Table 2). These were Coobah (*Acacia salcina*), Whitewood (*Atalaya hemiglauca*) and Round-leaved Mallee (*Eucalyptus rotundifoli*a).

Of the popular tree species Buloke Shire (i.e. species rated as having a high likelihood of planting in 2020-21), only four of these were ranked as having "low vulnerability" to future climate. These are the Crepe Myrtle (Lagerstroemia indica), Peppercorn Tree (Schinus molle), Carob (Ceratonia siliqua) and Callery Pear (Pyrus calleryana). And only two popular species in the Gannawarra Shire were ranked with "low vulnerability": Crepe Myrtle and Callery Pear.

It is highly recommended that Shires in the Mallee region consider broadening their tree selection to include some of the recommended species listed below Table 2.

TABLE 2 — **Tree species rated as having "low vulnerability" to projected climate in the Mallee region**; *Species with "very low vulnerability" to projected mean annual temperature and mean annual precipitation; ** Species with "lowest vulnerability" to projected climate, including maximum temperature of the warmest month; +Species on Council lists that are invasive/and or allergenic and not recommended for future planting).

SPECIES	COMMON NAME
Acacia pendula	Weeping Myall
*Acacia salicina***	Coobah, Willow Wattle
Allocasuarina inophloia	Stringybark She-oak
Allocasuarina luehmannii	Buloke
Allocasuarina torulosa	Forest Oak
Angophora costata	Rose Apple
*Atalaya hemiglauca***	Whitewood
Callistemon citrinus	Lemon Bottlebrush
Callistemon viminalis	Weeping Bottlebrush
Callitris canescens	Scrubby cypress pine
Callitris columellaris	Coast Cypress Pine
Callitris glaucophylla	White Cypress
*Callitris preissii**	Rottnest Island Pine
Ceratonia siliqua	Carob
Corymbia maculata	Ghost Gum
Corymbia citriodora	Lemon-scented Gum
Corymbia maculata	Spotted Gum
Eriobotrya japonica	Loquat
Eucalyptus cladocalyx	Sugar Gum
*Eucalyptus leucoxylon**	Yellow Gum
Eucalyptus macrandra	Long-flowered Marlock
Eucalyptus megacornuta	Warty Yate
*Eucalyptus orbifolia***	Round-leaved Mallee
Eucalyptus pachyphylla	Red Bud Mallee
Eucalyptus platypus	Round-leaved Moort
Eucalyptus porosa	no common name
Ficus rubiginosa	Port Jackson Fig
Geijera parviflora	Wilga
Hakea laurina	Pincushion Hakea
Jacaranda mimosifolia	Jacaranda
Lagerstroemia indica	Crepe Myrtle
Leptospermum laevigatum+	Coastal Tea-tree
Lophostemon confertus	Brush Box
Melaleuca halmaturorum	Salt Paperbark
*Melaleuca lanceolata**	Moonah
Melaleuca linariifolia	Flaxleaf Paperbark
Melaleuca styphelioides	Prickly-leaved Paperbark
Melia azedarach	White Cedar
Metrosideros excelsa	Pohutukawa
*Myoporum insulare**	Common Boobialla
*Pinus canariensis**	Canary Islands Pine
Pistacia chinensis	Chinese Pisctachio
Pyrus calleryana	Callery Pear
Schinus molle+*	Peppercorn Tree
Ulmus parvifolia	Chinese Elm

Recommended trees for Loddon-Campaspe region

Overall, ninety-four species were identified as having "low vulnerability" to projected climate in the Loddon-Campaspe region, estimated from a standardised ranking of both mean annual temperature and mean annual precipitation (Table 3). Of these, a total of thirty-two species were identified as having "lowest vulnerability" to all three climatic variables, including maximum temperatures of the warmest month (species marked **).

Of the popular species planted in the Loddon-Campaspe region (i.e. species with a high likelihood of planting in 2020-21), twelve species in the Central Goldfields Shire and twenty-three species from Mount Alexander Shire were ranked as having a "low vulnerability" to projected climate. It is highly recommended that both Shires in the region diversify their urban forest with climate resilient species.

Fraxinus angustifolia subsp. oxycarpa Claret Ash

TABLE 3 — Tree species rated as having "low vulnerability" to projected climate in the Loddon-Campaspe region; *Species with "very low vulnerability" to projected mean annual temperature and mean annual precipitation; ** Species with "lowest vulnerability" to projected climate, including maximum temperature of the warmest month; +Species on Council lists that are invasive/and or allergenic and not recommended for future planting).

