Synthesis: Climate Change Impacts and Vegetation Management in the Port Phillip and Westernport Region

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THE UNIVERSITY OF MELBOURNE

Technical Report 25.10

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Acknowledgment of Country

The University of Melbourne acknowledges the Traditional Owners of the unceded land on which we work, learn and live: the Wurundjeri Woi Wurrung and Bunurong peoples (Burnley, Parkville, Southbank and Werribee campuses), the Yorta Yorta Nation (Dookie and Shepparton campuses), and the Dja Dja Wurrung people (Creswick campus).

The University also acknowledges and is grateful to the Traditional Owners, Elders and Knowledge Holders of all Indigenous nations and clans who have been instrumental in our reconciliation journey.

We recognise the unique place held by Aboriginal and Torres Strait Islander peoples as the original owners and custodians of the lands and waterways across the Australian continent, with histories of continuous connection dating back more than 60,000 years. We also acknowledge their enduring cultural practices of caring for Country.

We pay respect to Elders past and present, and acknowledge the importance of Indigenous knowledge in the Academy. As a community of researchers, teachers, professional staff and students we are privileged to work and learn every day with Indigenous colleagues and partners.

Declaration

We have not used any generative AI tools or technologies in the preparation of this Melbourne Waterway Research-Practice Partnership Technical Report.

Contents

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1. Overview

Melbourne Water manages ~24,000 km of waterways across the 12,783 km^2 greater Melbourne region. In 2022, it also integrated the roles, responsibilities and functions of the Port Philip and Westernport (PPWP) Catchment Management Authority. Vegetation is a value in its own right, as well as supporting the conditions for other key environmental values such as birds, frogs, macroinvertebrates and social values such as amenity, recreation and creating cooler, greener and more liveable environments (Melbourne Water 2018). Vegetation management and revegetation are major activities that Melbourne Water undertakes to maintain and/or improve riparian and waterway habitat and condition and therefore involves significant investment by Melbourne Water and its stakeholders.

The Healthy Waterways Strategy 2018 identified climate change as a major threat to Melbourne Water's key environmental values. With respect to vegetation, a crucial performance objective in the Healthy Waterways Strategy is that: "*Climate change resilient revegetation management practices are understood and implemented by selecting plant species, provenances and vegetation communities that are suited to projected future climatic conditions*" (Melbourne Water 2018). This is a complex objective in a high uncertainty setting, as climate breakdown is driving rapid adverse and increased variability in climate conditions. An iterative, learning-oriented and adaptive approach to climate impacts and vegetation management will be necessary.

This report consolidates and synthesises relevant background and context to:

a) Outline legislation, obligations, policies and strategies that inform Melbourne Water's vegetation management responsibilities (Chapter 2, section 2.1)
b) Catalogue the diverse range of Melbourne Water's vegetation management activities under broad themes of planning, systems and governance, establishment, maintenance, research and evidence, monitoring and evaluation, and capacity building and knowledge sharing (Chapter 2, section 2.2)
c) Unpack major weather and climate phenomena that are important to understand for managing vegetation in a climate-impacted future (Chapter 3)
d) Outline potential climate change impacts on vegetation (Chapter 4)
e) Outline Intervention options for supporting vegetation resilience under climate change from the published literature (Chapter 5)
f) Take stock of intervention options for supporting vegetation resilience that Melbourne Water uses or has attempted (Chapter 5, section 5.1)
g) Consider what adaptation strategies and associated tactics could help with respect to specific climate stressors and hazards (Chapter 6)
h) Recommend intervention options in the near-term (Chapter 7, section 7.1)
i) Recommend intervention options that could be added to the vegetation climate resilience toolbox if knowledge gaps and dependencies or requirements for application were addressed (Chapter 7, section 7.2)
j) Identify targeted research that would enable promising additional intervention options (Chapter 7)

2. Responsibilities and activities under a changing climate

2.1 Obligations, policies, and strategies

In conducting Melbourne Water's vegetation management responsibilities, Melbourne Water must have regard for relevant Victorian legislation, obligations, policies, and strategies such as the:

- *Flora and Fauna Guarantee Act 1988*
- *Water Act 1989*
- Statement of Obligations (General) 2015 (under the *Water Industry Act 1994*)
- *Climate Change Act 2017*
- Protecting Victoria's Environment – Biodiversity 2037 (DELWP 2017)
- Healthy Waterways Strategy 2018 (Melbourne Water 2018)

These *Acts*, obligations, formal policies, and strategies explicitly recognise climate change risks and the obligations of public authorities like Melbourne Water to improve understanding of risks and impacts, develop capacity, plan and implement appropriate actions at short, medium, and long term timeframes. Some, such as Victoria's biodiversity strategy, Biodiversity 2037, articulate the broader context and goals that native vegetation management contributes toward. Examples of some of the obligations and responsibilities, guidance and preferred approaches under the listed *Acts*, obligations, policies, and strategies plans are given in Table 1.

Table 1 A selection of Victorian Acts, obligations, policies and strategies that are relevant to Melbourne Water's vegetation management responsibilities, particularly in view of climate change risks and impacts.

***Act*, Obligation, Policy, Strategy or Plan**	**Comment**
Flora and Fauna Guarantee Act 1988	**S-**4B Contains an obligation or duty on public authorities to consider potential impacts on biodiversity when exercising their functions. These impacts include short and long-term impacts, detrimental and beneficial impacts, direct and indirect impacts, cumulative impacts, and potentially threatening processes.
Statement of Obligations (General) 2015 (under the *Water Industry Act 1994*)	Guiding Principles state that in performing its functions and providing its services, "The Corporation should respond to the challenges of climate change with due consideration of mitigation and future adaptation measures, having regard to economic and social impacts.[1]" [1]refer to *Climate Change Act 2010* (Vic), preamble
Climate Change Act 2017	Decision makers must have regard to climate change and take climate change into account appropriately in policy making and implementation. One of the *Act*'s objectives is "to manage the State's natural resources, ecosystems and biodiversity to promote their resilience". The *Act* requires Adaptation Action Plans (AAPs) to be developed for 7 systems: water, the natural environment, the built environment, primary production, health and human services, transport, and education and training. Catchment Management Authorities are responsible for the development, review and implementation of Regional Catchment Strategies to "*address activities to promote sustainable use, conservation and rehabilitation of land and water resources, including*

	waterway restoration, reforestation and sustainable agriculture programs which benefit climate change adaptation." (DELWP 2018) The first AAP covers 2022-2027 and continues on a 5-year cycle until 2046.
Biodiversity 2037 (DELWP 2017)	Victoria's Biodiversity Strategy has the dual stated goal that: 1. Victorians value nature and understand that their personal wellbeing and the economic wellbeing of the state are dependent on the health of the natural environment 2. Victoria's natural environment is healthy with functioning plant and animal populations, improved habitats and resilient ecosystems even under climate change It Includes statewide targets that public authorities are expected to contribute toward. With respect to vegetation management, the targets are that by 2037 (DELWP 2017, p20): a) No vulnerable or near-threatened species will have become endangered b) All critically endangered and endangered species will have at least one option available for being conserved *ex situ* or re-established in the wild (where feasible under climate change) should they need it c) There will be a net gain in the overall extent and condition of habitats across terrestrial, waterway and marine environments d) There will be 4 million hectares of control of pest herbivores in priority locations e) There will be 1.5 million hectares of weed control in priority locations f) There will be 200,000 hectares of revegetation in priority areas for connectivity between habitats Biodiversity 2037 recognises the "game-changing influence of climate change" and the need for multiple approaches. It also emphasises that biodiversity investment "should be more strongly focused on prevention and early intervention, rather than crisis response" and also on "securing the greatest overall benefit".
Healthy Waterways Strategy 2018 (Melbourne Water 2018)	**S-**190 of the *Water Act 1989* requires the preparation of a Regional Waterways Strategy; Melbourne Water's current iteration of this is called the Healthy Waterways Strategy 2018-2018 Some Healthy Waterways Strategy regional performance objectives (RPOs) that relate specifically to vegetation are as follows: **RPO-10** An adaptive pathways approach is adopted to understand and manage the risks of climate change on waterways **RPO-22** Cooler, greener and more liveable urban environments are created through revegetation and as part of managing excess stormwater **RPO-28** Seasonal Herbaceous Wetland vegetation communities are identified and a management program is in place to protect them on public and private land (they are an ecological community listed as critically endangered under the federal Environment Protection and Biodiversity Conservation Act *EPBC Act*)

	RPO-29 Programs, standards, tools and guidelines are in place to protect wetland vegetation communities from urban and rural threats, including adequate planning controls **RPO-30** Climate change-resilient revegetation management practices are understood and implemented by selecting plant species, provenances and vegetation communities that are suited to projected future climatic conditions
Healthy Waterways Strategy Mid-term Review Science Inquiry (Melbourne Water 2024)	HWS Mid-term Review Science Inquiry highlighted the following recommendations to improve program delivery: **S-5.2** Prioritise the implementation of long-term intervention monitoring programs for key works such as vegetation establishment and maintenance, fishway performance and stormwater interventions to validate and support programs **S-6.1** Prioritise locations for deer management using modelling and field data and consider developing targets and metrics for annual reporting **S-6.2** Identify sites that could be used for direct seeding to build capacity in applying this technique that has the potential to increase the efficiency of revegetation efforts at suitable sites **S-6.3** Improve the success of revegetation outcomes by ensuring adequate mid-storey vegetation and native groundcover is established and maintained in revegetated areas **S-6.4** Update Melbourne Water's revegetation guidelines to include climate change mitigation actions, new information on chemical use, bird habitat design and amenity outcomes such as shading

There are a number of other statutory requirements that water authorities must comply with (DELWP 2019), including:

- *Catchment and Land Protection Act 1994*
- *Financial Management Act 1994*
- *Public Administration Act 2004*
- *Emergency Management Act 2013*

Based on the above, Melbourne Water have a number of obligations, as specified in various legislation, obligations, policies, and strategies, to plan for and manage the risks associated with a changing climate. These risks are outlined in Chapter 3: What might we expect climate-wise?

2.2 What does Melbourne Water already do in terms of vegetation management?

Melbourne Water is engaged in a diverse range of vegetation management activities under broad themes such as planning, systems and governance, establishment, maintenance, monitoring and evaluation, research, and capacity building and knowledge sharing. Figure 1 shows how these themes inter-relate. Research and evidence both informs and is informed by planning, systems and governance needs. Both themes support vegetation establishment and maintenance practices and these in turn are supported by purposeful monitoring, evaluation and review for continuous improvement. Collective lessons from each of the themes assists in capacity building and underpins evidence-based, practically-informed knowledge sharing. As the overlay of circles indicates, there are frequent overlaps amongst activities across themes.

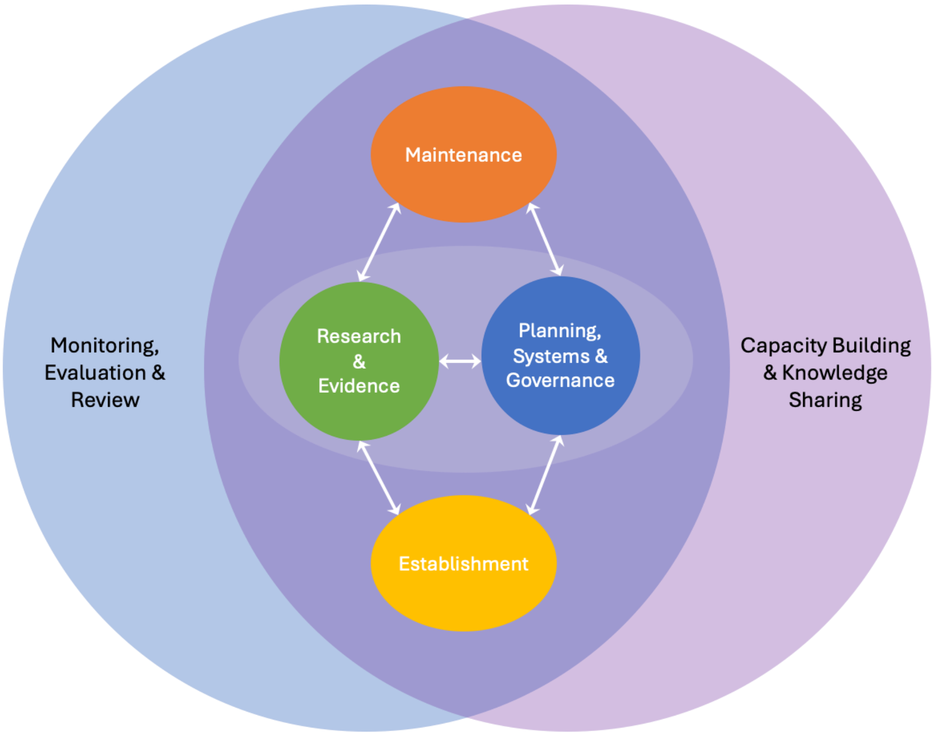


Figure 1 Conceptual representation of themes under which we might organise the diverse range of vegetation management activities Melbourne Water is engaged in. The arrows and overlaps indicate how the various themes inter-relate.

To give a sense of the range of vegetation management-related activities, Table 2 lists and briefly describes activities within each theme.

Table 2 List of vegetation management-related activities undertaken by Melbourne Water organised under the themes in Figure 1.

Planning, Systems & Governance	
PSG-1	Strategic land purchases to improve vegetation connectivity (e.g. Yering floodplain). Also retaining (i.e. not selling) strategic properties (e.g. Christmas Hills properties) to ensure ongoing vegetation connectivity in critical areas
PSG-2	Identification and design of revegetation projects to improve the extent and/or condition of native vegetation, and/or native vegetation connectivity across riparian and landscape corridors
PSG-3	Prioritising candidate revegetation projects to secure the greatest benefit (however defined)
PSG-4	Documenting vegetation projects including species and provenance to allow improved adaptation to climate change
PSG-5	Producing and updating Melbourne Water Plant Selection and Provenance Standard, Ephemeral and Terrestrial Plant Supply Standard, Ephemeral and Terrestrial Plant Installation Standard, Guidelines for Direct Seeding etc
PSG-6	Incorporating Traditional Owner values, knowledge, cultural perspectives and priorities into vegetation management plans and practices
PSG-7	Ongoing and increased promotion and support for cultural burning practices to vegetation management outcomes and biodiversity, as well as protecting vegetation from damaging extreme fire events

PSG-8	Incorporating stakeholder knowledge and priorities into vegetation management plans and practices
PSG-9	Policy improvements in relation to Melbourne Water projects impacting native vegetation on Melbourne Water-owned land. In the event that native vegetation is cleared/damaged in the course of project implementation, ensure vegetation improvement works on Melbourne Water land (preferably project site) ensures long-term no net loss. For instance, clearing of 1000 m^2 for a project, might be compensated for by revegetating 4000 m^2 on site (if opportunities exist, or equivalent land management activities)
PSG-10	Refining MapLab implementation for sharing predicted current and future climate-impacted habitat suitability maps for 31 commonly used revegetation species (Nitschke 2022) along with assumptions, uncertainties and guidance (see RE-6)
Research & Evidence	
RE-1	Exploring the use of Nearmap AI data packs for quantifying (treed) vegetation extent and change over time (2018, 2022)
RE-2	Exploring the use of Sentinel-2 remote sensing data for vegetation anomaly detection (associated with disturbances) (Hislop et al. 2025)
RE-3	Exploring the use of Sentinel-2 remote sensing data and field-surveyed Vegetation Visions data for modelling vegetation condition (Hislop et al. 2025)
RE-4	Assessing disturbance and recovery of vegetation using Landsat remote sensing data and multiple lines of evidence (Tran & Soto-Berelov 2024)
RE-5	Exploring the use of LiDAR-derived metrics for assessing vegetation structural change (comparing revegetated areas to remnant vegetation areas) (Fedrigo et al. 2022)
RE-6	Assessing the vulnerability of 31 key revegetation species to changing climate based on statistical and mechanistic species distribution modelling (Nitschke 2022)
RE-7	Designing climate-adjusted seed sourcing/provenancing for 10 commonly used revegetation species using a climate analogues approach (Greening Australia 2021)
RE-8	Desktop and expert-based advice and guidelines for sourcing seed and germplasm for revegetation (Ahrens & Weeks 2024)
RE-9	Assisting in the establishment of climate-adjusted provenancing trials in Dandenong, Knox and Maroondah City Councils (see Box 4)
RE-10	Synthesis of what to expect in a climate-impacted future, implications for vegetation management, interventions for supporting vegetation resilience, what's already in use, and what could be added if knowledge gaps, dependencies and requirements were addressed (present report)
RE-11	Traits-based understanding of plant climate resilience strategies for supporting species selection and vegetation resilience (Chu et al. In Prep)
RE-12	Assessing the impacts of deer on vegetation communities across the Melbourne Water region (Bennett & Greet 2024; Fedrigo et al. 2024; Greet et al. 2025)
RE-13	Understanding deer control effectiveness in peri-urban landscapes (Bennett et al. 2024; Bennett et al. 2025)
RE-14	Cockatoo Swamp vegetation condition monitoring to assess the vegetation response to hydrology works by Melbourne Water (Greet & Fischer 2023)

RE-15	Assessing the response of vegetation to flooding at culturally and socially important billabongs along the lower Birrarung (Yarra River) (Greet et al. 2023)
RE-16	Traditional Owner-led restoration of urban billabongs: investigating the billabong vegetation, faunal and water quality responses to cultural burns and wetting and drying through Traditional Owner-led monitoring and assessment (ARC Linkage Project LP220200160)
RE-17	Investigating instream vegetation status, distribution, drivers, temporal variability, and revegetation success to improve understanding, management and revegetation effectiveness (McKendrick et al. 2024; McKendrick et al. 2025b; McKendrick et al. 2025a)
Establishment	
E-1	Choosing a planting palette of species consistent with the Ecological Vegetation Classes (EVCs) of the relevant Victorian Bioregion - EVCs are a unit for classifying vegetation types in Victoria and consist of a collection of floristic communities that occur across a biogeographic range. Note the EVC's may change as the climate changes. Adhering to the Melbourne Water Plant Selection and Provenance Standard guidelines.
E-2	Factor in additional watering in dry years with low expected survival
E-3	Adhering to Melbourne Water's Ephemeral and Terrestrial Plant Supply Standard and Ephemeral and Terrestrial Plant Installation Standard
E-4	Consider the use of direct seeding where appropriate conditions are available (Greet et al. 2020)
E-5	Limited use of long-stem planting method (Dreesen & Fenchel 2014) in 7 kms within a Plenty-Chandler reach in 2011/2012. No formal monitoring or report of long-stem planting outcomes. [MW Ref: QO3131ScopeAgreement2012]
Maintenance	
M-1	Weed and pest animal control for the first three years of establishment
M-2	Assessing that 80% or more of the planted plants survive in the first two years post establishment, and adding additional plants if survival is lower than this
M-3	Removal of invasive weeds in remnant native vegetation
Monitoring, Evaluation & Review	
MER-1	Mapping and quantifying areas of revegetation (across all contributing vegetation establishment programs) for regular reporting against establishment targets [Target Mapper]
MER-2	Mapping and quantifying areas of vegetation management (e.g. fencing, weeding) across all contributing programs for regular reporting against condition targets [Target Mapper]
MER-3	Vegetation Visions monitoring: field-based rapid plot assessments of riparian vegetation condition across the PPWP region at 5-yearly intervals - 506 sites in 2021 (Dell 2020)
MER-4	Detailed riparian vegetation condition assessment for "accurate monitoring of vegetation changes over the long-term" - 80 sites in 2021 (Dell 2020)
MER-5	Index of Stream Condition (2) monitoring (Kaye 2021)

MER-6	Review of the Melbourne Water Riparian Vegetation Works Monitoring Method (Jellinek et al. 2021)
MER-7	Restoration Outcomes Monitoring Protocol (ROMP): long-term monitoring and evaluation program to better understand the factors that influence intervention effectiveness and restoration outcomes at capital works sites. Intervention sites are compared to appropriate remnant sites to track their structural and functional development over time (Jellinek et al. 2022a; Foley-Congdon et al. 2024)
MER-8	HWS Mid-term review and the Science Inquiry vegetation management discussion paper (Jellinek et al. 2022b)
Capacity Building & Knowledge Sharing	
CBKS-1	Working with Traditional Owners (e.g. Wurundjeri Woi Wurrung Cultural Heritage Aboriginal Corporation) to adapt and customise ROMP for TO-led revegetation and billabong restoration monitoring
CBKS-2	Assessing ecological outcomes of watering Birrarung billabongs in partnership with the Narrap team using customised field manuals designed and tested by the MWRPP and Narrap teams (Greet & Rangers. 2023; Greet & Rangers. 2025)
CBKS-3	Vegetation and ecology-focussed roles within Melbourne Water teams
CBKS-4	Shared roles between Melbourne Water and the University of Melbourne (Joint research fellows in the MWRPP)
CBKS-5	MWRPP Knowledge Broker-led activities under the Knowledge Exchange and Action Framework (e.g. riparian and vegetation management training provided by MWRPP, lunchtime seminars, annual research forum, Research Hub resources)
CBKS-6	Climate Resilient Vegetation Operational Advisory group within Melbourne Water and similar groups external to Melbourne Water

2.3 What do we mean by climate-resilient vegetation?

Melbourne Water's vision for climate resilient vegetation is to "maintain and extend thriving vegetation communities (and their ecosystem functions) across Melbourne Water catchment areas, through adaptive management to enhance environmental, social/cultural, and economic values and increase the resilience of vegetation to climate change". More specifically, 'resilience' denotes the ability of vegetation communities to "adapt, resist, recover, regenerate and/or transform in response to climate change to maintain essential ecological functions and self-sufficiency" (Alluvium 2022).

