

Garnaut Climate Change Review

Biodiversity and climate change

Prepared by

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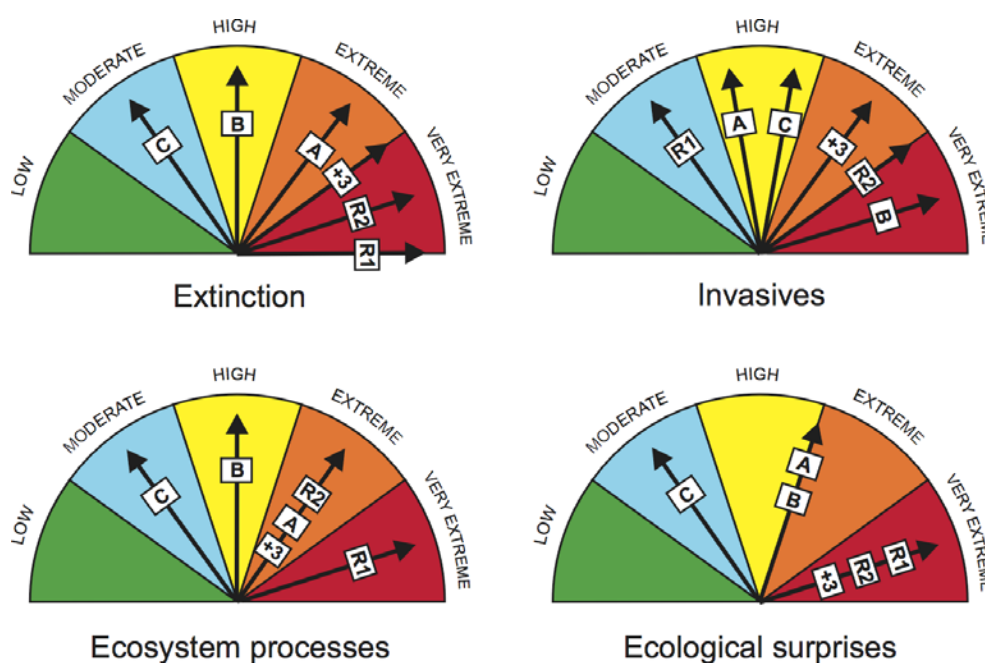
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1 Summary

- **Biodiversity** comprises the variety of living things and systems of which they are part, within species, populations, individuals, and genes, and across habitats, ecosystems, landscapes and bioregions. Biodiversity also incorporates key ecological processes, such as primary production and biogeochemical dynamics
- **Climate change** is adversely affecting all aspects of species' biology. Many species will be unable to adapt to climate change or to migrate to new areas. Loss of diversity and the formation of novel assemblages will drastically alter ecological processes. Climate change is exacerbating the deleterious effects of other human-induced environmental effects (e.g. land and vegetation degradation, over-harvesting of water)
- There are six climate scenarios: **R1** +4.5 °C mean temperature, -25% water availability; **R2** +4.5 °C, +15%; **A** +1 °C, -25%; **B** +1 °C, +15%; **C** +0.55 °C, -7%; and **'+3'** +3 °C, -7%. Anticipated effects of these scenarios on general 'currencies' of biodiversity effects (**extinction, invasive species, ecosystem processes and ecological surprises**) are shown below, where ratings to the 'VERY EXTREME' ends of the dials are most adverse



- Key steps to ameliorate these effects include
 - Broad-scale native revegetation including biolinks
 - Restitution of substantial amounts of water to natural ecosystems
 - Reduction of over-engineering and over-management of ecosystems to restore natural variability and disturbance regimes

2 What is biodiversity?

Biodiversity comprises the variety of living things and the systems of which they are part, within species, populations, individuals, and genes and across habitats, ecosystems, landscapes and bioregions. Importantly, it includes the complex network of interactions in and across these different levels of biological organisation, as well as their origins and evolution. Maintenance of biodiversity is fundamental to us and is critical to ecological and economic sustainability and to maintaining and improving the quality of our lives.

This view for biodiversity incorporates key ecological processes, including primary production, biogeochemical cycles (especially involving carbon and nitrogen), spatial dynamics of individuals and populations, and interactions among species (e.g. pollination, predation, mutualisms). Maintenance of biodiversity depends on sufficient genetic diversity in populations to sustain the on-going processes of adaptive evolution.