SPECIES	COMMON NAME
Acacia melanoxylon	Blackwood
*Acacia pendula***	Weeping Myall
*Acacia salicina***	Coobah, Willow Wattle
Agonis flexuosa	Willow Myrtle
*Allocasuarina inophloia***	Stringybark She-oak
*Allocasuarina luehmannii***	Buloke
Allocasuarina torulosa	Forest Oak
*Allocasuarina verticillata***	Drooping Sheoke
Angophora costata	Rose Apple
Angophora hispida	Dwarf Apple
Atalaya hemiglauca	Whitewood
Banksia marginata	Silver Banksia
*Brachychiton populneus***	Kurrajong
Callistemon citrinus	Lemon Bottlebrush
*Callistemon viminalis***	Weeping Bottlebrush
*Callitris canescens***	Scrubby cypress pine
*Callitris columellaris***	Coast Cypress Pine
*Callitris endlicheri***	Black Cypress
*Callitris glaucophylla***	White Cypress
*Callitris preissii***	Rottnest Island Pine
*Callitris rhomboidea**	Port Jackson pine
*Celtis australis***	European Nettle Tree
*Ceratonia siliqua***	Carob
*Cercis siliquastrum***	Judas Tree
Corymbia aparrerinja	Ghost Gum
Corymbia citriodora	Lemon-scented Gum
Corymbia ficifolia	Red Flowering Gum
Corymbia maculata	Spotted Gum
Cupressus lusitanica	Mexican Cypress
*Cupressus macrocarpa**	Monterey Cypress
*Eriobotrya japonica**	Loquat
Eriolobus trilobatus	Lebanese Wild Apple
*Eucalyptus albens***	White box
Eucalyptus arenacea	Desert stringybark
Eucalyptus baueriana	Blue box, Round-leaved box
*Eucalyptus behriana***	Bull mallee
*Eucalyptus cladocalyx***	Sugar Gum
*Eucalyptus conferruminata**	Bushy Yate
*Eucalyptus cornuta**	Yate
*Eucalyptus dolichorhyncha***	Fuschia Gum
*Eucalyptus leucoxylon***	Yellow Gum
*Eucalyptus macrandra***	Long-flowered Marlock
*Eucalyptus megacornuta**	Warty Yate
*Eucalyptus melliodora***	Yellow Box
*Eucalyptus newbeyi**	Newbey's Mallet
*Eucalyptus occidentalis**	Flat-topped Yate
Eucalyptus pachyphylla	Red Bud Mallee
*Eucalyptus platypus**	Round-leaved Moort
Eucalyptus polyanthemos	Red Box
*Eucalyptus porosa***	ncn
Eucalyptus saxatilis	Suggan Buggan Mallee
Eucalyptus scoparia	Wallangarra White Gum
*Eucalyptus sideroxylon***	Mugga Ironbark
Eucalyptus tricarpa	Red Ironbark
Ficus rubiginosa	Port Jackson Fig
*Fraxinus angustifolia subsp. oxycarpa**	Claret Ash
Fraxinus excelsior	Golden Ash
Fraxinus pennsylvanica	Green Ash
*Geijera parviflora***	Wilga
Ginkgo biloba	Gingko
*Gleditsia triacanthos**	Honey Locust

TABLE 3 — **Tree species rated as having "low vulnerability" to projected climate in the Loddon-Campaspe region**

SPECIES	COMMON NAME	SPECIES	COMMON NAME
*Gleditsia triacanthos**	Honey Locust	*Pinus pinea***	Stone Pine
*Hakea laurina**	Pincushion Hakea	*Pistacia chinensis***	Chinese Pisctachio
Jacaranda mimosifolia	Jacaranda	*Prunus cerasifera*	Myobalan Plum
*Koelreuteria paniculata***	Golden Rain Tree	*Pyrus calleryana*	Callery Pear
Lagerstroemia indica	Crepe Myrtle	*Quercus canariensis**	Algerian Oak
Leptospermum laevigatum+	Coastal Tea-tree	*Quercus cerris*	Turkey Oak
Lophostemon confertus	Brush Box	*Quercus coccinea*	Scarlet Oak
*Maclura pomifera***	Osage Orange	*Quercus ilex**	Holly Oak
*Melaleuca halmaturorum***	Salt Paperbark	*Quercus palustris*	Pin Oak
*Melaleuca lanceolata***	Moonah	*Quercus pyrenaica*	Pyrenean Oak
Melaleuca linariifolia	Flaxleaf Paperbark	*Quercus robur*	English Oak
Melaleuca styphelioides	Prickly-leaved Paperbark	*Quercus rubra*	Red Oak
Melia azedarach	White Cedar	*Quercus suber**	Cork Oak
Metrosideros excelsa	Pohutukawa	*Schinus molle*+*	Peppercorn Tree
*Myoporum insulare**	Common Boobialla	*Ulmus parvifolia***	Chinese Elm
*Pinus canariensis**	Canary Islands Pine	*Zelkova serrata*	Japanese Elm

Recommended trees for Central Highlands region

Overall, eighty-three species were identified as having "low vulnerability" to projected climate in the Central Highlands region, estimated from a standardised ranking of both mean annual temperature and mean annual precipitation (Table 4). Of these, a total of thirty-one species were identified as having "lowest vulnerability" to all three climatic variables, including maximum temperature of the warmest month (species marked **).

Of the trees popular in Shires of the Central Highlands region, twenty-four species in the Macedon Ranges Shire, seven species in Ararat Rural City and eighteen species in the Pyrenees Shire were ranked as having a low vulnerability to future climate. Additional species are worth exploring for planting in these shires, to diversify the urban forest with climate resilient species, particularly in Ararat Rural City.

TABLE 4 — Tree species rated as having "low vulnerability" to projected climate in the Central Highlands region; *Species with "very low vulnerability" to projected mean annual temperature and mean annual precipitation; ** Species with "lowest vulnerability" to projected climate, including maximum temperature of the warmest month; +Species on Council lists that are invasive/and or allergenic and not recommended for future planting.