To understand *what* vegetation needs to be resilient to, we review the different climate impacts of relevance and their expected future trajectories. We give an overview of potential climate change impacts on vegetation. We then consider broad strategies and options from the literature that have been proposed to support vegetation resilience under climate change. We unpack how these can be translated into interventions for specific climate impact phenomenon. Finally, we consider challenges that must be addressed to enlarge Melbourne Water's capacity to use these options and interventions.

3. What might we expect climate-wise?

Concentrations of all major long-lived greenhouse gases in the atmosphere such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) continue to increase. Global annual mean CO_2 concentrations reached 419.2 parts per million (ppm) in 2023 and the CO_2 equivalent ($CO_{2\text{-}e}$) of all greenhouse gases reached 524 ppm. These are the highest levels on Earth in at least 2 million years (CSIRO & BOM 2024).

As Australia's State of the Climate 2024 report noted, "Observations, reconstructions of past climate and climate modelling continue to provide a consistent picture of ongoing, long-term climate change interacting with underlying natural variability" (CSIRO & BOM 2024). Changes in weather and climate phenomena such as heatwaves, extreme rainfall, dangerous fire weather, droughts, floods, sea-level rise, and compound events are occurring at an increasing pace and impacting upon human and ecosystem health.

In this section, we draw on authoritative sources to give an overview of the major weather and climate phenomena that are important to understand with respect to vegetation management and summarise what we ought to expect in directions and trends climate-wise. The intent is to highlight the crucial suite of climate hazards, how they might combine or interact to produce novel or compound events and prompt thinking on what increasing risks of these phenomena mean for Melbourne Water's range of vegetation management responsibilities and activities. It is beyond the scope of this report to describe the mechanisms of the various climate phenomena in detail but this information is available from the cited references.

3.1 Temperature

Victoria's climate has warmed by about 1.2°C since 1910 (Figure 2, top) and by around 1.4 °C since the pre-industrial era (DEECA 2024). Every decade since 1950 has been warmer than preceding decades and since 2000 there has been a steady run of warm to very warm anomalies (Figure 2, bottom).

Seneviratne et al. (2021) noted that the frequency of hot temperature extreme events will very likely increase nonlinearly with increasing global warming with larger percentage increases for rarer events. This seems to be consistent with observations. In Melbourne, the number of hot days (defined as the 99^{th} percentile maximum daily temperature which corresponds to 37°C) has increased from 3.6 in the period 1986-2005 to 5.1 in the period 2003-2022 (DEECA 2024). The number of very hot days (defined as the 99.9^{th} percentile maximum daily temperature, corresponding to 41.2°C) has more than doubled from 4 in the period 1986-2005 to 10 in the period 2003-2022 (DEECA 2024).

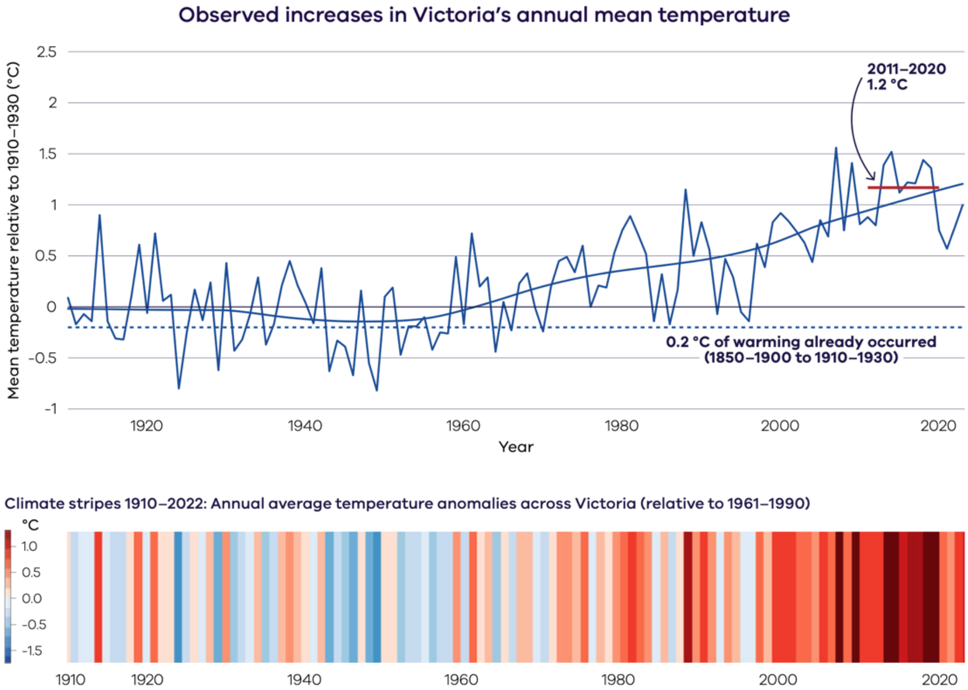
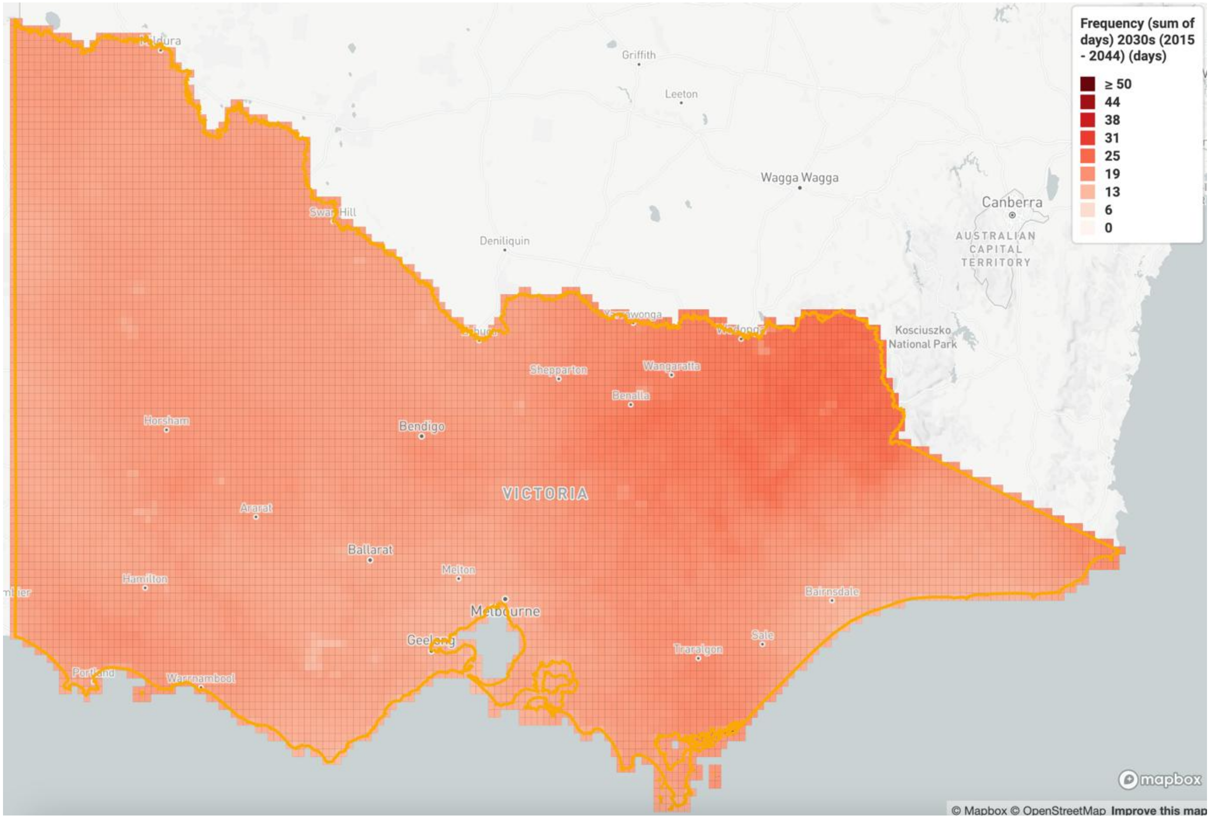


Figure 2 (Top) Observed annual mean temperature over Victoria from 1910 to 2023 relative to the 1910-1930 baseline period. The smooth blue line shows the long-term trend and the red horizontal line shows the warming for the most recent decade of 2011-2020. (Bottom) 'Climate stripes' of temperature anomalies for individual years relative to the period of 1961-1990. Blue shades indicate cooler temperatures and red shades indicate warmer temperatures. The more intense the colour, the stronger the anomaly in that year. Source: DEECA (2024).

Historically, the heatwave season in Victoria is November to March. Since the 1950s, the frequency, intensity, and duration of heatwaves in Victoria has increased and the heatwave season now starts earlier and lasts longer (DEECA 2024). Heatwaves are prolonged periods of excessive heat but there is no universally-accepted standard on either the minimum number of days a heatwave must last, or the threshold used to determine excessive heat (Perkins & Alexander 2013). In Australia, the Excess Heat Factor (EHF) method (Nairn & Fawcett 2015) is considered useful for forecasting and projecting heatwaves (DEECA 2024). The EHF takes into account minimum and maximum temperatures and compares conditions over a 3-day period with the previous 30 days as well as a threshold that represents extreme temperatures (in the local context) (DEECA 2024). Projections indicate significant increases in the frequency, intensity and duration of heatwaves (DEECA 2024). Figure 3 shows an example of what heatwaves could look like across Victoria in the 2030s and 2050s under a high emissions scenario (RCP 8.5). Across Victoria, these projections indicate an increase in heatwave frequency (total sum of heatwave days per year) from around 0-15 days in the 2030s to 3-35 days in the 2050s (Figure 3).



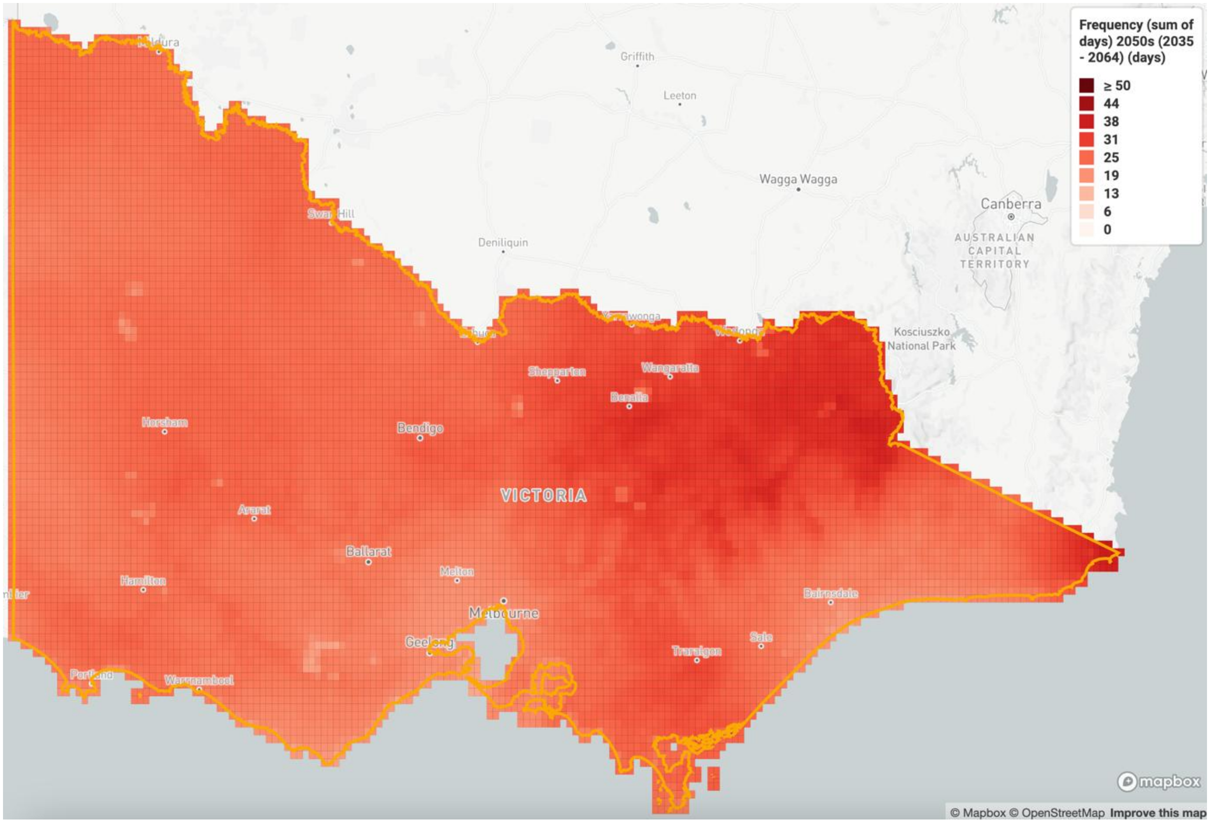


Figure 3 An example of what heatwaves could look like across Victoria under a high emission scenario (RCP 8.5) in the 2030s (top) and in the 2050s (bottom). The heatwave measure is the total sum of heatwave days per annum (calculated using the Excess Heat Factor method) over a 30-year period centred on 2030 (top) and 2050 (bottom). Source: Victoria's Future Climate Tool https://vicfutureclimatetool.indraweb.io

Since 1950, the frequency and intensity of cold extremes have decreased on a global scale (Seneviratne et al. 2021). Across Australia, the occurrence of very cold days and nights has declined, though there are exceptions in parts of south-east and south-west Australia. In Victoria, frosts are expected to become less frequent particularly when increasing minimum temperatures overpower other frost-conducive factors (DEECA 2024).

Victoria is projected to experience a warmer future climate with increasing average temperatures, more frequent and intense hot and very hot days, more frequent and longer heatwaves, and less frequent cold extremes (DEECA 2024).

Box 1. Thermodynamic processes and temperature and rainfall extremes (adapted from Seneviratne et al. (2021) and Swain et al. (2025))

An increase in the concentration of greenhouse gases in the atmosphere leads to the warming of tropospheric air and the Earth's surface. This direct thermodynamic effect leads to warmer temperatures everywhere, with an increase in the frequency and intensity of warm extremes, and a decrease in the frequency and intensity of cold extremes. The initial increase in temperature leads to other thermodynamic responses and feedbacks affecting the atmosphere and the surface. These include an increase in the water vapour content of the atmosphere and a change in the vertical profile of temperature.

A warmer atmosphere can hold more water and the Clausius-Clapeyron relation says that the maximum amount of water vapour that air can hold increases exponentially with temperature at a rate of ~7% per degree Celsius. Swain et al. (2025) introduces the analogy of the "Expanding Atmospheric Sponge" to convey that warming increases the size of the atmospheric sponge—the absorptive capacity or ceiling of evaporative demand increases. The higher ceiling of atmospheric evaporative demand or "thirstiness" of the "Expanding Atmospheric Sponge" sucks moisture from soil, bodies of water and vegetation. If water is available in these sources, actual evaporation and evapotranspiration increases; if water is not available, sensible heat-flux (the change of heat energy in terms of temperature increase) and near-surface air temperature rises (which may amplify heatwaves). Even in the absence of rainfall deficits, this increased evaporative demand in a warming climate has adverse implications for vegetation water stress and flammability. The other result of an "Expanding Atmospheric Sponge" is that a larger sponge can hold more water. When saturated and wrung out, the larger sponge yields more water, contributing to an increased risk of rainfall extremes.

3.2 Rainfall

Over the last 50 years, Victoria's average rainfall has decreased in all seasons, except summer (Round et al. 2024). Across the Port Phillip and Westernport region, the observed decline in total rainfall in all seasons (1970-2023) is spatially consistent within the range of 0 to -10 mm per decade (Figure 4).

About two-thirds of Victoria's annual rainfall occurs over the cool season (April-October). Cool season rainfall is more effective at generating runoff than warm season runoff since evapotranspiration is typically water-limited in the warm season but energy-limited in the cool season. Therefore, peak streamflow occurs in the cool season in most catchments in the region. It is when groundwater recharge is most likely to occur and is also the main growing season for many crops (CSIRO & BOM 2024). Over the last 30 years, Victoria's cool season rainfall has declined by >10% compared to the 1961-1990 period (DEECA 2024). The pattern of decline in cool season rainfall in Victoria is part of a broader decline across south-east Australia and is associated with decreased rainfall from weather systems and shifts in climate drivers that bring on higher surface atmospheric pressure, more highs, fewer lows and a reduction in rain-producing lows and cold fronts (CSIRO & BOM 2024; DEECA 2024).

In Victoria, average annual and cool season rainfall will likely continue to decrease in the future, but this long-term trend will be overlaid by year-to-year and decade-to-decade variability (DEECA 2024).