SPECIES	COMMON NAME	SPECIES	COMMON NAME
Acacia melanoxylon	Blackwood	*Eucalyptus cephalocarpa***	Mealy Stringybark
Acacia pendula	Weeping Myall	*Eucalyptus cladocalyx**	Sugar Gum
Acacia salicina	Coobah	*Eucalyptus conferruminata***	Bushy Yate
*Acer rubrum***	Autumn Blaze Maple	*Eucalyptus cornuta***	Yate
*Agonis flexuosa***	Willow Myrtle	*Eucalyptus cosmophylla***	Cup Gum
Allocasuarina inophloia	Stringybark She-oak	*Eucalyptus diversifolia**	Soap Mallee
Allocasuarina luehmannii	Buloke	*Eucalyptus dolichorhyncha**	Fuschia Gum
*Allocasuarina verticillata**	Drooping Sheoke	*Eucalyptus leucoxylon***	Yellow Gum
Atalaya hemiglauca	Whitewood	*Eucalyptus macrandra***	Long-flowered Marlock
Banksia marginata	Silver Banksia	*Eucalyptus mannifera*	Brittle Gum
*Brachychiton populneus**	Kurrajong	*Eucalyptus megacornuta*	Warty Yate
Callistemon citrinus	Lemon Bottlebrush	*Eucalyptus melliodora***	Yellow Box
Callistemon viminalis	Weeping Bottlebrush	*Eucalyptus newbeyi**	Newbey's Mallet
Callitris columellaris	Coast Cypress Pine	*Eucalyptus occidentalis**	Flat-topped Yate
*Callitris endlicheri***	Black Cypress	*Eucalyptus platypus*	Round-leaved Moort
Callitris glaucophylla	White Cypress	*Eucalyptus polyanthemos**	Red Box
*Callitris preissii***	Rottnest Island Pine	*Eucalyptus saxatilis*	Suggan Buggan Mallee
*Callitris rhomboidea***	Port Jackson pine	*Eucalyptus scoparia*	Wallangarra White Gum
*Celtis australis**+*	European Nettle Tree	*Eucalyptus sideroxylon***	Mugga Ironbark
Ceratonia siliqua	Carob	*Eucalyptus tricarpa***	Red Ironbark
*Cercis siliquastrum**	Judas Tree	*Ficus rubiginosa***	Port Jackson Fig
Corymbia aparrerinja	Ghost Gum	*Fraxinus angustifolia subsp. oxycarpa***	Claret Ash
Corymbia citriodora	Lemon-scented Gum	*Fraxinus excelsior*	Golden Ash
Corymbia ficifolia	Red Flowering Gum	*Fraxinus pennsylvanica*	Green Ash
Cupressus lusitanica	Mexican Cypress	*Geijera parviflora*	Wilga
*Cupressus macrocarpa**	Monterey Cypress	*Ginkgo biloba***	Gingko
Eriobotrya japonica	Loquat	*Gleditsia triacanthos*+*	Honey Locust
*Eriolobus trilobatus***	Lebanese Wild Apple,	*Hakea laurina***	Pincushion Hakea
*Eucalyptus albens***	White Box	*Koelreuteria paniculata***	Golden Rain Tree
*Eucalyptus arenacea***	Desert stringybark	*Leptospermum laevigatum+*	Coastal Tea-tree
*Eucalyptus behriana**	Bull mallee		

TABLE 4 — **Tree species rated as having "low vulnerability" to projected climate in the Central Highlands region**;

SPECIES	COMMON NAME
*Maclura pomifera***	Osage Orange
*Melaleuca halmaturorum***	Salt Paperbark
Melaleuca lanceolata	Moonah
Melia azedarach	White Cedar
*Metrosideros excelsa***	Pohutukawa
*Myoporum insulare***	Common Boobialla
*Pinus canariensis***	Canary Islands Pine
*Pinus pinea**	Stone Pine
*Pistacia chinensis***	Chinese Pisctachio
Prunus cerasifera	Myrobalan Plum
Pyrus calleryana	Callery Pear
*Quercus canariensis***	Algerian Oak
Quercus cerris	Turkey Oak
*Quercus coccinea**	Scarlet Oak
*Quercus ilex**	Holly Oak
*Quercus palustris**	Pin Oak
Quercus pyrenaica	Pyrenean Oak
Quercus robur	English Oak
Quercus rubra	Red Oak
*Quercus suber**	Cork Oak
Schinus molle+	Peppercorn Tree
*Ulmus parvifolia***	Chinese Elm

Hakea laurina Pincushion Hakea

Species climatic ranges (1970-2000) compared to projected climatic range for the regions (2050, RCP 8.5)

The following Boxplots illustrate the climatic ranges of the 100 species evaluated for this study, overlain with the projected climatic range for each region in 2050, under an extreme climate scenario (RCP 8.5). These plots can be used to aid councils in understanding species vulnerability to projected annual precipitation and annual temperature.

The vertical colour bands are the projected climatic range for reach region in 2050 (i.e. the projected climatic mean ± 1 standard deviation); the boxes represent the historic climatic range of each species (1970-2000 median and the interquartile range). To understand species vulnerability to projected climate, simply evaluate the extent to which species climatic range (the box) overlaps regional climatic range (the colour band).[7] The "whiskers" of each box represent the lower and upper bound of each species climatic range and are useful for evaluating species plasticity in tolerating climatic variation.

When considering these plots during species selection, regard species with "whiskers" that overlap those of projected regional climatic ranges as species with potential for cautious experimentation. Prioritise species with "boxes" that overlap those of projected regional climatic range as this is a conservative approach to planting for the future.

Also note that while a species may fall within a given rainfall or temperature range, it is important to consider both variables when selecting tree species. For example, a species might be able to withstand high temperatures, but only when it receives high rainfall (see *Lophostemon confertus*).

7. Note, each species climatic range illustrated in these boxplots is narrower than species climatic ranges used to calculate each species vulnerability to future climate, for the Tables above. This is because boxplots represent species climatic range as an interquartile range (each box represents 50% of the species records), whereas standard deviations (representing 68% of species records) were used in the calculations of species climatic overlap with future climate

FIGURE 4 — Boxplots illustrating species ranges for annual precipitation (mm) for 50 tree species on council inventories, relative to projected climatic range in each region (purple = Central Highlands, blue = Loddon-Campaspe, aqua = Mallee).

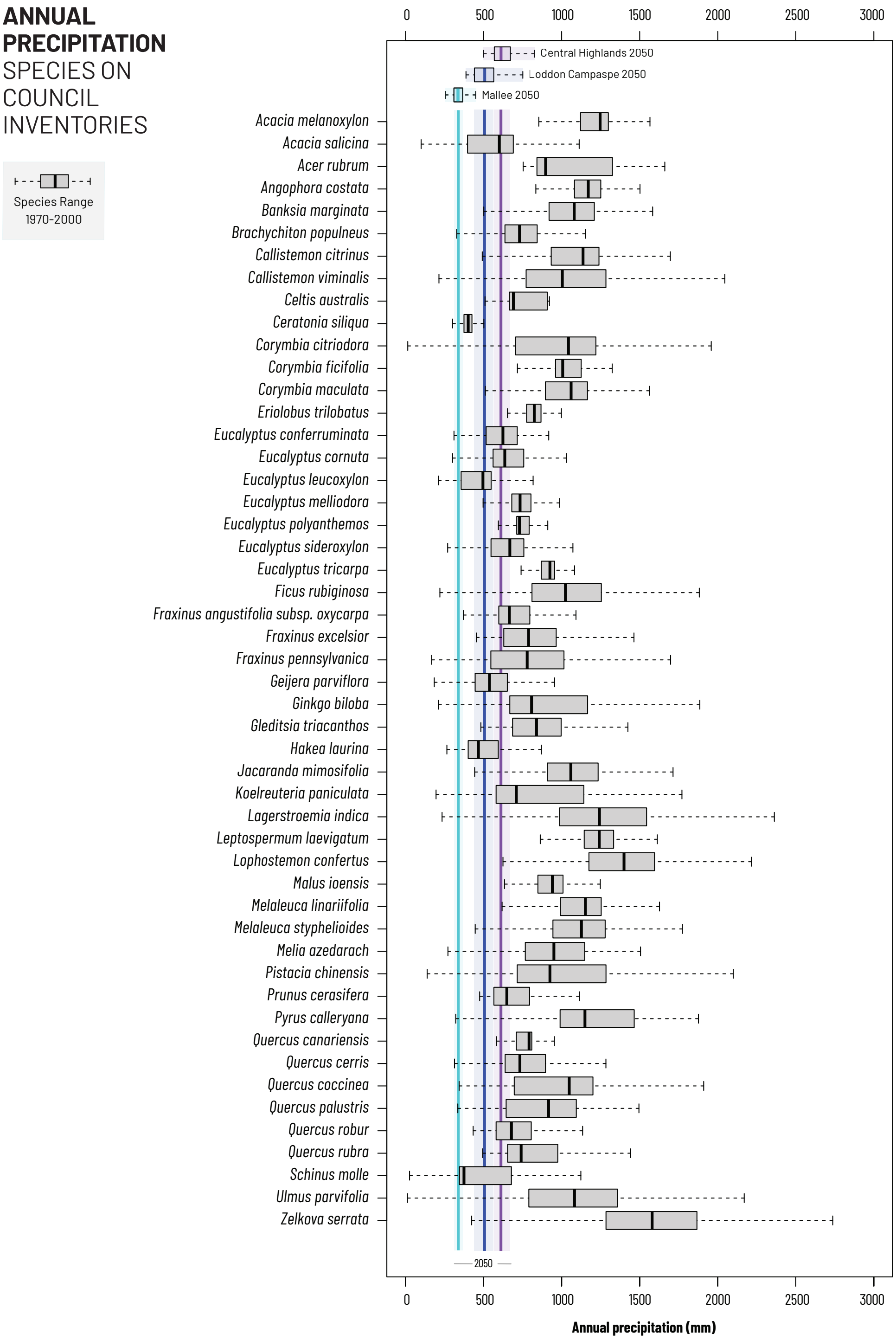


FIGURE 5 — Boxplots illustrating species ranges for mean annual temperature (°C) for 50 tree species on council inventories, relative to projected climatic range in each region (purple = Central Highlands, blue = Loddon-Campaspe, aqua = Mallee).