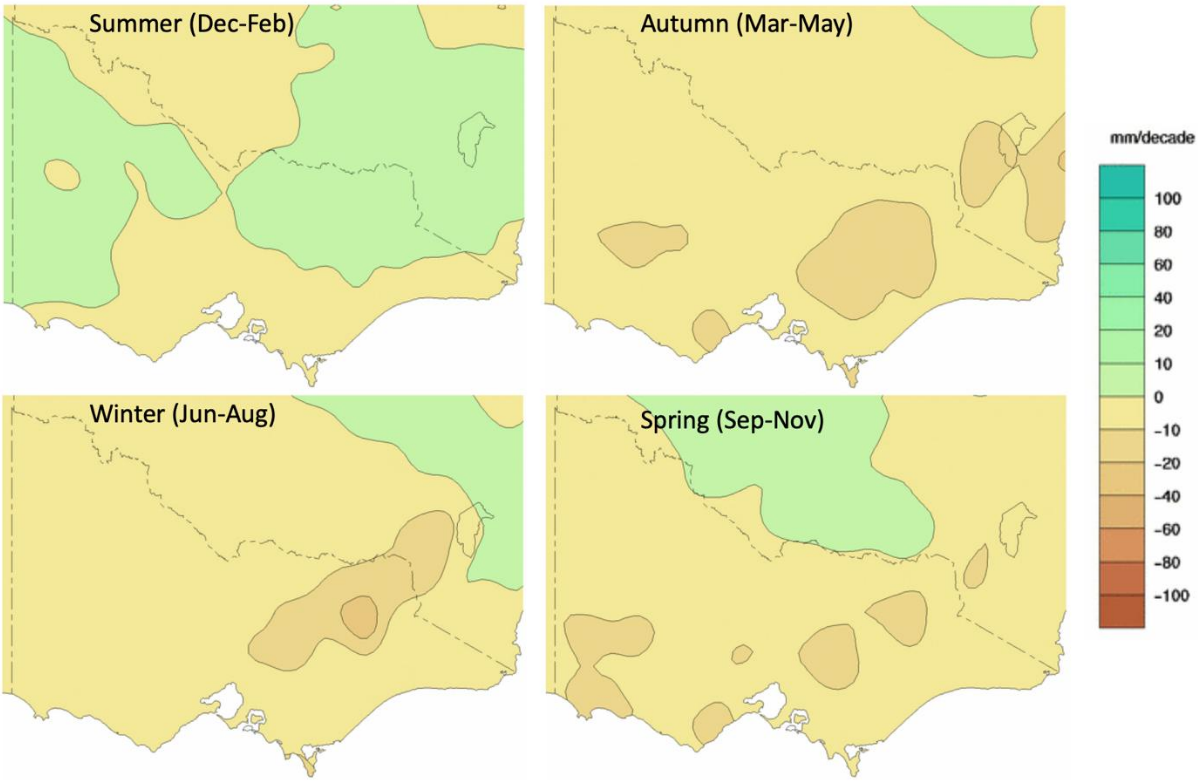


Figure 4 Observed linear trend in total rainfall (change in mm/decade) from 1970-2023 over Victoria for summer (Dec-Feb), autumn (Mar-May), winter (Jun-Aug) and spring (Sept-Nov). Brown shades indicate reductions in rainfall and green shades indicate increases. Source: Bureau of Meteorology (Australian climate variability & change – Trend maps)

Extreme rainfall (or heavy precipitation) events occur when a large amount of rain falls over a short period (e.g. hourly, sub-daily, daily or 5-day durations). Seneviratne et al. (2021)noted that "the frequency and intensity of heavy precipitation events have likely increased at the global scale over a majority of land regions with good observational coverage". In Victoria, extreme rainfall events are generally becoming more intense. Osburn et al. (2021) reported an almost 90% increase in the incidence of extreme hourly rainfall events with >18 mm per hour from 1958-1985 to 1987-2017. The most extreme rainfall events have increased in intensity more than less extreme events, especially in the warm season.

Even as Victoria is likely to become hotter and drier on average, extreme rainfall events are projected to become more intense. Short-duration rainfall extremes (e.g. hourly or sub-daily) are expected to increase more than longer-duration rainfall extremes (e.g. daily). In a recent overview of extreme rainfall observations and projections, Wasko and Nathan (2019) suggested that rainfall extremes in Australia may increase by about 15% and 8% more rainfall per degree of warming for sub-daily and daily rainfall, respectively. For Victoria, analysis of projections of *heavy* rainfall days (defined as 99th percentile) and *very heavy* rainfall days (99.9th percentile) found generally, a larger projected increase in amount of rainfall for *very heavy* rainfall days—in other words, larger increases for the rarer extremes (DEECA 2024).

3.3 Fire Weather

Fire naturally occurs in the Australian landscape and vegetation on the continent has co-evolved with fire and how humans have used fire in the landscape for tens of thousands of years. Nevertheless, it is clear that climate change is driving changes such as warmer temperatures, reduced rainfall (in Victoria) and increasing atmospheric aridity ("thirstiness"), all of which influence fuel availability, dryness and flammability, fire weather, and ignition sources (CSIRO & BOM 2024; DEECA 2024).

In south-east Australia and Victoria, a range of changes in fire regimes, activity and drivers has already been observed with a longer bushfire season, increased number of dangerous fire weather days (Figure 5), increased bushfire frequency (Figure 6), increased area burned and severity.

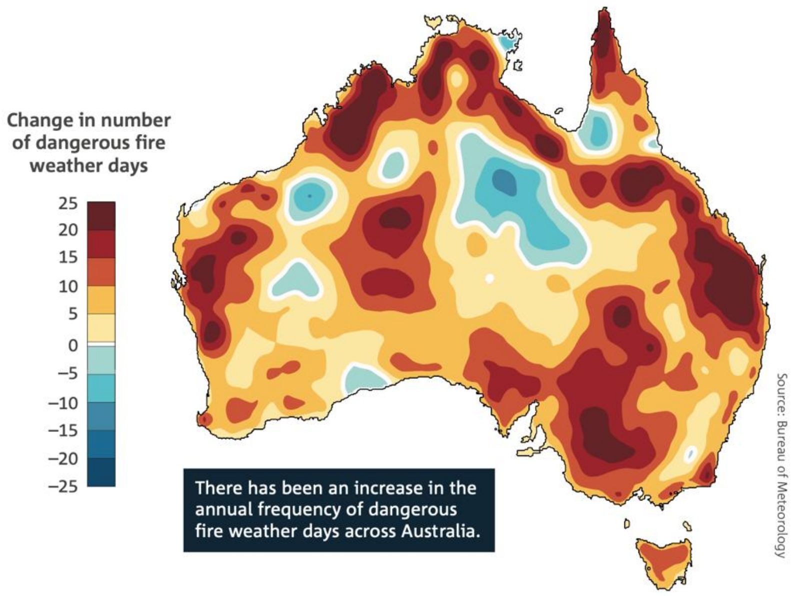


Figure 5 Change in the number of dangerous fire weather days across Australia. The map shows the change in the annual (July to June) number of days that the Forest Fire Danger Index (FFDI) exceeds its 90th percentile between two periods: July 1950-Jun 1986 and July 1986-June 2022. Red shades represent an increase in dangerous fire weather days while blue shades represent a decrease. Source: (CSIRO & BOM 2024; DEECA 2024).

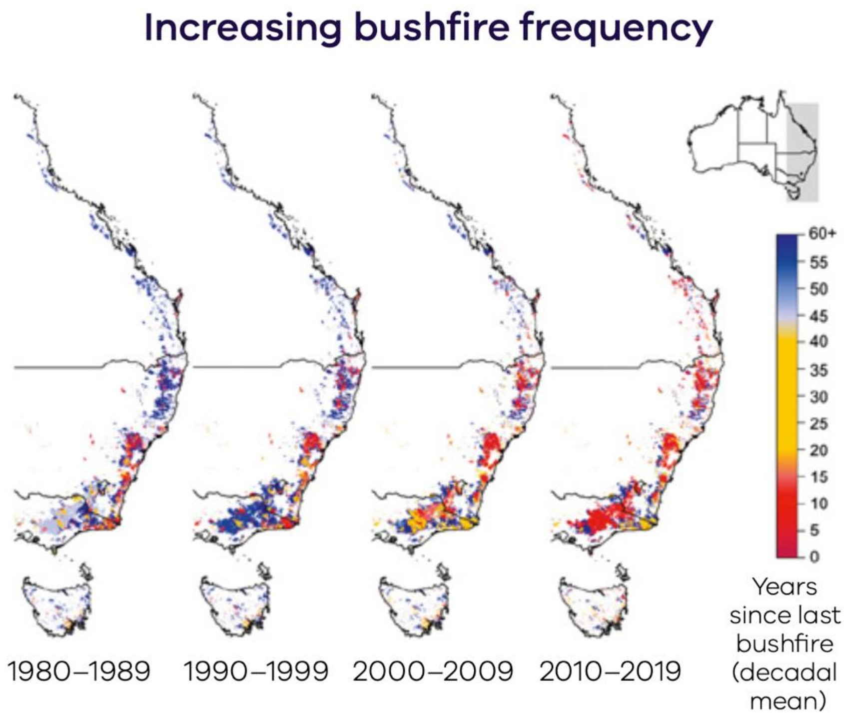


Figure 6 Number of years since the last bushfire (decadal mean) for forested areas, based on forested areas that have burnt at least once since fire records began in the 1930s for most states. Blue shades represent more years since the last bushfire while red shades represent fewer years since the last bushfire. Source: Canadell et al. (2021) and DEECA (2024).

Bushfires depend on a number of different factors coming together such as fuel availability and load, fuel moisture and ignition source. However, we lack high-quality, long-term data on these factors at landscape scales (DEECA 2024). Nevertheless, there is confidence that climate warming is causing increasing fire weather and fuel dryness (Abram et al. 2021) (Figure 7) and under warmer and drier future climates, fire weather, ignition risk and fire activity are projected to increase in many regions of south-east Australia. The observed incidence of fires at a landscape scale can be measured using fire radiative power (FRP) as measured by satellites. Abram et al. (2021) (Figure 6) showed that there is a strong relationship between fire weather and FRP. Though most of the focus has been on forest and woodland environments, important changes can also impact grassland and semi-arid environments though our knowledge about projected fire frequency and severity in these systems is much less certain (Figure 7).

Confidence in observed and projected changes related to fire activity and drivers

		Observed changes	Projected changes
Fire activity	Fire frequency, area burnt and fire severity – forests	Medium confidence of increase	High confidence of increase
	Fire frequency, area burnt and fire severity – grasslands	Low confidence in direction	Low confidence in direction
Drivers of fire	Fuel	Low confidence in direction	Low confidence in direction
	Fuel dryness	Medium confidence of increase	Medium confidence of increase
	Fire weather	High confidence of increase	High confidence of increase
	Ignition	Low confidence in direction	Medium confidence of increase

Figure 7 An assessment of the evidence related to fire frequency, area burnt and fire severity in forest and grassland environments in Victoria (top 2 rows). An assessment of the evidence related to fuel, fuel moisture, fire weather and ignition in Victoria (bottom 4 rows). High confidence equates to high agreement on robust evidence. Low confidence equates to low agreement and limited evidence. Source: Hamish Clarke, Victoria Reynolds and Tom Fairman for DEECA (2024).

3.4 Droughts

At the most basic level, droughts are about a deficit of water. But this deficit may arise from different causes, have different severity, duration, and effects. So in practice, drought is a socially-defined phenomenon with descriptions constructed to emphasise characteristics of particular interest such as in relation to meteorological, hydrological, ecological, socio-economic, and agricultural concerns. For instance, meteorological droughts refer to precipitation deficits relative to a long-term baseline, and agricultural droughts focus on soil moisture deficits and the impacts on crops and/or livestock. Figure 8 illustrates a typology of drought types, their defining characteristics, and the span of their indicative timescales from days to weeks, months, seasons, years, and decades (Source: DEECA 2024).

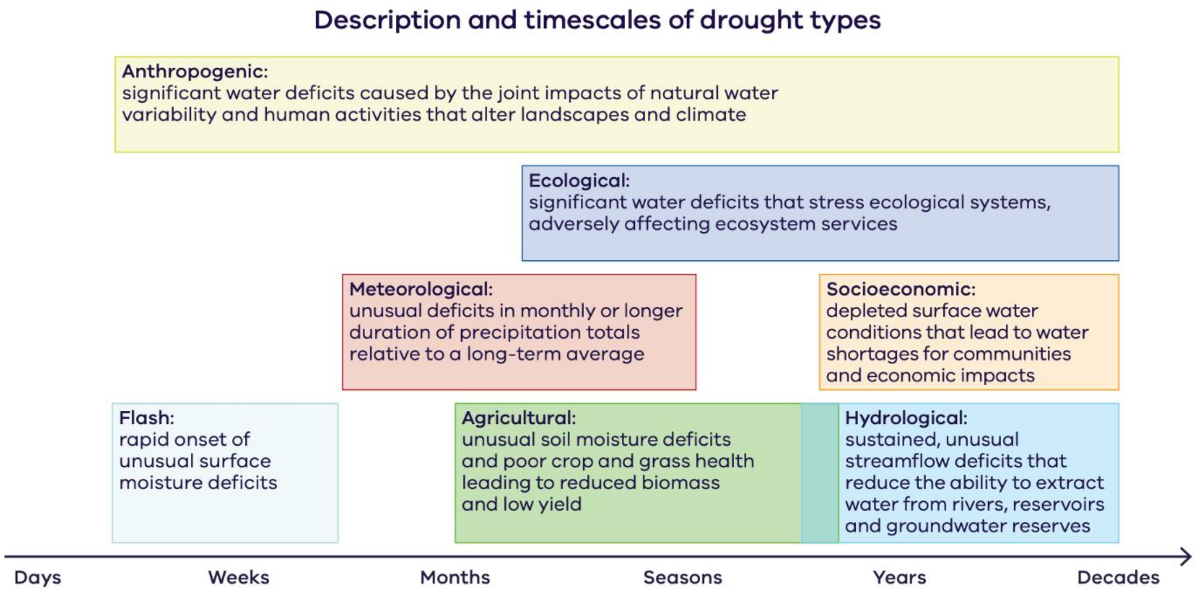


Figure 8 Description and typical timescales of different drought types as synthesized by DEECA (2024) from a range of publications (see DEECA 2024 for the full set of cited references).

Every drought is different, with different impacts, and may require careful unpacking as a single drought "may encompass more than one type of drought and different types of drought can coexist" (DEECA 2024). For instance, the multi-year Millennium Drought which featured ~13 years of below average rainfall, arguably encompassed meteorological, agricultural, ecological, hydrological, and socio-economic drought (Van Dijk et al. 2013).

In Victoria, increases in the frequency, intensity, and duration or meteorological and agricultural drought is likely to be associated with the reduction in cool-season rainfall (Holgate et al. 2020; Falster et al. 2024, see also Rainfall). Increases in hydrological drought are also linked to reductions in cool-season rainfall in south-east Australia (see also Streamflow).

Periods of drought are typically warmer in recent decades relative to past decades due to land-atmosphere feedbacks (Figure 9) and Australian droughts have become significantly warmer in the 21st century (DEECA 2024).

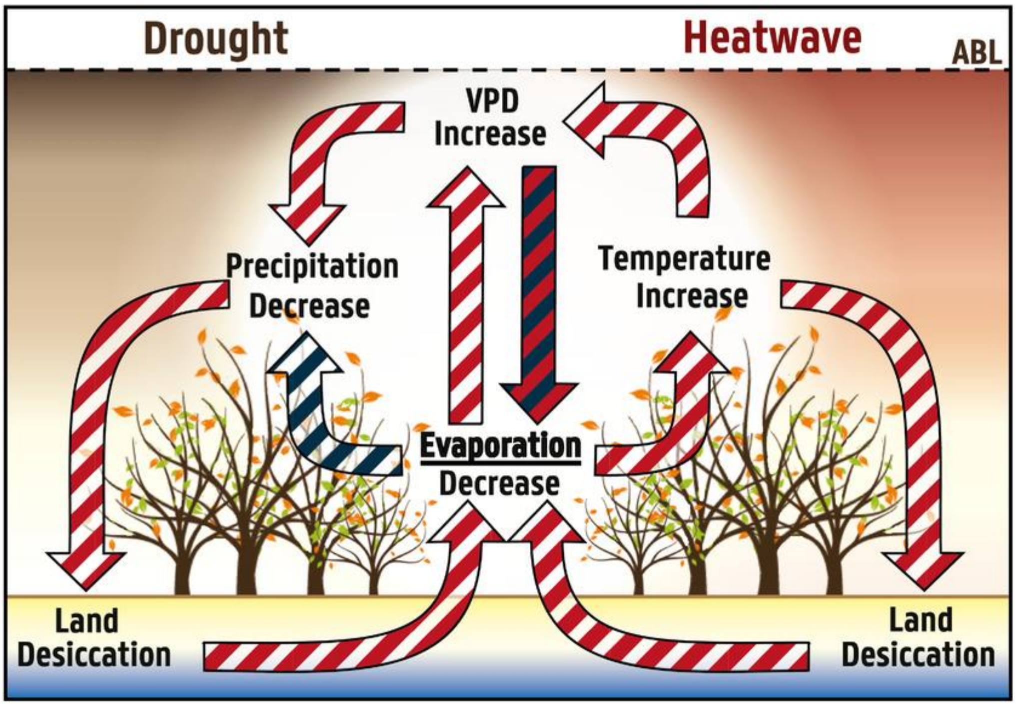


Figure 9 "Boldly simplified" conceptual diagram of key processes and feedbacks of soil and vegetation to (surface and atmospheric) water stress, heat and atmospheric aridity ("thirstiness") as "local intensifiers of hydro-meteorological extremes" from Miralles et al. (2019). The atmospheric boundary layer (ABL) is the lowest part of the atmosphere and its behaviour is directly influenced by its contact with the planetary surface. Red colours denote positive feedbacks (e.g. land desiccation strengthens evaporation decrease which in turn, strengthens temperature increase and vapour pressure deficit (VPD) increase. Dark blue denotes negative feedback. Miralles et al. (2019) figure highlights that VPD increase will typically reduce stomatal conductance and transpiration by vegetation under conditions of surface water stress.

In Victoria, droughts are likely to continue to increase in duration and intensity under a warming climate (Ukkola et al. 2020). We are more confident in climate impacts on shorter timescale droughts such as "flash droughts" to seasonal scale droughts than multi-year droughts. Future droughts will be hotter than past droughts and feedbacks can compound both heat and drought events (Zhou et al. 2019; DEECA 2024).

Rapid onset "flash droughts" may become more frequent. They develop when large deficits in precipitation coincide with high temperatures, low humidity and anomalously high evaporation and transpiration (Parker et al. 2021; Yuan et al. 2023). In this situation where soil moisture is already in deficit, higher temperatures and the "Expanding Atmospheric Sponge" effect (Box 1) may drive further soil drying together with increased evapotranspiration by plants, amplifying the deficit. Drought intensification can occur remarkably quickly—in the severe US drought in the summer of 2012 that caused an estimated economic loss of over US$30 billion, many locations went from drought-free to extreme drought conditions within a month (Yuan et al. 2023). In the Port Phillip and Westernport region, the median time to 'flash drought' onset (based on root zone soil moisture data from the Australian Water Resource Assessment Landscape model, AWRA-L) is around 20-25 days (Goswami & Gallant 2025). However, the fastest time to drought onset in the region can be as short as 15-20 days (Figure 1 in Goswami et al. (2025)). The rapidity of drought onset poses substantial challenges for drought monitoring, prediction and opportunities for risk management. In the Port Phillip and Westernport region, the median total duration of flash droughts is around 75-100 days (Goswami & Gallant 2025).

3.5 Streamflow

Since 1970, more than 28% of Australia's Hydrologic Reference Station (HRS) gauges show a "significantly declining trend in annual median streamflow" (CSIRO & BoM 2024). HRS gauges are in catchments with little disturbance from human activities and with at least a 30-year record. The observed long-term reduction in annual and (runoff-generating) cool season rainfall across large parts of southern Australia, including Victoria has led to reduced streamflow, though with considerable variability (CSIRO & BoM 2024).

A noteworthy phenomenon is the impact of drought on rainfall-runoff relationships. Watersheds are widely assumed to always recover from drought, where recovery is a function of duration after drought. However, recent research in Australia, the US and China has shown that streamflow recovery does not necessarily occur after prolonged drought (see references in Peterson et al. (2021)).

In Australia, the Millenium Drought (nominally 1997-2001 to 2009) was the longest uninterrupted low rainfall period in southeast Australia since 1900 (Peterson et al. 2021). Analysis of 161 unregulated watersheds with high-quality data within Victoria, found that one-third have not recovered from the Millenium Drought (shaded orange and red in Figure 10) and ~80% of these have a low-runoff state (Peterson et al. 2021).

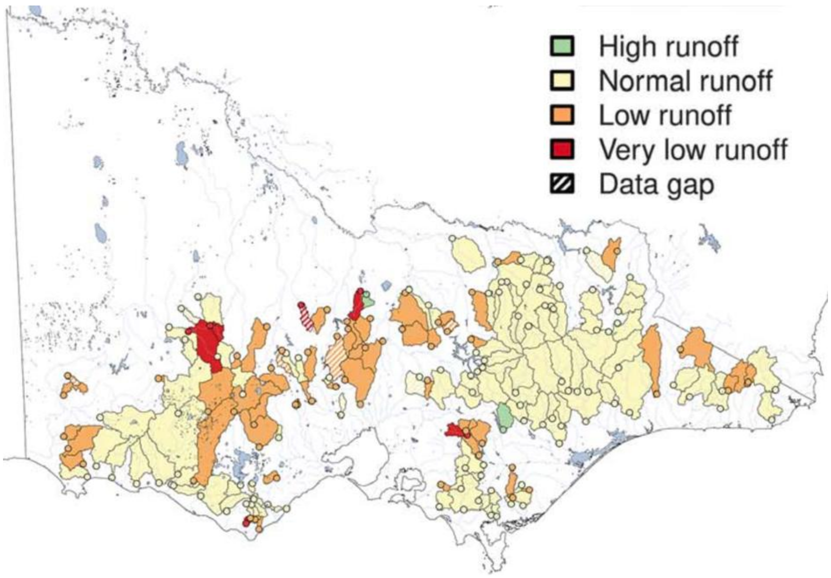


Figure 10 Map of the change in runoff state 7 years after the end of the Millenium Drought (i.e. 2016). Source: Peterson et al. (2021)

This suggests that watersheds can have multiple stable states and a finite resilience (Peterson et al. 2014). These findings suggest that "hydrological droughts can persist indefinitely after meteorological droughts and that the mechanisms for recovery remains an open question" (Peterson et al. 2021).

Streamflow is likely to continue to decline over the coming decades (Potter et al. 2016) driven mostly by declines in future cool season rainfall, along with the "Expanding Atmospheric Sponge" effect (Box 1) from increasing temperature and evapotranspiration demand (the transfer of water vapour to the air directly from soil, open water or vegetation). Potential shifts in rainfall-runoff relationships to persistent low or very low runoff states following prolonged drought is a further pressure on streamflow with significant consequences for flow-dependent ecosystems, vegetation management, and our communities.

3.6 Floods

Fluvial flooding (river flooding) is when water escapes the confines of a natural or constructed waterway such as rivers, creeks, dams and retarding basins. In hilly or mountainous areas, fluvial flooding can occur quickly following heavy rainfall but can also drain quickly. There may also be debris flows. In areas of flatter terrain, floodwaters tend to build and rise more gradually but may spread over a large extent, remain for longer periods and take longer to drain and recede.

Pluvial flooding (also called flash or stormwater flooding) is when an intense, short-duration extreme rainfall event overwhelms local drainage capacity. Pluvial flooding can occur in any location, urban or rural, and in settings with no nearby waterbodies or waterways.

Most floods are the result of natural weather phenomena and both characteristic and integral to the functioning and health of floodplain ecosystems. For instance, floods can recharge groundwater aquifers, trigger germination of plants for recruitment and ongoing vegetation persistence, provide cues for macroinvertebrate and fish spawning or dispersal, and create new and diverse temporary freshwater habitats in floodplain environments for water-dependent biota. However, they can also have devastating social, economic, and environmental impacts depending on the context. In Victoria, the occurrence and frequency of floods are primarily caused by large-scale climate drivers that vary greatly from year to year (DEECA 2024).

As floods are the result of multiple interacting factors (such as large-scale climate drivers, terrain, how wet the catchment is prior to an extreme rainfall event and so on) they are difficult to predict. Changes in stream flow and extreme rainfall events are often used as a proxy for floods but these are imperfect as there are many other possible contributing factors (Seneviratne et al. 2021). In particular, floods are sensitive to the spatio-temporal concentration of precipitation, including the antecedent conditions in the days or weeks prior to heavy rainfall events. Projections of floods are also uncertain as studies based on hydrological models do not tend to be able to account for important modifiers such as future changes in land cover, flood control measures and flood prevention policies (Seneviratne et al. 2021).

In Victoria, the historical trend is of small floods becoming smaller and large floods becoming larger (DEECA 2024). Climate projections from the Bureau of Meteorology suggest that this trend is expected to continue into the future with the rate of future change dependent on the emission scenario followed (Wasko & Nathan 2019).

3.7 Sea-level Rise

Rising sea levels are primarily caused by the combined impacts of the expansion of the ocean as it warms and the added mass of melting land-based ice, primarily from the Antarctic and Greenland ice sheets. Sea-level trends assessed between 1901 and 2018 indicate that globally, the average rate of sea-level rise is accelerating. The rate of sea-level rise around Australia's coastline since 1993 is assessed from measurements from coastal tide gauges and satellite altimeters. The rates of sea-level rise in the south-east and north of Australia have been higher than the global average, whilst rates of sea-level rise along other areas have been closer to or slightly lower than the global average (DEECA 2024).

Sea levels will continue to rise in the next 100 years under all emission scenarios. Following a lower emissions pathway will help slow the rate of sea-level rise but will not stop or reverse the rising trend. There is however, large uncertainty associated with sea-level rise due mainly to the lack of dynamic ice sheets in CMIP models.

More frequent extreme sea levels are linked to coastal inundation and coastal erosion (CSIRO & BoM 2024). A potentially useful tool for visualising coastal changes in how river mouths, tidal flats, beaches, and sandspits have grown and/or eroded over time is Geoscience Australia's [Digital Earth Australia Coastlines](). DEA Coastlines combines satellite data with tidal modelling to map the changing location of Australia's coastline since 1998 (Bishop-Taylor et al. 2021). By mapping rates of coastal change, and hotspots of erosion and growth (i.e. retreat and accretion) at every 30 metres along the entire Australian coastline, the product enables local and broader patterns of coastal change to be compared across years or decades (see for example, Figure 11). This can provide information and insights on areas of coastal vulnerability and their implications for vegetation assets and management.

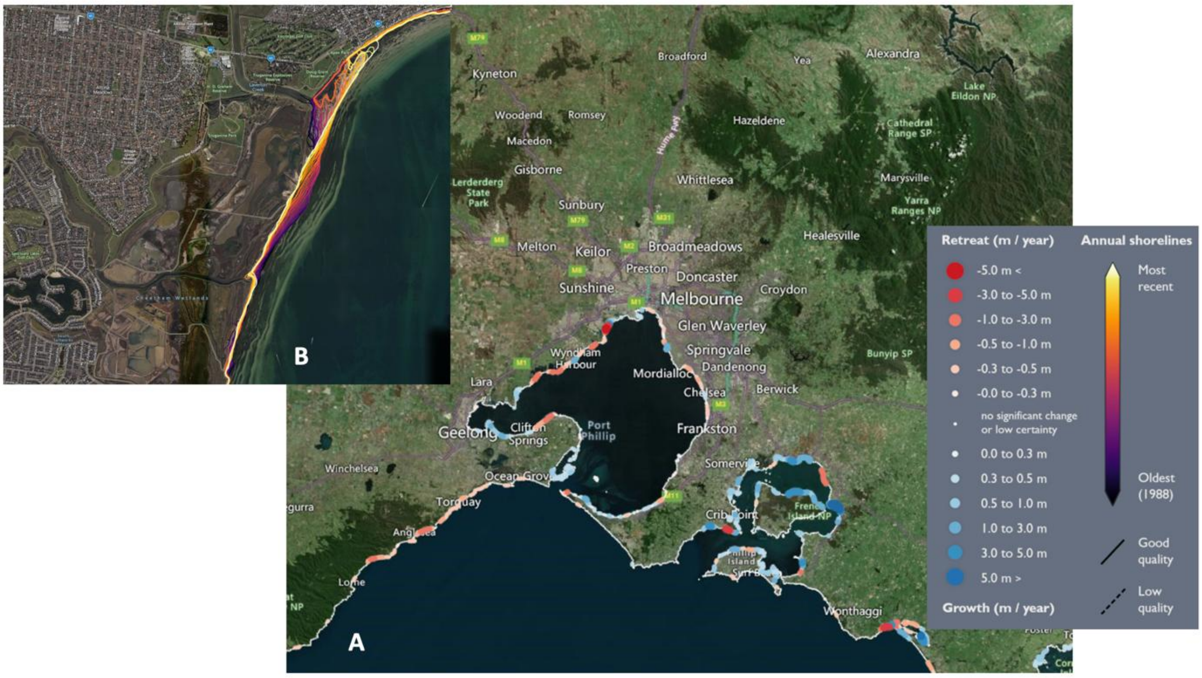


Figure 11 (A) Snapshot of DEA Coastlines in the Port Phillip and Westernport region showing hotspots of retreat (in red) and growth (in blue). Inset (B) shows a close-up view of annual shoreline locations (at annual mean sea level) near Laverton Creek, where dark purple shades represent the oldest shoreline position (1988) and light yellow shades indicate the most recent shoreline position. Source: https://maps.dea.ga.gov.au/story/DEACoastlines

3.8 Compound events

First introduced in 2012, in the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (known as the SREX report, IPCC (2012)), compound events are broadly speaking, a combination of multiple drivers and/or hazards that create societal and environmental risks with potential for severe impacts (Zscheischler et al. 2020). Compound events are highly diverse and come in many forms, combinations and permutations. A common combination is drought accompanied by heatwaves with impacts on say, crop production, native vegetation health and human health and wellbeing. Another common combination is extreme winds and heavy rainfall associated with fronts, thunderstorms, and cyclones. They can also be temporally compounding with locations impacted serially and repeatedly. An example is the 6 typhoons that hit the Philippines in a month between mid-October to mid-November 2024 (Armstrong 2024). These typhoons brought torrential rain, destructive winds, catastrophic flooding, landslides, storm surges, coastal, agricultural and infrastructure damage, population displacement of ~1.4 million, over 170 deaths, and little time for recovery or preparation between events (Otto et al. 2024).

Compound events can also be much more involved, with multiple drivers and hazards acting over time to cause a cascading chain of impacts. An example is California's Thomas fire in December 2017, followed by extreme rainfall over burn scars and the triggering of lethal debris flow-landslide events in January 2018 (AghaKouchak et al. 2020; AghaKouchak 2023). As illustrated in Figure 12, this compound event began several years prior, with the following sequence of events: prolonged extreme drought from 2012 to 2016, extreme rainfall in winter-spring of 2016-2017 that promoted dense growth of grasses, shrubs and other vegetation, then an unusually warm, dry summer and record-setting Santa Ana (Diablo) winds in autumn that together dried out vegetation and created perfect conditions for the Thomas fire (over 110,000 hectares burned), and finally, extreme rainfall over the burned landscape, triggering debris flows that took 23 lives and destroyed over 400 homes.

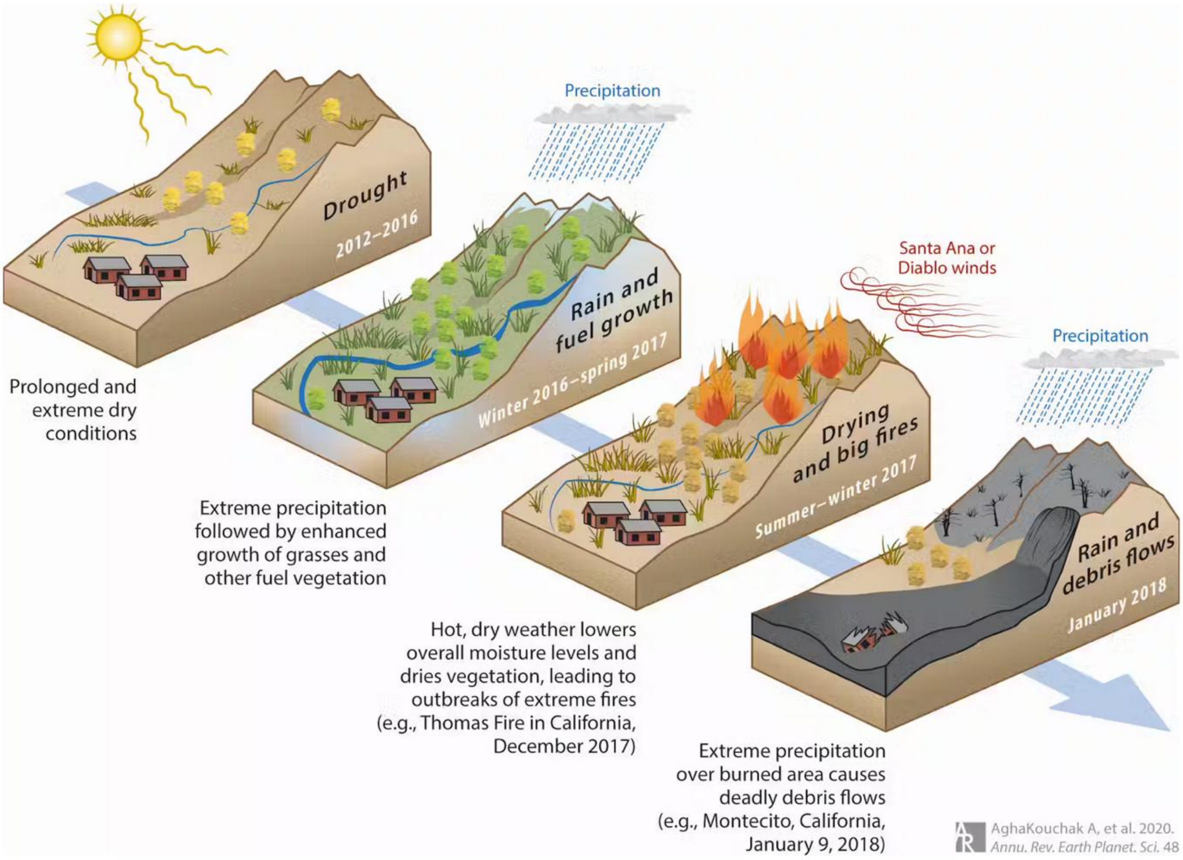


Figure 12 Illustration of the compound event (chain of consecutive events) that culminated in California's Thomas Fire and Montecito deadly debris flows. They included: a prolonged extreme drought from 2012-2016, extreme rainfall in winter-spring 2017-2017 promoting growth of grasses, shrubs and other vegetation, an unusually warm, dry summer and record-setting Santa Ana (Diablo) winds in autumn that together dried out vegetation, extreme fires in December 2017, extreme rainfall over the burned region in January 2018, leading to a deadly extreme debris flow event in Montecito. Source: AghaKouchak et al. (2020) and AghaKouchak (2023).

Such complex, compound events are not unique. Closer to home, Australia had the Millennium Drought (nominally 1997-2001 to 2009) followed by the massive, widespread floods of 2010-2011 that impacted rural and urban areas across Queensland, New South Wales and South Australia, leading to loss of lives, extensive damage to infrastructure and buildings and widespread disruption of agriculture and economic activities. More recently, we had the Tinderbox Drought of 2017-2019 (Devanand et al. 2024) followed by the Black Summer fires of 2019-2020, followed by torrential rain and dangerous flooding in New South Wales (Carlowicz & Dauphin 2020). The Tinderbox Drought was three consecutive years of intense drought encompassing meteorological, agricultural, ecological, socioeconomic and hydrological drought (see Figure 8). Along with severe rainfall deficits, there were record high maximum temperatures and vapour pressure deficit (atmospheric demand or “thirst”) which intensified soil moisture and vegetation drying and impacted streamflow and groundwater (Devanand et al. 2024). The drought-parched land surface also amplified heatwaves by ~2.5°C (Devanand et al. 2024). Extreme vegetation dryness in combination with fire weather set the stage for the cataclysmic Black Summer fires (Abram et al. 2021) that burned over 24 million hectares, caused 33 direct and almost 450 indirect human deaths. As Abram et al. (2021) reported, “80% of the forest area burnt during the 2019/2020 fire season occurred in the southeast Australian states of NSW, ACT and Victoria. In these states, 23.6% of their 27.7 million hectares of native forest was burnt during the Black Summer fires.” Extreme rainfall over Queensland and New South Wales in February 2020 then extinguished several large fires but also caused floods and associated damage and disruption (Carlowicz & Dauphin 2020).

The three complex compound event examples described above all exhibited hydroclimate volatility—sudden, large and/or frequent transitions from dry-to-wet conditions (or wet-to-dry conditions) relative to a local baseline (Swain et al. 2025). Using a metric based on the Standardized Precipitation Evapotranspiration Index (there is no uniform definition of hydroclimate volatility), Swain et al. (2025) show that hydroclimate volatility (which has been dubbed ‘climate whiplash’) is already observed to have increased globally since the mid-20th century because of global warming and consequential whiplash events can occur in virtually all land areas globally.

As seen in the examples above, impacts of climate whiplash events are more multi-faceted and severe than those associated with drought, fire or flood events in isolation. The conceptual model by Swain et al. (2025) of pathways through which hazards cascade and are amplified by whiplash illustrates the known interactions and their impacts (Figure 13).

Swain et al. (2025) are confident in further increases in hydroclimate volatility with ongoing warming because “extensive evidence links these increases primarily to thermodynamics, namely, the rising water-vapour-holding capacity and potential evaporative demand of the atmosphere” (the “Expanding Atmospheric Sponge” effect, Box 1).