ANNUAL MEAN TEMPERATURE
SPECIES ON COUNCIL INVENTORIES

Species Range 1970-2000

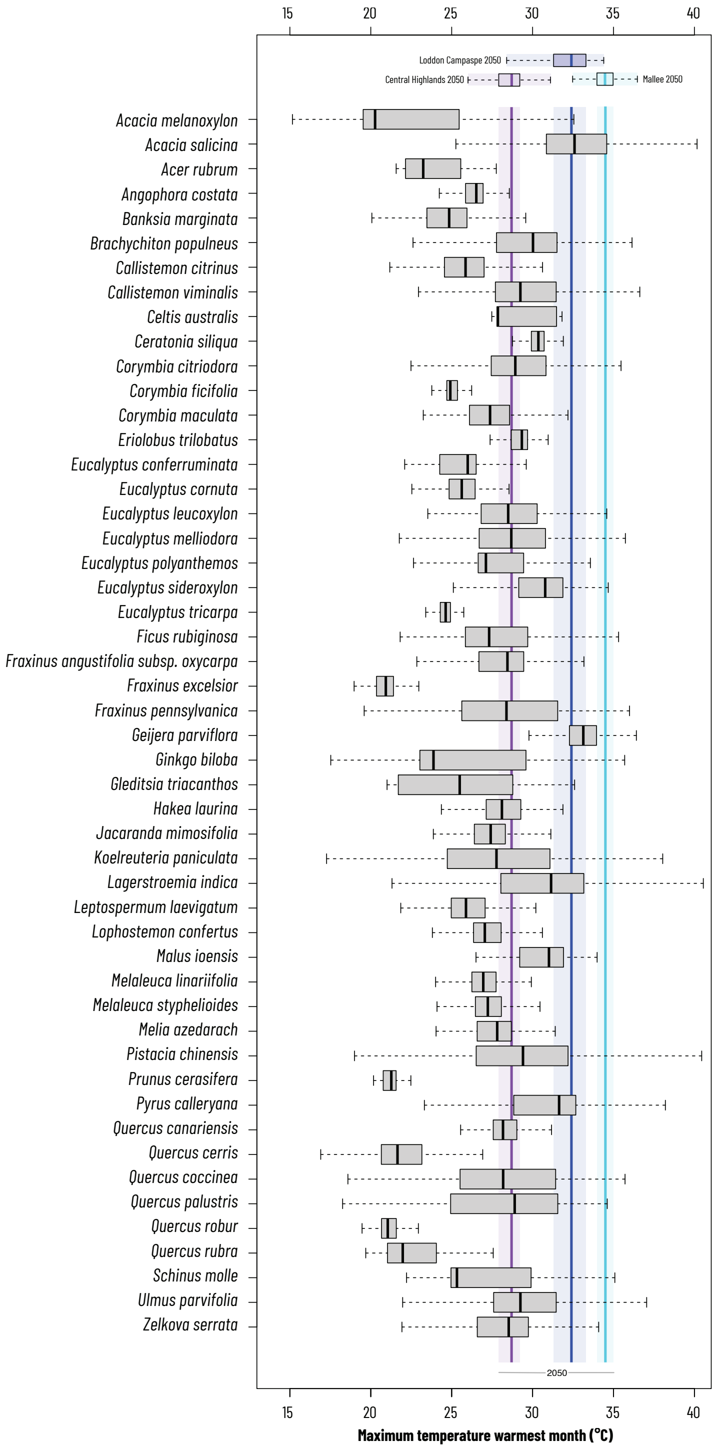


FIGURE 6 — Boxplots illustrating species ranges for annual precipitation (mm) for 50 tree species on council inventories, relative to projected climatic range in each region (purple = Central Highlands, blue = Loddon-Campaspe, aqua = Mallee).

ANNUAL PRECIPITATION
EXPERIMENTAL SPECIES

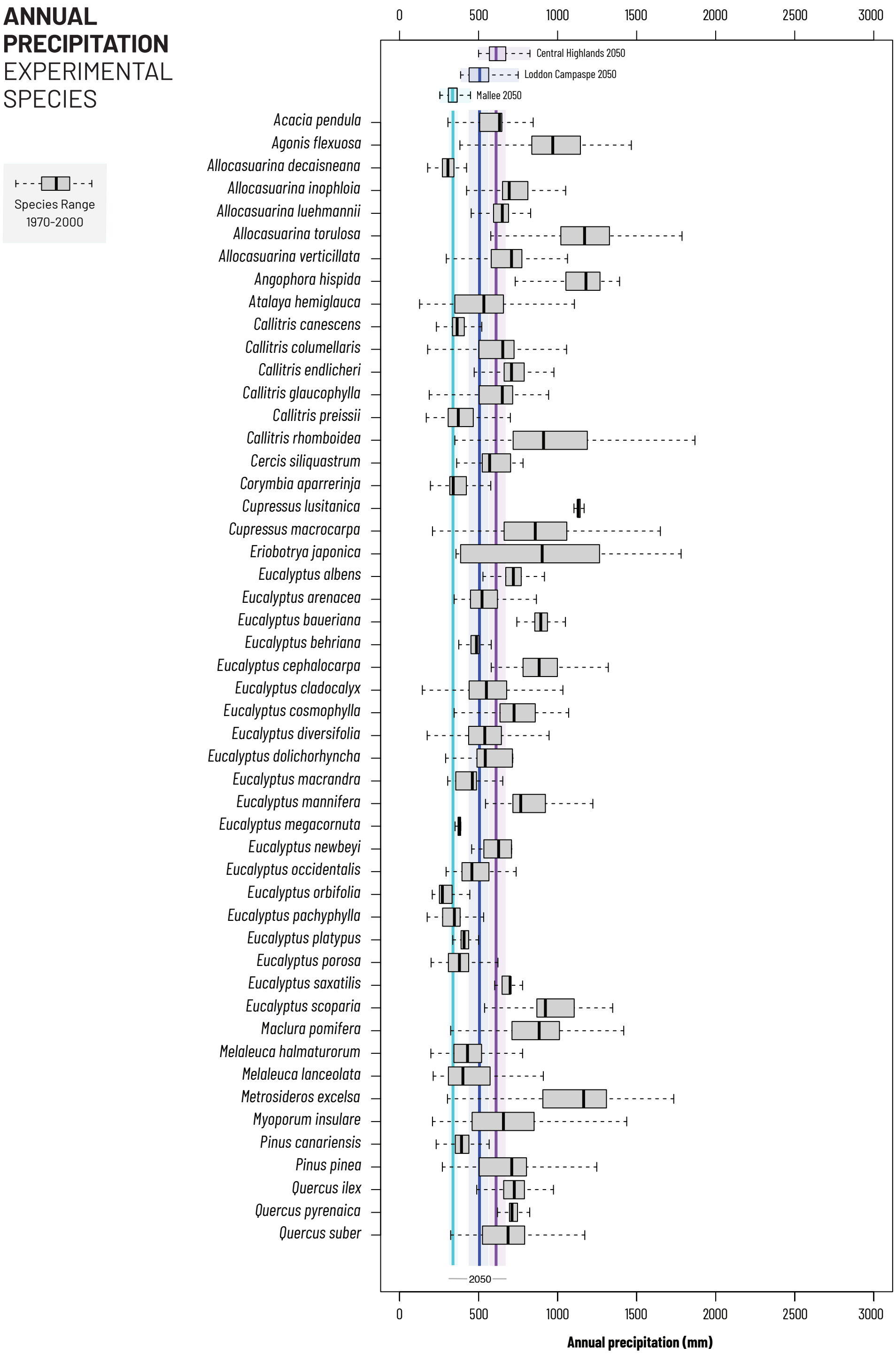
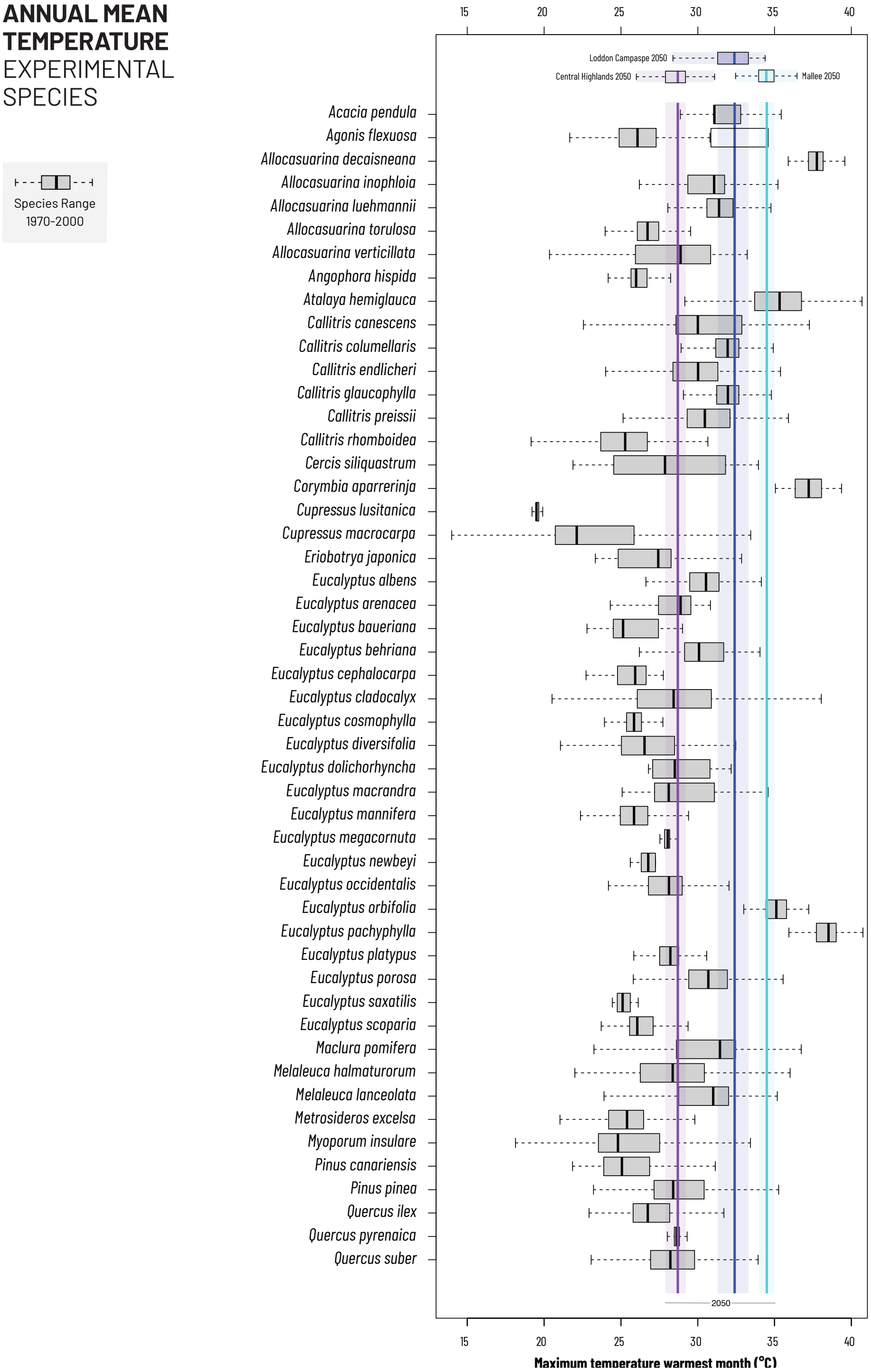