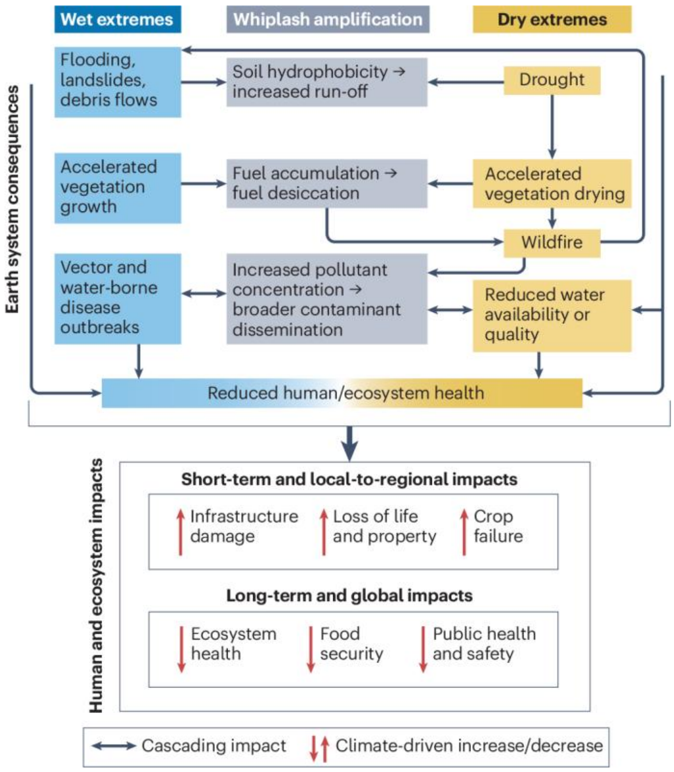


Figure 13 Pathways of cascading hydroclimate whiplash hazards in a warming climate. The dark arrows represent cascading relationships (in which the initial event causes indirect but substantial downstream effects via an intermediate step of process) and the red vertical arrows should increases or decreases in specific impacts under anthropogenic warming. The processes in blue boxes represent effects caused by wet events alone while processes in yellow boxes represent those caused by dry events alone. Processes in grey boxes represent those caused or amplified by whiplash transitions. Source: Swain et al. (2025)

So far we have focused on the physical dimensions of compound events (drought, heatwaves, wildfires, extreme wind, heavy rainfall, landslides, floods etc) but it is important to recognise that the interaction of physical processes with socioeconomic context, factors and mechanisms are also hugely important in terms of what and how impacts eventuate. For instance, are a large number of people directly exposed to the compound event? Do they have inherent capabilities and/or resources (e.g. emergency responders, stockpiles, reserves, insurance) to respond to or recover from the compound event? Can they access such capabilities and resources via political, financial, infrastructural, logistical, community or cultural networks? Are there flow on consequences such as exhaustion of the pool of emergency responders, food system shocks, transport network disruptions, supply-chain disruptions, destabilisation of the insurance industry? What will repair and recovery require? How will recovery be planned, resourced, coordinated, and overseen? The concept of “connected extremes” recognises that compound event impacts are “often substantially and non-linearly influenced by non-physical factors such as exposure and vulnerability, cutting across sectors and scales (from personal to society wide)” (Raymond et al. 2020). As Raymond et al. (2020) point out, this is an inherently interdisciplinary challenge and “successfully parsing, preparing for and responding to connected extreme events requires deep collaboration across sectors and disciplines”.

4. Impacts of climate change on native vegetation

Climate change is already negatively influencing forest ecosystems nationally and internationally (Hoffmann et al. 2019). This includes plant species becoming more restricted in their distribution, the movement of some species to higher latitudes, a loss of species from some ecosystems, and examples of broadscale dieback of vegetation communities in forested landscapes (Hughes 2003; Hoffmann et al. 2019). As the climate changes and landscapes in southern Australia become increasingly hotter and drier, local species survival may depend on their ability to migrate, acclimate or adapt (Peters et al. 2014):

- **Migration** along a favourable climate gradient, which alters a species distribution (also known as a *range shift*). In this case the species of interest needs to have suitable propagule dispersal mechanisms (usually via wind, water or animal dispersal) to migrate, or they may be moved directly or indirectly by humans. This migration may occur at a landscape scale but can be impeded for species found in small and fragmented habitats.
- **Acclimation**, or becoming accustomed to a new climate within their range of phenotypic plasticity (*niche shift*). Phenotypic plasticity can involve morphology (e.g. shape and size), physiology (e.g. photosynthetic pathways and metabolic rates), life-history traits (e.g. time to maturity, fecundity and resprouting ability) and more such as behaviour, learning, adaptive immunity and microbiome composition (Stollewerk et al. 2025). However, our understanding of the forms, roles and fitness consequences of different types of plasticity in the face of accelerating climate change is still elementary (Stollewerk et al. 2025).
- **Adaptation** at the plant scale morphologically, physiologically, and genetically. These changes are driven by natural selection and result in a *trait shift*, whereby there is a change of existing traits (e.g. leaf stomatal ratio, see Becklin et al. (2016)) or the evolution of new ones.

However, these abilities may not be available for all species in the greater Melbourne region and we do not have a good grasp of the relative importance of these abilities in different species.

Climate change stresses such as increased temperature, heatwaves, changed rainfall seasonality and regimes (e.g. reduced total annual rainfall but increased extreme rainfall), increased fire activity, frequency and severity, and drought frequency, intensity and duration all have direct and indirect impacts on vegetation communities. Changes in temperature and rainfall have a direct effect on photosynthesis, physiological and metabolic processes and reproductive outputs of plants. This can directly impact plant productivity, growth, reproduction, health and susceptibility to pests and diseases (Keenan 2015). Vegetation communities are networks of interacting species, so impacts to vegetation can also alter species interactions. For instance, changes in plant nutritional quality, growth and anti-herbivore defences can alter plant-herbivore interactions (Becklin et al. 2016). Changes in nectar and pollen rewards or temporal asynchrony, that is, mismatches in flowering times and pollinator activity can impact plant-pollinator interactions (Becklin et al. 2016). And changes in plant investment in mutualisms and shifts in mycorrhizal dynamics can impact on mycorrhizal associations (Becklin et al. 2016).

A report by Dell (2020) outlined some of the impacts climate change is likely to have on local vegetation communities in the Port Phillip and Westernport region by 2070 under a high emissions scenario (RCP 8.5):

- Decline or loss of fire sensitive species
- Decline in areas of occupancy of Sub-alpine Wet Heathland and related vegetation types
- Regional extinction of some species, such as cool temperate rainforest flora
- Vegetation loss from disease and invasive species, for example, declines in *Nothofagus cunninghamii* populations resulting from Myrtle rust outbreaks
- Reduction in tree canopy cover of wetter communities including Riparian Forest, Wet Forest, Damp Forest and Cool Temperate Rainforest, with expansion of dry eucalypt forest and woodlands
- Increases in C3 and particularly C4 grasses (e.g., weeping grass and kangaroo grass but also introduced species such as perennial ryegrass and couch grass)
- Declines in non-vascular plant diversity and areas of occupancy (e.g., mosses).
- Increases in more drought resistant sclerophyll forests, with an increase in resprouters and a loss of obligate seeders

4.1 Climate change impacts on vegetation communities

Below we outline potential impacts of particular climate stressors on vegetation communities and how vegetation communities are anticipated to respond. These impacts are summarised in Table 3. In some cases these impacts can be compounded by multiple factors, so understanding how climate change interacts with other variables to effect vegetation is often complex and not well understood (Sykes 2009).

Changes in temperature and rainfall

Warmer temperatures, reduced rainfall and changed rainfall patterns, and increased atmospheric CO_2 concentrations impact water availability, water use and vegetation growth (Medlyn et al. 2001; Donohue et al. 2017; Vicente-Serrano et al. 2022). Higher temperatures can increase evaporative demand and water stress but higher CO_2 concentrations can enhance plant water use efficiency and stimulate growth. It is well understood that elevated CO_2 increases leaf-level water use efficiency and common responses include increased growth rates. However, how canopy-level transpiration and assimilation varies as a result of leaf-level water use efficiency is uncertain, and has been found to differ between disturbed and undisturbed vegetation (Donohue et al. 2017). Predicting outcomes is complicated as the interacting effects can be difficult to identify and attribute against a background of high climate variability and lags in vegetation response. Below, we confine ourselves to describing dieback, changes in phenology and range shifts.

Dieback

Dieback has been associated with forest decline across the globe and can be defined as tree mortality noticeably above usual mortality levels (Allen 2009; Allen et al. 2010) and '*stands of dead and dying trees whose dieback cause is not obvious and that typically occur in several locations of a larger forest ecosystem'* (Mueller-Dombois 1986). Dieback can be distinguished from the chronic-decline of trees, which is more related to human management actions (e.g., livestock grazing, pollution, etc), whereas dieback is generally related to climatic extremes (Jurskis 2005). While climatic extremes cause some forms of dieback, dieback has also been related to disease spread and pest animals impacts, or a combination of these stresses (Mueller-Dombois 1986). Dieback usually occurs at multiple locations with adjacent trees as well as spatially separated trees dying at roughly the same time and foliage loss occurring from the top downwards (Mueller-Dombois 1986). Studies have shown that hotter climatic conditions can alter respiration in plants, evapotranspiration, and increase soil moisture loss, negatively influencing vegetation growth and thus causing dieback (Afuye et al. 2021).

For example, in southwestern Australia, higher than average temperatures (~1°C) and lower rainfall (15-20%) over the last 30 years, combined with drought (40-50% reduction in annual rainfall) and heatwaves have resulted in large-scale dieback in a range of forest and woodland types (Hoffmann et al. 2019). Keppel et al. (2023) found that dieback resulted from two droughts in South Australia that killed >40 % of individuals in a threatened eucalypt species. Their research suggested north-facing sites were more likely to be negatively affected by drought than other aspects, but they also found that the two droughts had different effects on the population. After the first drought (2000-2009) marginal sites with low biomass and sites located on flat plateaus were more heavily impacted, but after the second drought (2017-2019) heat stress was a more important driver of dieback (Keppel et al. 2023).

Changes in flowering, reproduction and germination

Warming can result in changes in flowering phenology and other changes such as in the timing of seed maturation and plant germination (Sykes 2009). For example, some species flower earlier as a result of warmer temperatures, and similarly the seeds of some species mature earlier under hotter conditions (Hoffmann et al. 2010). Warming climates can also result in plants producing leaves earlier, flowering and fruiting earlier and delayed leaf fall (Sykes 2009).

These changes in phenology may alter the reproductive success and growth of a plant. For example, delayed flowering may result in changes to pollination success of a species, and earlier seed maturation may put the germinating plant at greater or lesser risk of herbivory by animals (Hoffmann et al. 2019). While many species in the southern hemisphere germinate in spring, climate change will potentially lead to a shift from spring to autumn emergence for some species (Mondoni et al. 2012). This may mean that germinating plants are put at greater stress from lower rainfall in the summer period.

Range shifts

The physiological tolerance of a species to climate-related factors such as drought or frost can strongly influence a species' geographic range. Other factors such as competition with other species can also influence how a species performs at its range limit (MacLean & Beissinger 2017). Increases in temperatures and lower rainfall can drive vegetation changes, such as in alpine areas, with species from lower altitudes moving to higher, cooler areas towards more suitable climatic zones (Garamvölgyi & Hufnagel 2013).

For example, a study by Wahren et al. (2013) in alpine regions of Victoria found that the cover of grasses and other graminoids decreased by up to 25%, and forb and shrub cover increased by 9% and 20% respectively in relation to climatic changes. The sharp decline in grass cover resulted from severe drought, while the increases in shrub and forb cover resulted from increases in temperature, bare ground and climate-induced changes in biotic interactions between these life-forms (Wahren et al. 2013). However, there is a lack of research regarding lowland vegetation communities and if they are likely to shift their range as a result of climate change (Lenoir & Svenning 2015).

Fires

In a review of the 2019/20 Black Summer bushfires in Southeast Australia, Abram et al. (2021) identified four forest fire switches that are necessary for large forest fires to develop. These are fuel biomass (leaf and bark litter, dead wood and living foliage), fuel dryness (resulting from a lack of rainfall and drought like conditions, generally increasing fuel loads), ignition (from anthropogenic or natural sources such as lightning strikes) and fire weather (hot, dry and windy weather) (Abram et al.

2021). With increases in hot and dry conditions in southern Australia, risk of extreme fire weather is projected to increase (CSIRO & BOM 2024).

While many Australian forests are adapted to fire, and recover relatively rapidly after fires, if fires are intense and/or occur over short time intervals, forested areas are less able to recover (Driscoll et al. 2024). The intensity of a fire is influenced by the interplay of land tenure, drought and recent fire history, but high intensity fires, such as those in southern Australia in 2019-2020, can be highly destructive (CSIRO & BOM 2024; Driscoll et al. 2024). Frequent and high intensity fires may result in a change in the vegetation community over time, and result in a shift from a forest to a more open woodland community (Lloret & Zedler 2009), or from a wet forest/rainforest community to a drier eucalypt dominated community.

When a forest burns, a significant amount of carbon sequestered in trees is released into the atmosphere, altering forests from a carbon sink to a carbon source (Singh et al. 2010). Fires can also have a detrimental impact on revegetated areas, especially if they are relatively young and plants have not become reproductive or are not tall enough to escape canopy scorch.

Droughts

Drought often has detrimental impacts on germinating and emerging plants and revegetation. Drought trials have shown that drying conditions decrease seed germination in most species, and cause significant changes in species composition (Lloret et al. 2009). Lloret et al. (2009) also found that drying conditions as a result of climate change altered recruitment rates in different species and the adult performance of those species. Severe drought is likely to cause mortality in seedlings and young recruits, but is less likely to cause mortality in more mature plants (Hanson & Weltzin 2000). However, the effects of severe or prolonged drought can weaken mature trees, making them more susceptible to impacts such as diseases or pest attacks (Hoffmann et al. 2019). Drought can also reduce rates of litter decomposition in forests, causing a buildup in litter and other debris and increasing the risk of fire in these landscapes (Hanson & Weltzin 2000).

Drought can also cause changes in vegetation community composition, altering both the species richness and abundance of plants within a given area, having long-lasting effects on the vegetation composition (Ploughe et al. 2019). Composition can also be influenced by plant interactions, whereby competition can be decreased during a time of drought, but facilitative mechanisms such as habitat modification, resource enhancement, provision of a refuge from predators and competitors, and recruitment enhancement can possibly increase during times of stress (Ploughe et al. 2019).

Community composition can reduce the negative effects of drought. For example, higher species richness and/or functional diversity can reduce the effects of drought on a community and mediate the effects on ecosystem functioning (Grossiord 2020). Grossiord (2020) outlines three classes of mechanisms in forests that can help maintain species during drought: resources partitioning, facilitation and selection effects (Figure 14). Resource partitioning is related to the dissimilarity in functional traits between species, which reduces competition (in this case root stratification and stomatal regulation), whereas facilitation occurs when one species has a positive net effect on the functioning of cohabiting species (Grossiord 2020). The selection effect on forest communities can be enhanced by droughts where there is a dominance of species with particular traits in the initial species pool. The literature shows that tree diversity regulates drought impacts in forests, allowing more species to survive after a drought than communities that had a lower species pool prior to the drought (Figure 14).

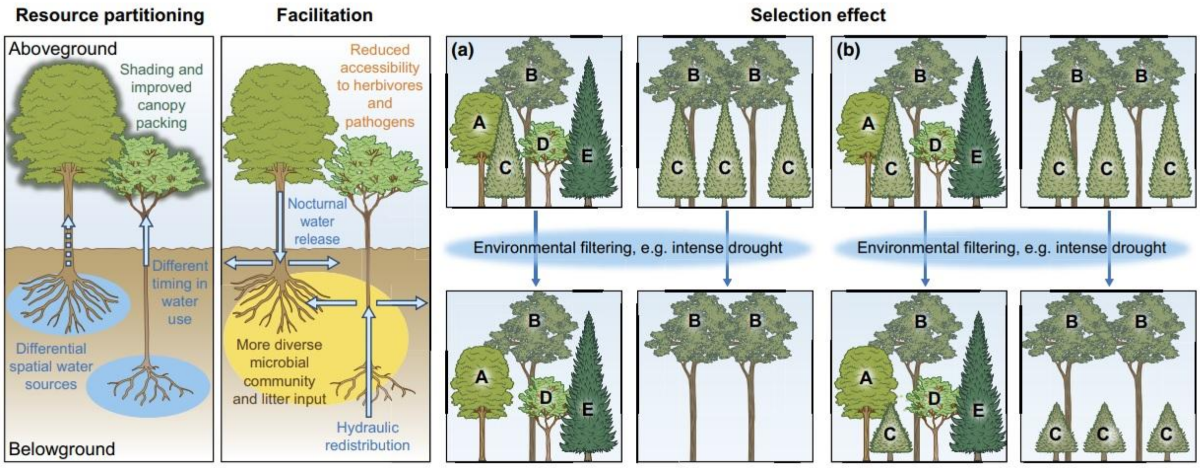


Figure 14. Conceptual representation of the three classes of mechanisms: resource partitioning, facilitation, and selection effect. For resource partitioning and facilitation, two tree species characterized by contrasting traits related to their water and nutrient acquisition and use (that is canopy structure, phenology, tree height, rooting depth and mycorrhizal associations) are shown, highlighting the physical and biological mechanisms of resource partitioning and facilitation taking place in mixed forests (that is resulting from tree species interactions in aboveground and belowground compartments). The conceptual representation of selection effects includes an example (a) highlighting how a given forest community hosting a higher number of tree species (species A, B, C, D and E) is more likely to have an increased number of species surviving an environmental or climatic filtering event (e.g. intense drought) than a forest community hosting the same number of individuals but fewer tree species (species B and C). In this example, species C is particularly vulnerable to drought stress and suffers complete drought-induced mortality at the community level following the filtering event. The second example (b) highlights how a given forest community hosting a higher number of tree species is more likely to have an increased number of drought-tolerant species maintaining major functions (e.g. growth) during an environmental or climatic filtering event than a forest community hosting the same number of individuals but fewer tree species. In this example, species C is particularly vulnerable to drought stress and suffers strong growth reductions following the filtering event. Source: Grossiord (2020)

Destructive wind events

Severe storm events can result in extensive windthrow in forested landscapes and the immediate alteration of forest structure, composition and functioning. The frequency and intensity of these events is highly uncertain, but may increase as a result of climate change (Brown & Dowdy 2021), and if so, may effect a wide range of ecosystems previously not impacted by these events (Hinko-Najera et al. 2024). Long-term climate model projections of the frequency and severity of extreme wind events remain quite uncertain, due in part to the fine spatial scales of the physical processes at play relative to the typically coarse resolution of climate change projections from coupled models (Brown & Dowdy 2021). When these events do occur, they can cause major damage to natural ecosystems, and pose risks to local infrastructure and public safety (Hinko-Najera et al. 2024).

An example of a severe windthrow event occurred in southeastern Australia in the Wombat State Forest, Victoria, which overlaps the Port Phillip and Westernport catchment area. In June 2021 a severe wind event was reported, and a study by Hinko-Najera et al. (2024) found that out of the >60,000 ha of forest area that was assessed, 63% was impacted by windthrow. The researchers categorised these effects as low severity (<30% canopy cover loss - 46%), moderate severity (30–50% canopy cover loss - 11%) and high severity (>50% canopy cover loss - 6%).

The severity of the impacts of these windthrow events is influenced by site physiography, soil moisture and soil depth, stand characteristics and tree characteristics (Peterson 2000). The speed and the direction of the prevailing wind and the amount of stress the forest is under leading up to the event occurring are also factors that are likely to determine the impact of these events (Peterson

2000). Furthermore, the buildup of debris from fallen trees and tree limbs is likely to increase the risk of severe fire in these landscapes, increasing the risk to biodiversity and community safety.

Floods

In Victoria, climate projections from the Bureau of Meteorology suggest that the historical trend of small floods becoming smaller and large floods becoming larger is expected to continue into the future with the rate of future change dependent on the emission scenario followed (Wasko & Nathan 2019). Flood events can have a detrimental impact on revegetation efforts along riparian zones and potentially deplete instream vegetation in some systems. Flooding can also increase erosion of waterways, especially where plants are not present, increasing turbidity and decreasing water quality (Espeland & Kettenring 2018).

Longer duration of flooding, higher flood depths and a combination of these two factors can reduce seedling survival in most riparian species, and cause a shift in species composition over time (Garssen et al. 2015). Garssen et al. (2015) found that species richness can be reduced in regularly flooded areas, and selecting for species that grew higher than the flood level, had elongated shoots and had a more porous root structure could reduce the risk of flooding on native plant species in flood-prone areas.

Revegetation, particularly during its establishment phase, is also susceptible to flooding. Increased flood frequency is likely to increase the cost of restoring some riparian areas and the uncertainty of revegetation success. Planting further away from the flood zone may be one way of reducing the negative impacts of floods on native plant establishment and recruitment.

Pathogens and pest plant and animal species

Weeds are already a problem in many forest ecosystems, as they can compete with native species for nutrients, sunlight and water, limiting natural regeneration and recovery in communities degraded by biotic and abiotic influences (Singh et al. 2010). Competition by weeds reduces the growth and survival of young native plants, especially in revegetated areas (Foley-Congdon et al. 2024), and can potentially increase the risk of fire in some landscapes (Singh et al. 2010). Climate change is likely to increase the spread of non-local and non-native plant species, due to their high degree of phenotypic plasticity allowing to invade a variety of habitats (Clements & Ditommaso 2011). Increases in weed invasions is likely to result in higher costs of reducing weed loads through chemical or mechanical controls. Using suitable species to maintain a healthy and dense native vegetation cover is crucial in reducing weed invasion under a changing climate.

Climate change is likely to advantage the movement and impact of some pathogens and pest animal species, with potentially detrimental impacts on native vegetation communities. For example, *Phytophthora cinnamomi* is already present in many Australian forests, and alternate wet and dry periods caused by climate change could exacerbate the spread of this root-rot fungus, causing further dieback in eucalypt species and other forest plants (Singh et al. 2010). Ash dieback disease, caused by the fungus *Hymenoscyphus fraxineus*, is an example of a disease impacting large areas of forested landscapes in Europe, and predictions indicate that climate change impacts are interacting with this fungus to alter the distribution of these Ash forests (Goberville et al. 2016)

Similarly, the cumulative impacts of climate stresses (higher temperatures and lower rainfall) as well as insect infestations have caused widespread dieback in Western Sydney’s critically endangered Cumberland Plain Woodland (Hoffmann et al. 2019). It is predicted that lower than average rainfall events and extreme maximum mean temperatures will increase the likelihood of these event in the future (Hoffmann et al. 2019).

Table 3. The projected impacts of climate change in southern Australia, our confidence in these projections, the processes that are likely to affect vegetation communities and the anticipated impacts of these processes on vegetation communities.

Projected impacts of climate change in southern Australia	Confidence in these projections	Description of processes likely to affect vegetation communities	Anticipated impacts on vegetation
Increasing temperature	Very high (CSIRO & BOM 2024)	Increases stress responses in plants, inhibiting photosynthesis and increasing respiration. Also effects nutrient availability and uptake (Rennenberg et al. 2006)	Changes in flowering, reproduction and germination (Becklin et al. 2016), reduced revegetation survival, dieback or loss of established vegetation, species range shifts
Declining rainfall totals	Medium-high (CSIRO & BOM 2024)	Changes in leaf morphology as well as inhibiting photosynthesis. Reduction in tree growth (Brzostek et al. 2014)	As above
Increases in fire weather risk	High (CSIRO & BOM 2024)	Fire-induced cambium/phloem necrosis and xylem damage, resulting in tree death and greater fuel loads (Bär et al. 2019)	Changes in species composition in forested landscapes, especially in fire sensitive ecosystems such as alpine areas
Increasing drought conditions	Medium-high (CSIRO & BOM 2024)	Hydraulic dysfunction in drought-affected trees, xylem embolism that can lead to mortality, carbon starvation associated with prolonged stomatal closure (Bär et al. 2019)	Loss of revegetation, germinating and juvenile plants during droughts, declines of established trees and shrubs possible in prolonged/severe droughts (canopy dieback, vegetation die-off). Changes to vegetation community composition, and species and/or ecosystem loss.
Increasing incidents of destructive wind events	Low (Brown & Dowdy 2021)	Windbreak, stem snap, uprooting (Mitchell 2013)	Loss of branches, loss of individual trees or groups of trees, creation of canopy gaps, changes in vegetation community structure,

			composition and functioning (Mitchell 2013; Hinko-Najera et al. 2024)
More extreme rainfall and flood events	Medium (CSIRO & BOM 2024)	Erosive flows, scouring of stream channels and banks, waterlogging	Loss of instream and riparian vegetation, changes in vegetation community structure, composition and functioning, species and/or ecosystem loss
Increases in pest animals, pest plants and pathogens	Medium	Increased grazing pressure, increased competition for resources, increased pathogen load (Clements & Ditommaso 2011)	Reduced vegetation survival, declines or dieback of established vegetation, changes in vegetation community structure, composition and functioning

4.2 Climate impacts on habitat restoration and revegetation

The restoration of native vegetation is vital in the face of climate change, as it helps facilitate the recovery of vegetation communities. However, trying to restore ecosystems to their historic state or composition is very difficult or may in fact be impossible due to changed biophysical conditions in the future (Harris et al. 2006). For example, in Victoria ecosystem restoration is usually guided by Ecological Vegetation Community (EVC) species lists and benchmarks. But will these EVC communities be viable under hotter and drier conditions and the range of stressors discussed in Section 3? Trying to reinstate historical plant communities in landscapes altered by agriculture and urbanisation has often resulted in the creation of novel ecosystems (Hobbs et al. 2014). The nature and range of climate impacts places a further overlay of constraints on trying to recreate what was present prior to European settlement.

Climate change and particularly lower rainfall and higher temperatures are likely to impact the survival of revegetation. For example, in a study of revegetation in South Australia, Jellinek et al. (2020) found that lower average rainfall and higher mean maximum temperatures over the hottest months (January and February) had the greatest impact on plant survival in the first year. Similarly, a revegetation project in northern Victoria found that drought was likely to have the greatest impact on plant survival in a climate-ready revegetation trial (McDonald et al. 2021).

Nolan et al. (2018) suggested that the potential impacts of climate change on revegetated areas are likely to be a function of their exposure and sensitivity to climate-related impacts. They suggest that the increasing number of hot days and nights, decreasing number of cool days and nights, increased frequency of heatwaves, heavy rainfall events, and increased areas effected by drought are likely to increase the exposure of revegetation to climate-related stimuli. The sensitivity of revegetation to these climate events will be a function of their resistance (capacity to absorb a disturbance) and resilience (capacity to recover from a disturbance) and is likely to be dependent on species traits (Nolan et al. 2018) (Figure 15). How vulnerable a revegetated area is to these impacts is dependent on the system's adaptive capacity, and may be influenced by how the revegetation project is undertaken through actions such as robust planting design, and species and genotype selection. Monitoring is a vital part of revegetation, as it allows project managers to adapt and learn and ultimately improve their restoration outcomes (Nolan et al. 2018).

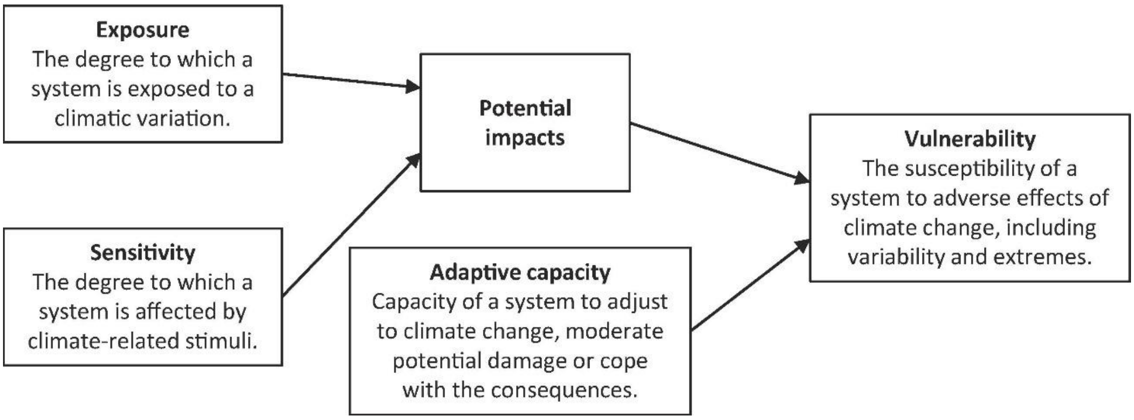


Figure 15. The impacts of climate change on revegetated areas are a function of exposure to unfavourable climatic conditions, and the sensitivity of the vegetation to those conditions. These collectively determine the vulnerability of the system. However, vulnerability can be modified with the adaptive capacity of the system. Source: Nolan et al. (2018).

5. Supporting vegetation resilience under climate change

There is a diverse array of recommendations for adapting nature conservation management to climate change. Prober et al. (2019) produced an influential review that helped to make sense of the "sea of adaptation ideas" (Heller & Zavaleta 2009). They reviewed 473 papers and produced a synthesis and typology of on-ground tools or actions and the intended mechanism or process through which climate adaptation would be facilitated (Prober et al. 2019). These were distilled into 23 intervention option types organised across four quadrants (Figure 16).

The vertical axis places the strategy of evading or ameliorating climate impacts (or conditions) at one end and the strategy of building species', communities' and ecosystems' resistance, adaptive capacity and resilience to climate impacts at the other end of the continuum. The horizontal axis has 'low regrets' at one end, denoting "beneficial regardless of the rate or extent of climate change" and 'climate-targeted' at the other end, denoting purpose-designed but potentially resource-intensive with inherent risk (e.g., unexpected maladaptation of translocated supposedly climate-adjusted genotypes).

An important insight from the Prober et al. (2019) review is that there is limited empirical data to demonstrate the effectiveness of the different intervention options. As they point out, most of the inference about intervention options has been based on ecological theory, ecological reasoning, expert knowledge and experience, and modelling, rather than empirical evidence (Prober et al. 2019). They flag that "limited empiricism was particularly conspicuous for options intended to build adaptive capacity or resilience". This is important to acknowledge whilst bearing in mind that empirical evidence to assess effectiveness of facilitation of persistence or adaptation of biodiversity and ecosystems in a climate that can be changing in myriad ways is very challenging.

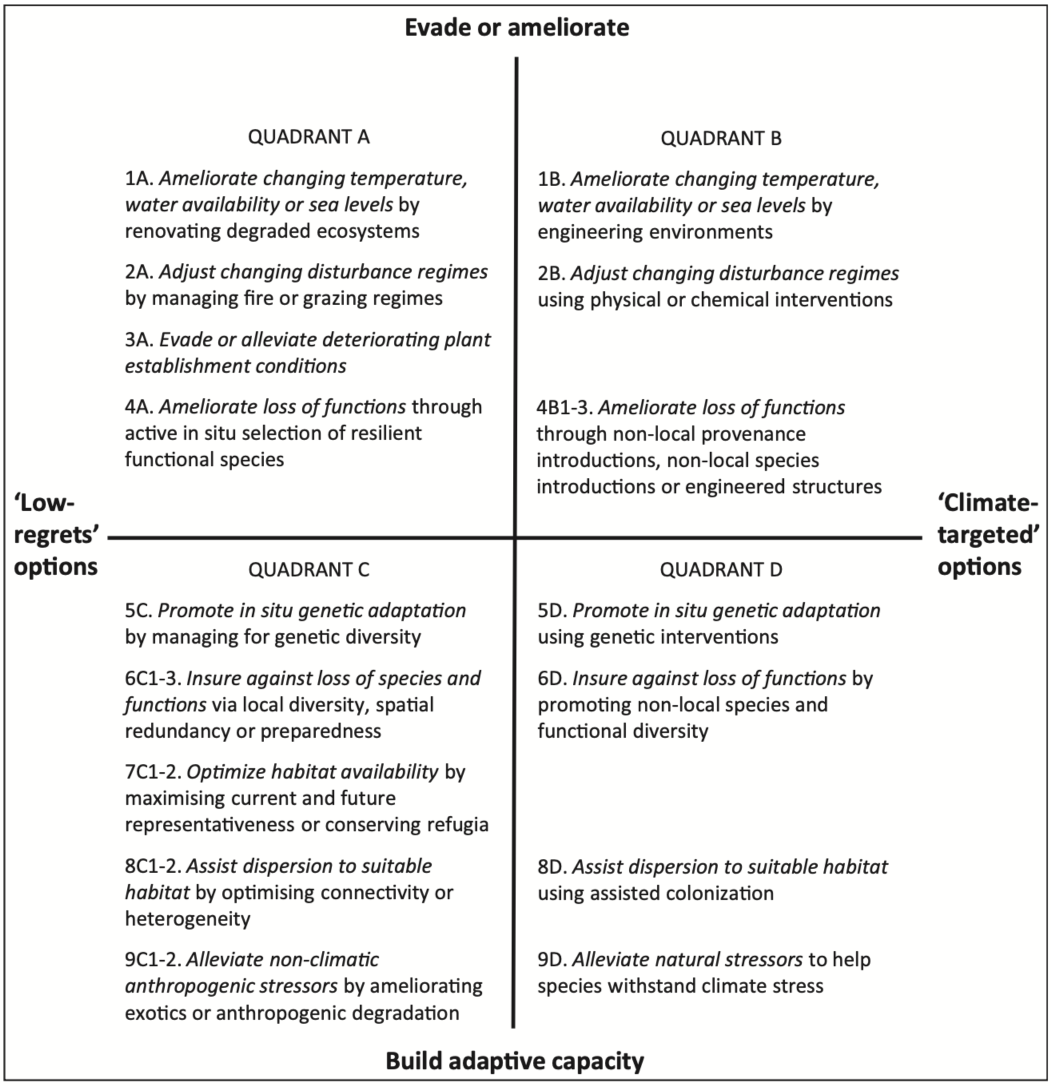


Figure 16 Typology of 23 options to facilitate persistence or adaptation of biodiversity and ecosystems in a changing climate. The options are organised across four quadrants. The vertical axis places 'Evade or Ameliorate' at one end and 'Build Adaptive Capacity' at the other end. The horizontal axis places 'low regrets' at one end and 'climate-targeted' at the other end (Prober et al. 2019).

This classification of 23 options into four quadrants is heuristic and pragmatic rather than definitive and some options (e.g. 2A Adjust changing disturbance regimes by managing fire or grazing regimes) arguably span both quadrants A and B (Figure 16). To elaborate on what is involved in each of the options, Prober et al. (2019) provided examples from the literature for 'Evade or Ameliorate' (Figure 17) and for 'Build Adaptive Capacity' (Figure 18). These examples show that options range from small-scale applications such as 'irrigate or provide water to enhance water availability' (1B in Figure 17) to options that can be scaled up such as 'sow seeds that are able to accrue in seedbanks until suitable conditions prevail' (3A in Figure 17), to options that are intended to operate at the landscape-scale such as 'protect, manage or renovate climate-resilient areas e.g. cooler parts of species' ranges, areas not prone to coastal inundation, climate refugia' (7C2 in Figure 18).

EVADE OR AMELIORATE: ADDRESS CHANGING CONDITIONS AND FUNCTIONS DIRECTLY	
A. 'Low-regrets', 'do anyway' options	**B. 'Climate-targeted' options**
1. Ameliorate rising temperatures, altered water availability or rising sea levels	
1A. *Ameliorate changing conditions by renovating degraded ecosystems* *renovate vegetation cover to reduce temperatures *renovate soil and landscape biophysical processes to optimize soil water capture in drying environments *remove artificial drainage or release water from other uses to increase water availability in drying environments *renovate coastal vegetation (e.g. mangroves) to increase sedimentation as sea-levels rise	1B. *Ameliorate changing conditions by engineering environments* *construct shade structures to reduce temperatures *install solar-powered sprinklers to cool animals *manage release of cold water from storage to reduce stream temperatures *irrigate or provide water to enhance water availability *thin trees to reduce ecosystem water requirements *install snow fences or manage forest density to slow snow-melt and regulate water supply *engineer topography to create moisture concentrations *engineer coastal barriers (including beach nourishment) or flood control systems to limit inundation
2. Adjust changing disturbance regimes to steer change in desired directions	
2A. *Manage changing fire or grazing regimes* *limit increasing frequency or extent of hot fires through suppression and fuel management *maintain low intensity fires to constrain shrub invasions where desired *manage changing vegetation-grazing interactions, e.g. suppress herbivore increases by managing habitat or re-introducing predators	2B. *Adjust changing disturbance regimes using physical or chemical interventions* *apply chemical controls or thin trees to ameliorate increases in pest and disease burdens *respond to problematic increases in native vertebrate herbivores directly through culling
3. Evade or alleviate deteriorating plant establishment conditions	
3A. *Evade or alleviate increasing establishment limitations using strategic planting or renovation tools* *plant seedlings to avoid vulnerable germination phase *use pre-conditioned seedlings in deep containers *create cool or moist planting micro-habitats (e.g. using mulches, water crystals, fog collectors or hollows) *sow seeds that are able to accrue in seedbanks until suitable conditions prevail *plant in high precipitation years or over multiple years *adjust planting season according to changing climate *coppice to rejuvenate mature plants and avoid vulnerable seedling phase	
4. Ameliorate loss of specific ecological functions	
4A. *Ameliorate loss of functions through active* in situ *selection of resilient functional species* *e.g. by using resilient local species expected to continue to provide key functions when undertaking plantings or other renovation efforts *e.g. by using appropriate disturbance regimes to favour such species *e.g. by preferentially retaining such species during routine thinning operations	4B1. *'Functional introductions' of non-local populations* *source germplasm from climatically-diverse populations of local species for renovation plantings *actively facilitate gene flow from adapted populations into natural populations (e.g. pollen introductions, transplants) to promote persistence of functions 4B2. *'Functional introductions' of non-local species* *plant other tree species to replace shade, tree hollows and other habitat values *introduce resprouting species to cope with increasing fire *introduce other species to maintain trophic interactions 4B3. *Engineered structures* *e.g. install tadpole rearing cups, artificial nest boxes, or burrow structures to replace loss of these services

Figure 17 Examples from the literature of tools or approaches used to implement each 'Evade or Ameliorate' option. Source: Prober et al. (2019)