FIGURE 7 — Boxplots illustrating species ranges for mean annual temperature (°C) for 50 tree species on the experimental list, relative to projected climatic range in each region (Central Highlands purple, Loddon-Campaspe blue, Mallee aqua).

ANNUAL MEAN TEMPERATURE
EXPERIMENTAL SPECIES



Quercus robur English Oak

Planting for the future

Select species likely to be resilient to future climate in each region, from the lists of species identified as having low vulnerability to projected climate (Table 2, Table 3, Table 4). Refer to the Species Selection Matrix (supplied) to ensure appropriate selection of species for specific sites, by considering their environmental tolerances.

Nurse trees through drought years. Unpredictable growing seasons will be a considerable management concern. Therefore, long term planning of water storage, irrigation and appropriate fertilising will be key.

Incorporate water sensitive urban design.
Explore opportunities for stormwater harvesting and storage to irrigate street trees; use permeable paving; prioritise nature strips over concrete to maximise water infiltration and water storage deep in the soil.

Use best horticultural practice.
Several environmental stressors such as drought, severe temperatures, and insect and pest attack can lead to reduced photosynthesis and growth. This will become more common as climate change intensifies. To give trees best chance of survival and providing best canopy shade, source high quality tree stock that meets the Australian Standard AS 2303:2018

Tree stock for landscape https://www.westernsydney.edu.au/hie/topics/tree_stock_standard

Use mulch, appropriate fertiliser and irrigation as required and ensure soil health is retained and improved.

Generate community support by demonstrating significant savings in the form of carbon storage, reduced power use for cooling, removal of pollutants and property values. McPherson et al. (2018) used iTree to show that for every dollar spent on trees in California, $5.82 was returned in these annual services. Estimate your planting costs using the free Tree Costing Tool that runs in Excel:

https://www.horticulture.com.au/growers/help-your-business-grow/research-reports-publications-fact-sheets-and-more/tree-costing-tool-and-instruction-manual/

Create opportunities for positive social and community education by promoting benefits of plantings – explaining tree uses and benefits.