BUILD ADAPTIVE CAPACITY: ENHANCE THE CAPACITY OF SPECIES, ECOSYSTEMS AND LANDSCAPES TO WITHSTAND OR RESPOND TO CHANGE

C. 'Low-regrets', 'do anyway' options	D. 'Climate-targeted' options
5. Promote *in situ* genetic adaptation of local native species	
5C. *Promote adaptation by promoting genetic diversity* * manage for large meta-population sizes, e.g. manage connectivity, conserve large areas, infill within populations * use genetically diverse germplasm for ecological renovation * apply variable management regimes to favour varied genotypes	5D. *Accelerate adaptation through genetic interventions* * introduce more diverse or adapted non-local germplasm * apply human assisted-evolution (e.g. genetic engineering or screening and culling of non-adapted genotypes) * manage hybridization processes * manage for short generation times to expedite adaptation, e.g. using short fire or harvest intervals
6. Insure against loss of species and functions	
6C1. *Promote site-scale redundancy through species, functional and structural diversity* * plant a diversity of local species for ecological renovation * promote diversity through management (e.g. fire regime, thinning operations in a forestry context) 6C2. *Build in spatial redundancy* * conserve, manage or renovate large areas * conserve, manage or renovate multiple sites * minimize further loss * create ex-situ populations, e.g. zoos/seedbanks 6C3. *Prepare for contingencies by enabling rapid response* * increase preparedness for response to harmful events such as crown fires, floods or cyclones	6D. *Promote site-scale redundancy in ecological functions by promoting diversity of non-local species* * include a diversity of non-local species in ecological renovation if local species unlikely to persist
7. Optimize current and future habitat availability	
7C1. *Protect, manage or renovate a full range of current and potential future habitats* * e.g. representative land facets * e.g. land for managed coastal realignment 7C2. *Facilitate species' persistence by targeting climate-resilient locations* * Protect, manage or renovate climate-resilient areas e.g. cooler parts of species' ranges, areas not prone to coastal inundation, climate refugia	
8. Assist dispersion to suitable habitats or isolate refugia	
8C1. *Manipulate landscape connectivity* * plant for connectivity (afforestation, renovation) * capture climate gradients in reserves * create ecological networks * reduce dissection by roads, engineer wildlife crossings * conserve leading-edge populations * maintain isolation to avoid unwanted incursions 8C2. *Promote local spatial heterogeneity* * protect, manage or renovate to ensure diverse environments are available within close range, e.g. diverse fire regimes or topographies	8D. *Assist species to reach and establish in projected suitable environments outside their current range* * actively assist dispersal and colonization
9. Alleviate non-climatic stressors	
9C1. *Control undesired exotic invasions* * apply site-focused measures such as nutrient limitation * use species-focused measures such as biological control 9C2. *Avoid or ameliorate anthropogenic degradation* * e.g. reduce salinization, erosion, stream sediments, pollutants or edge effects; re-introduce predators or other keystone species; renovate facilitative relationships (e.g. mycorrhizas to enhance plant nutrient and water uptake) * sustainably manage any ongoing utilization	9D. *Alleviate natural stressors to help highly valued species or ecosystems withstand climate stress* * alleviate natural disease, competitor or predator burdens * feed animals during normal feed gaps to offset reduced survival due to climate stress

Figure 18 Examples from the literature of tools or approaches used to implement each 'Build Adaptive capacity' option. Source: Prober et al. (2019)

5.1 What has Melbourne Water tried so far?

Comparing the vegetation management-related activities that Melbourne Water is already engaged in (Table 2) with examples in Figures 17 and 18, we can see that Melbourne Water is making use of a few options under both the 'Evade or Ameliorate' and 'Build Adaptive Capacity' strategies. For instance, with respect to 'Evade or Ameliorate', Melbourne Water:

- provides water to enhance water availability for planted seedlings (1B in Figure 17 *cf* E-2 and E-3, Table 2; Ephemeral and Terrestrial Plant Installation Standard)
- plants seedlings to avoid the vulnerable germination stage (3A in Figure 17 *cf* E-3, Table 2)
- has undertaken limited long-stem planting to evade or alleviate increasing establishment limitations using strategic planting or renovation tools (3A in Figure 17 *cf* E-5, Table 2)
- has explored using species modelling to attempt to identify resilient local species expected to continue to provide key functions when undertaking planting (4A in Figure 17 *cf* RE-6, Table 2; Nitschke 2022). Some of the modelling outputs are being translated into tools and guidance for vegetation managers (see PSG-10, Table 2 and Box 2)
- has explored how to identify climate-adjusted source material from climatically-diverse populations of local species for renovation plantings (4B1 in Figure 17 *cf* RE-7, Table 2; Greening Australia (2021)) (see also Section 5.2)

With respect to 'Build Adaptive Capacity' Melbourne Water:

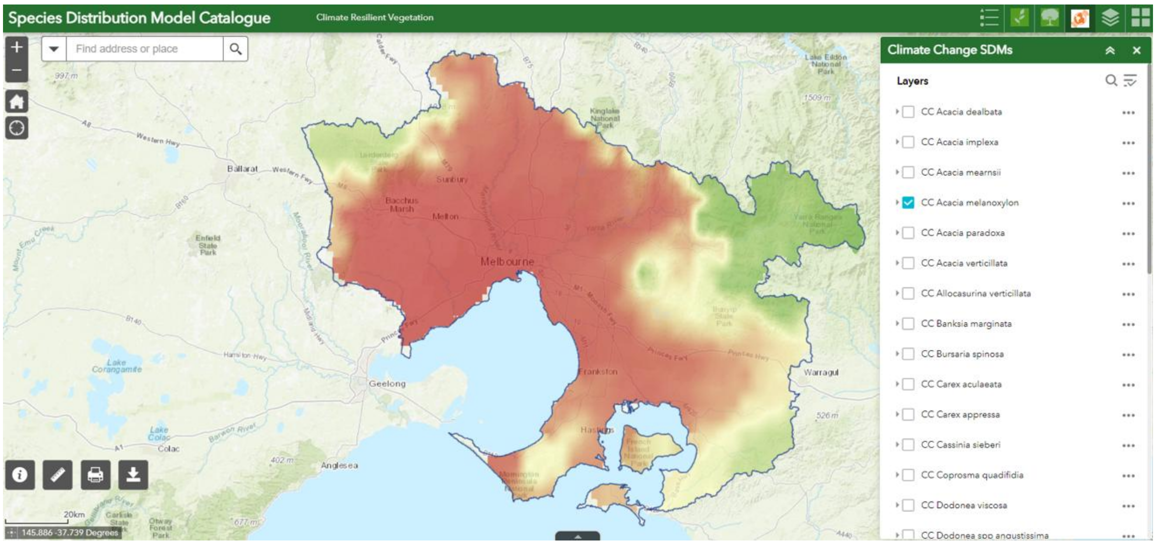
- practices planting a diversity of local species for ecological renovation (6C1 in Figure 18 *cf* E-1, Table 2; Melbourne Water Plant Selection and Provenance Standard)
- designs and plants for connectivity (8C1 in Figure 18 *cf* PSG-1 and PSG-2, Table 2)
- has invested in alleviating non-climatic stressors such as by controlling undesired exotic invasions in high-value native vegetation (9C1 in Figure 18 *cf* M-3, Table 2), and
- is exploring accelerating adaptation through genetic interventions such as via more diverse, climate-adapted, non-local provenancing of plant material (5D in Figure 18 *cf* RE-7, RE-8 and RE-9 Table 2; Greening Australia (2021)) (see also Section 5.2)

Box 2 Modelling the impacts of climate change on 31 key revegetation species

Nitschke (2022) modelled the impact of climate change on 31 native plant species that are commonly used by Melbourne Water in revegetation activities. Species presence data were collated from the Atlas of Living Australia. Pseudo-absence data were generated for each species, predictors were various bioclimatic variables and correlative models for individual species were developed using boosted regression trees. To make predictions for a climate-impacted future, Nitschke (2022) used projections from CSIRO's ACCESS 1.0 GCM under a high emissions scenario (RCP8.5) for 2090.

According to the correlative modelling, the 2090 predicted change in extent and severity of suitable habitat at the PPWP and southeast Australia scale resulted in a risk rating of 'High' or 'Very High' for most of the 31 species. For a small number of species such as *Eucalyptus viminalis* and *Eucalyptus ovata*, the risk rating was 'Extreme'.

Mapped predictions of 2090 habitat suitability for these 31 species is being made available to Melbourne Water staff to help inform the design and planning of revegetation projects. The example below shows 2090 predicted habitat suitability for *Acacia melanoxylon* across the PPWP region. Red shades denote Category 1: lower expected 2090 habitat suitability, consider adjusting species mix in favour of species with higher expected suitability. If using the selected species, use very careful plant placement to maximise favourable microclimate conditions. Yellow shades denote Category 2: higher uncertainty in species response to 2090 habitat suitability, consider adjust species proportions in favour of species with higher expected suitability. Green shades denote Category 3: high expected 2090 habitat suitability, use species as usual but monitor survivorship and health over time.



We note that the ‘quadrant C’ options (Figure 16) with respect to ‘Build Adaptive Capacity’ are options that have been found to dominate the literature (Prober et al. 2019) so it is not surprising that these are prominent in Melbourne Water’s vegetation management ‘toolbox’. An option like managing and restoring connectivity is ecologically sound and widely embraced because it benefits multiple ecological functions and processes and contributes directly to policy goals (Prober et al. (2015b) and below).

The history of land clearing and land use in the PPWP region means that native vegetation across the region is already highly impacted and fragmented. From this starting point of ecological degradation and deteriorating climate conditions, it is vital to protect remnant and extant native vegetation to maintain overall extent and to build upon this with revegetation gains that will contribute towards Healthy Waterway Strategy 2018 (Melbourne Water 2018) as well as state-wide Biodiversity 2037 area targets and connectivity goals. Restoring connectivity allows smaller populations to function as a larger population (a meta-population). It enhances resource and habitat availability, and facilitates movement, dispersal and gene flow. Improved resource and habitat availability supports persistence, access for movement and dispersal supports persistence as well as facilitating potential range shifts under changing climate conditions. Fragmentation and degradation can reduce genetic diversity and gene flow can mitigate against that by expanding genetic variation, reducing inbreeding, bolstering adaptive capacity and facilitating evolutionary responses to selection (Frankham 2005). Notwithstanding the many benefits of restoring connectivity, it is important to note that restored vegetation corridors can act as conduits for animal and plant pests, disease and fire.

Accelerating adaptation to climate change by introducing more diverse, future climate-adapted, non-local genetic material is a prominent intervention option in the literature (Broadhurst et al. 2015). It incorporates multiple ideas, requirements and considerations and we elaborate on these below.

5.2 Climate-adapted, climate-smart, climate-ready

Provenance is usually defined as the geographic place of origin of a population of seed or plants (Turnbull & Griffin 1986). Different provenances are assumed to reflect the distinct genetic variability found at different locations. Conventional practice has emphasised protecting and maintaining the genetic integrity of local indigenous floral populations ('local is best') on the understanding that local species provenances are geographically appropriate, well-adapted to local conditions and therefore provide replanted areas with the best chance of success under local conditions (see Melbourne Waters Ephemeral and Terrestrial Plant Selection and Provenance Standard). However, this does not take into account future climate impacts.

A concept that does, is climate-adapted provenancing (also called 'climate-smart' or 'climate-ready' provenancing). The underlying concept of climate-adapted provenancing is to "combine genetic diversity and adaptability, targeting projected climate change directions whilst allowing for uncertainty in projections as well as unforeseen selective agents" (Prober et al. 2015b). It banks on capturing genetic variation (in species) as a resource for climate adaptation and broader evolutionary potential and it requires some prediction of expected future climate conditions (and uncertainty) for targeting or 'climate-matching'.

To implement this rigorously, one would ideally have measures of genetic variation (of the candidate species) that are informative about adaptive potential and estimates of projected future climate conditions (plus uncertainty). These information demands have many different possible interpretations and can be resource-intensive to acquire. So, in practice, climate-adapted provenancing has been implemented to varying degrees of sophistication. For instance, with respect to genetic variation, some simply assume that different provenances reflect distinct and desirable levels of genetic variability without any genetic testing or analysis. However, if the source material is from a location that previously experienced a massive population contraction or population bottleneck, the material might have low levels of genetic diversity.

There is publicly available data on projected climate futures from many different climate models and some of it has been packaged into user-friendly tools for interactive use. Two relevant examples are Climate Change in Australia's 'Climate Analogues Explorer' and the Sydney Royal Botanic Garden's Restore & Renew 'Site Matching' tool. To use them, a user chooses settings for their purpose or design such as the locality to be revegetated, the emissions scenario of interest (e.g. moderate, RCP 4.5 or high, RCP 8.5) and a future time point of interest (e.g. 2050). The tools then identify, for the selected emission scenario and future timepoint, areas in the landscape that are analogues for future climate for the sites of interest. This information can then guide a user to locations or areas where they can source climate-adapted seeds or plants for use in revegetation.

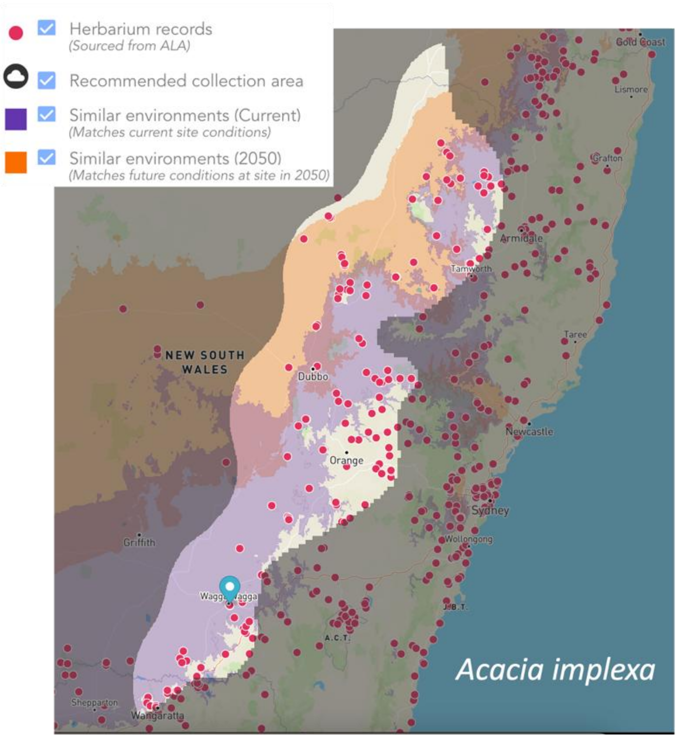
Auxiliary species occurrence data, modelling tools such as species distribution modelling and climate projection datasets provide additional opportunities to refine the climate-matching or targeting aspect of climate-adapted provenancing (e.g. Silva et al. 2025). But none of this gives us any useful information on genetic diversity and adaptive capacity. The Sydney Royal Botanic Garden's Restore & Renew framework and tool is an attempt to make empirical genetic provenance data accessible for implementing climate-adjusted provenancing (Rossetto et al. 2019). Over more than a decade, tens of thousands of samples from more than 125 native species commonly used in restoration across NSW have been collected and genetically tested to quantify genetic diversity. These data were used in modelling to delineate genetic provenances and so translate empirically-derived genetic data into guidance for practitioners on where to source genetically-appropriate, climate-adjusted material for revegetation (see example in Box 3). This is a valuable knowledge resource but unfortunately, this kind of detailed genetic data is not available for Victoria or most species commonly used in revegetation in the PPWP region.

Box 3 The Restore & Renew Webtool (Royal Botanic Garden, Sydney; Rosetto et al. 2019)

Practitioners specify the location of their restoration site and select from a dropdown list of species that may be suitable for the site. For each species, they can view a map showing:

- the current distribution of the selected species (herbarium records sourced from Atlas of Living Australia, red dots)
- the distribution of areas that match the current environment of the specified restoration site (in purple)
- the distribution of areas that match the modelled future (2050, moderate emissions scenario RCP 4.5) environment of the specified restoration site (in orange)
- the distribution of the recommended collection area—genetic provenance boundary (highlighted)

The example shown below for restoration site in Wagga Wagga (NSW) using *Acacia implexa* can guide the collection of genetically-appropriate, climate-adapted material for revegetation and seed production applications.



5.2.1 Proportional provenancing

An additional point of consideration in climate-adjusted provenancing is whether or how to implement proportional provenancing which is about what relative quantities of seed or plant material from each population provenance to use at the revegetation site. There is a great deal of variation in how proportional provenancing is discussed and interpreted in the literature, but the main approaches are eco-geographic distance, and multi-temporal climate-future choices. For instance, with respect to eco-geographic distance, Sgro et al. (2011) discussed it as local, intermediate, and long-distance sources based on a natural gene flow dispersal kernel that they described schematically using an exponential decay curve (Figure 19).

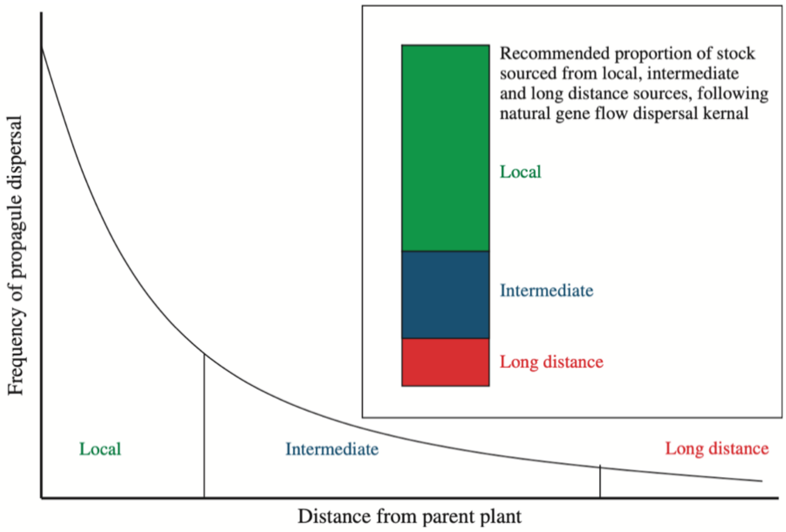


Figure 19 Schematic representation of proportional provenancing based on following a natural gene flow dispersal kernel that might be approximated by an exponential decay curve. Mimicking this implies sourcing the largest proportion of seed or plant material locally, followed by sourcing material from intermediate eco-geographic distance in moderate proportion and finally in the smallest proportion by long eco-geographic distance. Source: Sgro et al. (2011).

The multi-temporal climate-future approach involves targeting source areas that are analogous to the restoration site across multiple future time periods. Examples from the literature include the following recommendations or proposals:

- 50% from 'baseline climate', 25% from area matched to projected 2020s climate, 15% from area matched to projected 2050s climate and 10% from area matched to projected 2080s climate (Harrison et al. 2017)
- 70% local, 20% from hotter and drier climates (preferably 10% from a 2050 analogue location and 10% from a 2070/2090 analogue location) and 10% from a wetter, cooler climate (future time point not specified) (DELWP 2020)
- 60% local/baseline climate, 15-20% from areas matched to 2030-2050 projected climate, 15% from areas matched to 2070-2090 projected climate, 5-10% from 'wetter and cooler' (future time point not specified) (Greening Australia 2021)

These proposals are broadly consistent and reflect a sensible strategy of hedging. Nevertheless, there is no particular evidence attesting to the effectiveness of the nominated proportions for each timepoint or the 'wetter, cooler' climate location. Likewise, there is no specific evidence on whether these nominated proportions for provenancing are appropriate across different species, emissions scenarios and climate models (e.g. different candidate general circulation models and regional climate model) used for projections.

In view of the limited available empirical evidence, the judicious use and integration of research, monitoring, evaluation and review will be important for learning and guiding decision making (Figure

1). 'Climate Future Plots' are a tool that have been proposed to enable this research testing, monitoring, evaluation, and learning from climate-adapted plantings in the landscape. Box 4 describes a small-scale Climate Future Plot trial in the PPWP region.