Employ real-time climatic data to help take preventative action. Methods might include using sensors and dataloggers to understand environmental stressors; using BoM weather predictions to make near-term decisions about watering, pruning etc.

Establish trials and monitoring of species performance.
This will need to be done to evaluate how new species will perform in cultivation. Implement data collection of key variables with the establishment of new plantings; use drone and remote imaging to understand species performance under different climatic conditions.

Create open data tree inventories.
Councils should strongly consider collecting tree inventory data and publishing the data as open source data. Open source data facilitates data sharing, speeds up solutions and enables community engagement. An excellent guide to publishing council open source data can be found at *Open Council Data: Tools and guidance for local government* (https://opencouncildata.org). Some Victorian councils have published open source datasets, providing an opportunity to learn from their experience and knowledge. Examples of current tree inventories for Victoria can be viewed at websites such as OpenTrees (http://www.opentrees.org) and the *City of Melbourne Urban Forest Visual* (http://melbourneurbanforestvisual.com.au). These data can be downloaded as a comma separated files (.csv) and used as a template for council tree data collection.

Experiment with pruning to create lateral growth to increase the area shaded. Large, lateral branches have lots of strong, compression wood and don't have deep forks where moisture and disease can enter the tree.

Design Multistory canopies to create deep shade.
During drought, leaves close their stomata and transpiration declines. This means that there is shade, but the cooling effect is lower because trees are not humidifying the local microclimate. Drought-stressed trees also drop leaves, leading to sparser canopy cover. Drought-adapted trees typically have small, narrow and/ or hanging leaves – meaning their canopy does not create deep shade. In situations where large-leaved, drought tolerant trees are limited, develop planting designs that create deep shade through vertical layering of the canopy. Large and small trees can be used to create a forest canopy. This gives the feeling of protection and when trees are large will inspire wonder.

Increase diversity of plantings by broadening species selection to reduce vulnerability of the urban forest to future climate, extreme events, pests and diseases. Achieve this by:

- Accepting “messy” species and employing street cleaners or supporting community volunteers to keep urban areas under trees clean and welcoming. This will provide social cohesion benefits as these people can becoming advocates of the planting approach.
- Tolerating slow-growing species. Plants have different drought tolerances depending on the environment they have evolved in. While drought-tolerant species can grow using low amounts of water, they tend to be slow growing, have smaller leaves and thinner canopies, and because they are water-efficient they do not provide lush, humidifying canopies. Creating plantings that combine fast- and slow-growing species may be a way to allow slow growing trees to establish and develop into shade trees.
- Prioritising mixed, complementary plantings that could highlight different seasons, plant forms etc.
- Embracing within-species genetic diversity, rather than uniform plants that are genetic clones.
- Educating the community about the value of planting diversity for future climate resilience to shift mindsets prevalent in planting design and landscape architecture that value uniform, monoculture street tree.

Embrace green infrastructure and ecosystem services into the future by recognising and nurturing the multiple values of an urban forest.
Trees create urban oases of cool green. In particular, irrigated greenery provides spaces for social gathering, areas for eating, meeting, resting etc. These opportunities have social cohesion benefits. Because hydrated trees reduce local temperatures by providing cooling shade, they provide an ecosystem service and can be considered ‘green infrastructure’. Further, by providing flood management, water treatment and improved urban climates, trees will be an essential tool in establishing the infrastructure of water sensitive cities. Understanding the functional ecology of tree species will be valuable in designing these systems. More information on the concept and design of water sensitive cities can be found at https://watersensitivecities.org.au

Caveats

All recommended species are those identified as being least vulnerable to future climate in each region. Species rated as having higher vulnerability could still be grown if given appropriate care regimes, particularly irrigation. Further, our recommendations are based on regional averages. As can be seen in Figure 3 there is wide variation in projected climate across each region. Consideration should be given to regional climate variation as change will be greater in some local areas than other. More amenable microclimates at a local scale will also support more vulnerable species.

Species evaluations based on bioclimatic models have limitations, because a tree species country of origin and current distribution does not always indicate its physiological plasticity and the range of habitats to which it can adapt (McPherson et al., 2018). This limitation is illustrated in Roloff et al (2009) whose analysis revealed that although honey locust' (*Gleditsia triacanthos*) native habitat is moist bottomlands, it has proven to tolerate very hot and dry situations.

In a similar vein, Kendal and Bauman (2016) found a higher proportion of Australian species compared to exotic species were identified as vulnerable to climate change and therefore not appropriate for planting, because a high proportion of Australian species were identified as having a narrow climate envelope, whereas exotic species had a wide climate envelope. However, this finding may likely to be purely an artefact of a wider global distribution of exotic, horticultural species that have had the long timeframes and broad public interest to be grown in more locations and climates across the world. In contrast, many regional endemics may not have had widespread horticultural popularity and may in reality have much wider tolerances than the plots capture for their native range.

Using bioclimatic models to predict tree survival in urban environments is also complicated by a mismatch between water available to trees urban environments and annual precipitation and the evapotranspiration ratio, due to reduced ground water through impermeable surfaces preventing water infiltration and also due to enhanced ground water from irrigation (Huber et al., 2015).

Therefore caution should be applied when evaluating species climatic tolerances from their current climatic ranges. Take an experimental approach and cautiously trial species with higher climate vulnerability in new climates outside their current range

Using the Species Selection Matrix

The overarching goal of species selection for urban cooling must be primarily be to optimise tree survival in urban streets and parks and secondarily to meet requirements for urban amenity. To aid Shires in species selection we provide a Species Selection Matrix that scores species (rows) by their attributes (columns).

Importantly, this matrix ranks species that are most likely to survive and persist in the three regions in 2050 under the projected extreme climate scenario (RCP 8.5).