Box 4 Climate Future Plot plantings in 2024

This project has established Climate Future Plots using climate-adjusted seed from 5 species from 4 provenances. It aims to assess plant survival, growth, reproduction and genetics of these species and their provenances. It is a collaboration between Melbourne Water, Dandenong, Knox and Maroondah City Councils with Federation University undertaking the vegetation monitoring, in consultation with the University of Melbourne, and Bunurong Land Council Aboriginal Corporation undertaking the site preparation and site management.

The species trialled were:

- *Eucalyptus ovata* (Swamp gum; tree)
- *Bursaria spinosa* (Prickly Bursaria; shrub)
- *Acacia melanoxylon* (Blackwood wattle; tree)
- *Melaleuca ericifolia* (Swamp paperbark; shrub)
- *Acacia dealbata* (Silver Wattle; tree)

Each of the 5 species were made up of 4 provenances from locations representing:

- current/local conditions (Warrandyte)
- 2050 hotter-drier conditions under a high emissions (RCP 8.5) scenario (Moama)
- 2090 hotter-drier conditions under a high emissions (RCP 8.5) scenario (Dubbo)
- cooler-wetter conditions (Inverloch)

Climate analogue locations were identified using Climate Change in Australia's 'Climate Analogues Explorer' tool. Plots were planted between June to August 2024, with Dandenong having three separate plots and Knox and Maroondah having one plot each. Each plot contained 16 "blocks", each of which contained 20 plants made up of a random species and provenance mix, making up a total of 320 plants in each plot.

Monitoring surveys were undertaken prior to planting from July to September 2023. Quadrats (3m x 3m) were placed in the top left corner of each planting "block". All species found in the quadrats were identified and recorded, including their abundance, percentage of foliage cover, status (native or introduced) and environmental weed risk rating. At the time of planting, all plants were measured for height (cm) and diameter (mm). In September 2024 post-establishment surveys were undertaken, whereby half the plants in each block were surveyed (ensuring equal species/provenance combinations were assessed) assessing their height, largest stem diameter at ground level, and number of stems per plant. Ground cover percentages were recorded for each quadrat, and the presence/absence of grazing animals recorded. These measurements will continue annually in spring for the next three years, and ideally longer depending on funding.

The results 3 months post-plant establishment showed good overall mean survival for all provenances, with over 95% survival for all species across all provenances. The exception to this was *Bursaria spinosa* which had a mean survival rate of 82.7% across all provenances.

6. Adaptation strategies and tactics for supporting vegetation resilience

The cross-referencing exercise in Section 5.1 highlighted two important practical points: i) Prober et al. (2019)'s high-level framing of the 23 intervention options is not directly linked or addressed to specific climate stressors and hazards, and ii) there are potentially additional valuable intervention options for supporting climate-resilient vegetation that Melbourne Water has yet to explore.

In Table 4 below, we map out some examples of vegetation vulnerabilities to climate stressors and hazards described in Section 3 and how intervention strategies, options, tools and approaches can be translated to adaptation strategies and tactics to support vegetation resilience. We also outline some of the actions that Melbourne Water are undertaking, or if these actions are not currently being implemented (Table 4).

Table 4 Summary of climate change vulnerabilities, adaptation strategies, and adaptation tactics for supporting the resilience of forest and grassland ecosystems. The last column outlines if Melbourne Water have undertaken these actions.

Vulnerability to climate change	Adaptation strategy	Adaptation tactic	Example Melbourne Water actions
		Temperature, rainfall and droughts	
Vegetation will be subject to higher temperatures, more frequent, intense and longer heatwaves (Section 3.1). Mean annual rainfall is expected to be lower, particularly cool season (winter/spring) rainfall (Section 3.2)	Monitor and detect change in seedling survival, species composition, and mortality of mature trees	• Install and analyse vegetation and revegetation plots to track important demographic and condition measures over time, targeting areas where changes are expected (e.g., Yarra Ranges, Dandenong Ranges and Werribee area)	• Vegetation Visions and Detailed Vegetation monitoring to track vegetation condition change (Dell 2020)
		• Use existing field monitoring such as ROMP and Vegetation Visions/Detailed Vegetation monitoring data to detect change in plant establishment and survival (Foley-Congdon et al. 2024)	• Restoration Outcomes Monitoring Protocol (ROMP) to assess revegetation outcomes (Jellinek et al. 2022a), and Vegetation Visions and Detailed Vegetation monitoring (Dell 2020)
		• Use remote sensing technologies (e.g., Sentinel-2, LiDAR, Nearmap) to detect change in vegetation extent and condition over large areas (Hislop et al. 2025)	• Sentinel-2/ Landsat monitoring to detect large-scale changes in condition and extent • Exploring Nearmap AI data pack products to assess vegetation extent change over time
		• Model the predicted impact of climate change on plant species and vegetation communities using mechanistic and/or correlative modelling (Nitschke 2022)	• Climate risks to revegetation species modelling (Nitschke 2022)
Increased vegetation drought stress and decreased woodland, forest and grassland	Increase resilience in forests, woodlands and grasslands	• Consider thinning dense forest stands or dense revegetated areas, and/or plant lower densities of large tree species in water constrained environments (Keenan 2015)	• Thinning not undertaken at Melbourne Water but undertaken by councils and other agencies

persistence, especially at lower elevations		• Plant a diversity of native vegetation species during revegetation projects. This could include for instance, selecting and planting a mix of revegetation species that are drought 'escapers', 'avoiders' or 'tolerators'.	• Low-moderate planting diversity with no explicit consideration of plant traits relating to drought resilience
		• Use prescribed burns and cultural burning to reduce stand densities and drought stress, and facilitate new growth (Morgan et al. 2020)	• Undertaken to a degree by the Narrap Rangers and other Traditional Owner groups
		• Increase the use of native plants that are early successional species in revegetation projects to promote species diversity and allow later successional species to establish via revegetation or natural succession. This could promote greater resilience of different species and lifeforms to drier conditions (McClain et al. 2011)	• Not undertaken but could be implemented with longer-term funding which allows for the procurement of species for a site across years
		• Consider staged plantings over multiple years, first establishing an overstory (where appropriate) before planting small shrubs and grasses (McClain et al. 2011)	• While funding cycles do not generally allow staged plantings, longer term projects could trial this
		• Track if dieback is occurring within the PPWP region through field surveys and remote sensing	• Not undertaken (though there is interest to do so)
	Protect genotypic and phenotypic diversity of species with different drought strategies (e.g. drought tolerance, drought avoidance and drought escape)	• Identify individual or groups of trees and shrubs in the landscape that appear to be more resilient to times of low water stress/high temperatures and collect seed from them for future regeneration projects (Gibson-Roy et al. 2021). This would also require keeping good records of mother trees	• Not undertaken but links with nurseries and Melbourne Water works teams could be used to identify populations to collect from

		• Work with nurseries to ensure information on provenancing and genetic information is collected and stored on an online database. This would allow greater knowledge about the plant species and provenances available (Gibson-Roy et al. 2021)	• Some provenance data is collected but not consistently. Melbourne Water could drive this with the Victoria State Government
		• Develop seed orchards that contain a broad range of native plant species and climate-adjusted genotypes (Halofsky & Peterson 2016)	• Seed orchards have been proposed on Melbourne Water-owned land such as at the Western Treatment Plant
		• Undertake genetic testing of commonly revegetated plant species to test their genetic differences and inform provenancing strategies (Rossetto et al. 2019)	• Very limited genetic testing of plant species - just provenances of River Red Gum, *Eucalyptus camaldulensis* (Miller & Ahrens 2025)
		• Plant a broad range of native plant species (such as drought 'escapers', 'avoiders' or 'tolerators') and climate-adjusted genotypes in revegetated and remnant areas to increase resilience to climate change	• Climate Future Plot plantings underway (Box 4). Similar plantings in the western regions of the PPWP area would be beneficial
	Focus on maintaining ecosystem functions and processes even if it involves non-local species	• Trial the use of non-local plant species to fill functional gaps	• Not undertaken. Would require trials and consultation with Traditional Owner Groups
Increased temperatures and lower cool season rainfall will limit plant restoration effectiveness	Revegetate with climate resilient native plant species	• Consider mixing climate-adjusted provenances from hotter and drier (and a small proportion from wetter and cooler) locations with local seed (Prober et al. 2015a; Jellinek & Bailey 2020)	• Climate Future Plot plantings underway (Box 4)
		• Use plant traits to guide climate-resilient plant selection for restoration taking into account future climate stressors and hazards	• Under active research in 'Trait-based approaches to understanding plant

			performance and resilience to climate impacts' (Chu et al. *In prep*)
	Alter management strategies to increase revegetation effectiveness	• Alter planting timing over the winter/spring months to ensure planting occurs when sustained rainfall is most likely (Hagger et al. 2018)	• This already occurs, planting is undertaken in late autumn/winter
		• Consider not planting or reducing planting over drought/low rainfall years	• Not currently undertaken due to funding cycles, but could be implemented if funding rules are more flexible
		• Consider watering plants during and after planting and over sustained dry periods	• Already specified in Melbourne Water Ephemeral and Terrestrial Plant Installation Standard
		• Consider the use of long-stemming - growing plants in pots for 10-18 months and then planting these longer stemmed plants deeper into the soil so they have greater access to soil moisture (only possible for some trees/shrubs) (Australian Plants Society 2010)	• Attempted in 7 kms within a Plenty-Chandler reach in 2011/2012. No systematic monitoring or report of long-stem planting outcomes
		• Reduce the impact of weeds and pest animals on plant species	• For the first 3 years and often afterwards via on-going maintenance
		• Consider trialling different guard types (e.g., cartons, deer guards, plastic, etc.) and planting methods (e.g., ripping, mounding, direct seeding, etc.) to maintain soil moisture	• Some different guard types have been trialled and some direct seeding projects have been undertaken (Ede 2020; Greet et al. 2020) but the technique is not widely used
		• Select sites and species mixes where direct seeding could be undertaken	• See direct seeding guidelines (Ede 2020; Greet et al. 2020)
Fire weather			
Increased fire weather, ignition risk and fire activity which can		• Incorporate climate change into fire management plans	• Yes

mean increased fire frequency, area burnt and fire severity (Section 3.3). Reduced fire return intervals could mean more areas in recently burned or early-successional stages	Plan and prepare for greater areas effected by fire	• Plan post-fire response for large fires	• Not known if undertaken
		• Anticipate more opportunities to use burning to facilitate transition from weedy to more native states (Paynter & Flanagan 2004)	• Not undertaken
	Increase resilience of existing vegetation by reducing hazardous fuels and forest density	• Thin and use prescribed burns to reduce hazardous fuels in the urban-forest interface	• Not undertaken
		• Use natural regeneration and planting of native species to influence forest structure	• Yes
Floods			
Increased flood frequency and intensity, erosive flows, flashy flows, shear stress and loss of restored areas	Experiment with and properly evaluate different strategies to increase vegetation resilience to flooding	• Reduce planting along flood zones/riparian areas over predicted wetter months/years	• Not undertaken, although flood risk is taken into consideration when planting
Compound events			
Increased warming, drought and fire will reduce plant vigour and increase susceptibility to insects and pathogens	Increase resilience of forest stands to disturbance by increasing tree vigour	• Thin to accelerate development of late-successional forest conditions (Halofsky & Peterson 2016)	• Not undertaken, although thinning is used by councils and other organisations
		• Increase stand-scale biodiversity and minimise monocultures through planting a diversity of species (Halofsky & Peterson 2016)	• Yes, multiple species are used in revegetation projects
	Increase forest landscape resilience to large and extensive insect or pathogen outbreaks	• Plant insect/pathogen resistant species or genotypes where species-specific insects or pathogens are a concern	• Not undertaken and in many instances this information is not available
Following compound event disturbances, increased		• Implement early detection/rapid response for exotic species treatment	• Yes, exotic species are detected and managed

opportunity for exotic species establishment within forest areas	Increase exotic species control efforts	• Consider managing weeds past the 3 years post plant establishment	• Already part of Melbourne Water practice, large scale projects should have ongoing maintenance.
		• Reduce management practices (e.g., movement of vehicles) that encourage the spread of non-native species or pathogens like cinnamon fungus (*Phytophthora cinnomomii*)	• Chemical controls (e.g. phytoclean) are used on vehicles to reduce the spread of disease and weeds at some Melbourne Water sites
	Prevent exotic plants from establishing after disturbances	• Include exotic species prevention strategies in all projects, such as carrying out surveys of disturbed areas and remove/control environmental weeds if detected	• Weed control undertaken on all revegetation projects to 3 years, including post disturbances
	Increase resilience by promoting native genotypes and adapted genotypes of native species	• Consider assisted migration of key species or species that are threatened or endangered	• Not undertaken
		• Use species habitat suitability modelling to inform species selection for restoration taking into account projected future climate conditions, ideally for a range of emission scenarios	• Some guidance available from climate risk to revegetation species modelling by Nitschke (2022).
		• Use plant traits to guide climate-resilience plant selection for restoration taking into account future climate stressors and hazards	• Some guidance available from research into trait-based approaches to understanding plant performance and climate-resilient strategies (Chu et al. *In prep*)
		• Plant genetically adapted species from appropriate hotter and drier provenances	• Climate Future Plot plantings underway (Box 4)

7. Recommendations

7.1 'No regrets' intervention options

Climate-resilience intervention options in this category include options in Melbourne Water's toolkit that are already in regular use:

A) increase extent and maintain/improve condition of native vegetation
B) plan for connectivity of native vegetation patches/assets (includes strategic land acquisition and strategic retention of properties, see PSG-1 in Table 2)
C) purposeful on-ground monitoring for ongoing learning and adaptation (e.g. ROMP, climate future plots) and condition tracking (e.g. Vegetation Visions) (Foley-Congdon et al. 2024)
D) landscape-scale, remote-sensing monitoring for understanding vegetation extent, anomaly and change detection (Hislop et al. 2025)
E) ongoing and where possible, long-term management of weeds and pest animals
F) hygiene protocols to reduce the spread of weeds and pathogens
G) manage revegetation risks by
    i) adhering to Ephemeral and Terrestrial Plant Supply Standard and ensuring good quality seed or plant materials
    ii) hedging by using a diverse mix of species and consider adjusting overall species mix in favour of species with higher predicted habitat suitability for sites in question (where this information is available, e.g. Nitschke (2022))
    iii) use very careful plant placement (e.g. higher soil moisture, sheltered areas) and adhere to Ephemeral and Terrestrial Plant Installation Standard
    iv) altering timing of revegetation activities depending on seasonal conditions
    v) considering staged plantings

7.2 Next-step intervention options

The climate-resilient intervention options in this category are potentially valuable additions to Melbourne Water's toolkit but there are knowledge requirements and/or dependencies that need to be addressed before these can be put into use and practice (Table 5).

Table 5 Potential climate-resilient intervention options and their corresponding knowledge requirements and/or dependencies that need to be addressed before they can be put into use.

Intervention option	Requirements/Dependencies
Update guidance on plant species selection for revegetation	• Knowledge and evidence base about species likely to fare better under the range of anticipated climate impacts (e.g. knowledge about traits such as resprouting ability, hydraulic vulnerability) • Policy regarding use of non-local, non-EVC compliant species • Consultation and involvement of Indigenous stakeholders regarding use of non-local species and species selection (e.g. 'Authorising environment to Care for Country' – see Shields et al. (2025)) • Purposeful monitoring to learn, adapt and improve plant selection outcomes

Update guidance on plant provenancing for revegetation	• Knowledge and evidence base about climate-adapted provenancing • Training on how to undertake climate-adapted provenancing (e.g. understanding emission scenarios of interest, identifying 'climate-matched' locations at target future time points, genetic considerations etc) • Knowledge and evidence base on genetic data of seed or plant material supplies • Logistics of procuring genetically-appropriate seed or plant materials at required scale of operations • Protocols for documenting climate-adapted provenancing at revegetation projects • Consultation and involvement of Indigenous stakeholders regarding use of non-local seeds/plant material (e.g. 'Authorising environment to Care for Country' – see Shields et al. (2025)) • Purposeful monitoring to learn, adapt and improve plant provenancing practices and desired outcomes
Update guidance on plant supply and installation for revegetation	• Knowledge and evidence base about innovative techniques such as long-stem planting and direct seeding • Logistics of obtaining/producing plant materials at required scale of operations • Quality assurance of required plant materials • Purposeful monitoring to learn, adapt and improve on the outcomes of innovative techniques • Consultation and involvement of Indigenous stakeholders regarding where and how to revegetate
Update guidance to enable flexibility in timing of revegetation planting	• Reliable projections of unfavourable dry conditions, or favourable/unfavourable wet conditions that affect expected seed/plant survival and establishment • Governance and policy that explicitly allows for flexibility to adapt to greater variability in climate conditions. For instance, rigid targets for vegetation establishment might conflict with prudent management options such as reduced planting in predicted dry years. Extended drought might result in multiple years of reduced planting and underspend and look like 'failure' to implement management actions and meet targets
Update guidance on the management of invasive non-local and introduced weeds and pest animals	• Consultation and involvement of Indigenous stakeholders regarding cultural burning to heal country • Protocols for managing species that are/becoming invasive
Update guidance on assessing existing	• Reliable detection of sustained adverse changes in remnant vegetation communities (e.g., dieback) across the PPWP region

(remnant) vegetation communities throughout PPWP region	• Reliable diagnosis of the causes of these adverse changes in remnant vegetation communities • Development and testing of methods to effectively address the symptoms and causes of adverse changes in remnant vegetation communities • Investigate policy improvements in relation to Melbourne Water projects impacting native vegetation on Melbourne Water-owned land. In the event that native vegetation is damaged/impacted/cleared in the course of project implementation, as well as adhering to state legislation on net gain policy, ensure vegetation improvement works on Melbourne Water land (preferably project site) satisfies long-term no net loss on Melbourne Water-owned land. For instance, clearing of 1000 m^2 for a project, might be compensated for by revegetating 4000 m^2 on site (if opportunities exist, or equivalent land management activity). Opportunities exist readily on Melbourne Water Sites of Biodiversity Significance (SOBS) sites

MWRPP project W13 'Approaches to increasing the resilience of vegetation to climate change' is making a start at addressing the knowledge and evidence base for species likely to fare better under the range of anticipated climate impacts. This research will use a trait-based approach to provide a more mechanistic understanding of plant performance and plant climate resilient strategies for different stressors (Chu et al. *In prep*). This research will synthesise ecological theory, and past studies to identify climate-resilient plant strategies (e.g. to drought). It will then identify traits related to climate-resilient plant strategies (e.g. drought escape, avoidance, and tolerance). For traits that are difficult to measure, we will also identify appropriate proxy traits (e.g. vessel diameter and wood density as proxies for hydraulic vulnerability/cavitation resistance). We will then develop and populate (to the greatest extent possible using open data) a database of climate-resilience relevant traits for species of interest to Melbourne Water (e.g. species of conservation interest and species used in revegetation). This database will serve as a foundational knowledge resource and tool for vegetation management. Populating it will also provide a better understanding of any important gaps in knowledge relating to plant climate-resilience traits, and a basis for prioritising knowledge acquisition. Ultimately, these knowledge elements could be developed into a practical, trait-based decision-support tool to guide species management and selection for conservation and restoration plantings, with users supplying site locations and receiving species recommendations and trait profiles, or nominating species and receiving suitable site profiles matched to locations across the PPWP region.

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