When using the Species Selection Matrix to identify species for planting in each Shire, follow the steps listed below:

1. Identify species most tolerant of projected climate (2050) in the region of interest by sorting the Species Selection Matrix on "climate tolerance 2050," from highest to lowest for that region. Species ranked "0" have a very low tolerance/very high vulnerability to projected climate; species ranked "10" have a very high tolerance/very low vulnerability. Alternatively, filter the list by de-selecting all species with a "climate tolerance" of zero. Species tolerance rankings can be compared to scores for drought tolerance, based on literature and data survey.
2. Identify species suitable for a specific planting site by sorting and filtering the Species Selection Matrix on environmental tolerances, including Light, Cold (minimum temperature), Wind, Waterlogging, Compaction and soil pH.
3. Identify species with suitable amenity, place of origin using attributes such as Height, Width, Seasonality, Native/exotic.

Ideally, species selection should be supported by long-term monitoring and adaptive management. This is particularly the case for novel species plantings, where the limits of horticultural utility and resilience are largely unknown.

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Appendix I

Top 30 species planted across participating Shires

Preferred species and planting likelihood across participating Shires (preferred species for Hepburn Shire are unknown). Staff in charge of tree selection from each Shire were asked to rank the likelihood of planting each species on their tree list the next two years (Planting likelihood rankings were: 0=no chance of planting, 1= low chance and 3=high chance of planting). Number of Councils with each species on their planting list are also counted. From these rankings we identified 30 species most likely to be planted in 2020-21 (below).

Species name	**Common name**	Ararat Rural City	Buloke Shire	Central Goldfields Shire	Gannawarra Shire	Pyrenees Shire	Mount Alexander Shire	Macedon Ranges Shire	Planting likelihood	Count of Councils
Acacia melanoxylon	Blackwood						2	2	4	2
Acer rubrum	Autumn Blaze Maple					2		2	4	2
Angophora costata	Rose Apple					2	2		4	2
Banksia marginata	Silver Banksi					2		2	4	2
Brachychiton populneus	Kurrajong			2	1		2	2	7	4
Callistemon citrinus	Lemon Bottlebrush			1			2	2	5	3
Callistemon viminalis	Weeping Bottlebrush		2	1	2	2			7	4
Celtis australis	European Nettle Tree						2	2	4	2
Corymbia ficifolia	Red Flowering Gum	0	3		2	2		2	9	4
Eucalyptus leucoxylon	Yellow Gum			1	1	2	2	2	8	5
Eucalyptus melliodora	Yellow Box				2		1	2	5	3
Fraxinus angustifolia subsp. oxycarpa	Claret Ash		0		1	2	2	2	7	4
Fraxinus excelsior	Golden Ash					2	2		4	2
Fraxinus pennsylvanica	Green Ash				2			2	4	2
Geijera parviflora	Wilga						2	2	4	2
Gleditsia triacanthos	Honey Locust	3						2	5	2
Hakea laurina	Pincushion Hakea	2				2			4	2
Jacaranda mimosifolia	Jacaranda		2	0	2				4	2
Koelreuteria paniculata	Golden Rain Tree						2	2	4	2
Lagerstroemia indica	Crepe Myrtle	2	3		2	3	2		12	5
Malus ioensis	Prairie Crabapple						2	2	4	2
Melaleuca linariifolia	Flaxleaf Paperbark		2	2					4	2
Melia azedarach	White Cedar		0	0			2	2	4	2
Pistacia chinensis	Chinese Pisctachio						2	2	4	2
Prunus cerasifera	Myobalan Plum	3		1			1		5	3
Pyrus calleryana	Callery Pear	3	3	3	1		3	2	15	6
Quercus coccinea	Scarlet Oak				2	3			5	2
Quercus palustris	Pin Oak			2		3	2	2	9	4
Ulmus parvifolia	Chinese Elm			3			2	2	7	3
Zelkova serrata	Japanese Elm	1		1		2			4	3

Appendix II

Sources of data on species tolerances & attributes, presented in Species Selection Matrix

Data source type	Title
Data source type	**Title**
Database	*Arid zone Trees*. 2000-2020. www.aridzonetrees.com
	Atlas of Living Australia. 2020. https://www.ala.org.au
	Burnley Plant Guide. 2012. University of Melbourne. https://www.bpg.unimelb.edu.au
	CiTree database. 2015. TU Dresden. http://citree.ddns.net/index.php
	Growing Native Plants. 2012 Australian National Botanic Gardens and Centre for Australian National Biodiversity Research, Canberra. https://www.anbg.gov.au/gnp/index.html
	Plant selector+. 2020. Botanic Gardens SA. http://plantselector.botanicgardens.sa.gov.au/home.aspx
	PLANTS Database. 2020. United States Department of Agriculture. http://plants.usda.gov
	Plants For A Future. 2021. http://pfaf.org
	SelecTree: A Tree Selection Guide. 1995-2021. https://selectree.calpoly.edu
	TRY – Plant Trait Database. 2020. http://www.try-db.org
	Woody Plants Database. 2018. http://woodyplants.cals.cornell.edu/home
Books & papers	Brune. 2016 Urban trees under climate change. Potential impacts of dry spells and heat waves in three German regions in the 2050s. Report 24. Climate Service Center Germany, Hamburg
	Peate, Macdonald & Talbot. 2006. Grow what Where. Bloomings Books, Melbourne
	Bassuk et al. 2009. Recommended Urban Trees: site assessment and tree selection for stress tolerance
	Forrest. 2006. Landscape trees and shrubs; selection, use and management. Athenaeum Press, Gateshead
	McPherson et al 2018. Shade factors for 149 taxa of in-leaf urban trees in the USA. Urban Forestry & Urban Greening. 31:204-211
	Dubbo Regional Council. Dubbo Street Tree Masterplan
	Flemings Nurseries Pty. Ltd. 2012. Flemings Urban Tree Guide. Flemings Nurseries, Monbulk

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