3 The biological context for climate change

Natural biological systems in Australia have been dramatically altered by human actions, particularly since European settlement. As a consequence, *climate change is not acting on a 'clean slate' in relation to biodiversity*. The added stresses from climate change will exacerbate existing environmental problems, such as widespread loss of native vegetation, over-harvesting of water and reduction of water quality, isolation of habitats and ecosystems that formerly interacted strongly and frequently (e.g. loss of the connectedness caused by flooding of floodplains), and the influence of introduced species (stock, pests, pathogens, and weeds).

Second, *climate scenarios will not play out evenly across the continent*. Regions will experience different biodiversity outcomes with distinctive and inequitable consequences for different parts of Australia. Some scenarios suggest that southern Australia, already massively altered and degraded ecologically, will be harder hit by climate change than northern Australia, causing potentially dire synergistic effects on the plants and animals of the south. Most of the climate scenarios for Australia indicate that southern and central Australia will become drier on average, whereas northern Australia may become wetter. This means that adapting to climate change will require two entirely different sets of measures dependent on location.

Elevated concentrations of CO₂ and other greenhouse gases will have both direct and indirect effects on biological systems. Systematic effects will reduce snowfall relative to rainfall and increase frequency of extensive forest fires. As temperatures rise, differences between land and water temperatures will increase resulting in greater storm frequencies and intensities and produce more southerly cyclones. Thermal increases will lead to greater water stress on land due to higher evaporation and evapotranspiration.

For biological systems, climate changes will affect: (1) physiology (individual organisms), (2) timing of life-cycles (phenology), (3) demographic processes, such as birth and death rates (population processes), (4) shifts and changes in distribution (dispersal, and shifts in geographic range), and (5) potential for adaptation (rapid evolutionary change). These effects on individual organisms and populations cascade into changes in interaction networks among species, including predator-prey, host-parasite, mutualistic (e.g. pollination) and competitive relationships. These changes in interaction networks further heighten extinction rates and geographic range shifts. The ultimate outcomes are expected to be declines in biodiversity favouring weed and pest species (a few native, most introduced) at the expense of the rich variety that occurred naturally.

4 How might species respond to climate change: Stay, move or die-out

Organisms will respond to climate change in one of three ways. **Stay** where they are because they can tolerate the changes or adapt to change through evolution. **Move** to more suitable habitat if possible. **Die-out**—species may dwindle in numbers *in situ* and ultimately go to extinction. Changes in species distributions and shifts in timing of reproduction and migration in response to climate change could arise in two ways. First, organisms may change within their own lifetimes without undergoing genetic change (phenotypic plasticity). Second, organisms may adapt, where genetic change (i.e. evolution) occurs in response to climate change.

The capacity of plants and animals to respond to environmental change rests primarily with genetic diversity. The speed of any adaptive evolutionary change will be critical to organisms' responses to rapid climate change: plastic responses will be insufficient because they are not inherited. However, heritable adaptation (evolution) may not be an option for many species, particularly those already under threat. Species with characteristics including restricted distributions, small population sizes and long generation times have limited capacity to adapt to rapid climate change.

5 Staying: impacts on individual organisms (physiology and behaviour)

As a plant or animal's environment changes, a possible response is to adjust physiologically or behaviourally. Species differ in their range of tolerance of environmental conditions. Seasonal patterns of growth, migration, and reproduction are often driven by physiological mechanisms that are sensitive to environmental cues.

Climate change will alter the rhythms of growth and reproduction in plants and animals because these are synchronised to thresholds of temperature, rainfall and day-length. Alterations in rainfall under climate change are likely to have a greater effect than temperature on the timing of the growing season because Australian plants are adapted to highly variable rainfall.

Successful plant recruitment depends on suitable environmental conditions within the lifespan of a species. Recruitment success will differ among species, with arid species favoured under drying climates and more mesic species favoured under wetter conditions. Recruitment in the iconic river red gum (*Eucalyptus camaldulensis*) is rare under the current dry period and is depressed further by grazing and lack of flooding. Extensive death of mature trees indicates the entire ecosystem will not survive the continued dry conditions with concurrent lack of recruitment.

Changes in timing and distribution of river flows will have major effects on freshwater and riverine biota. Australia has the world's most highly variable running and standing water environments. Freshwater systems are highly dependent on both quantity and timing of flow within and among years. Within-year changes in timing of rainfall events and distribution of rainfall will affect life cycles of aquatic plants and animals. Changes in aquatic biota will be driven largely by changes in the magnitude and duration of maximum temperatures and changes in the patterns of stream and wetland drying. Many native (and introduced) species of fish have specific thermal tolerances for survival and initiation of breeding. Cool-adapted species, such as the exotic brown and rainbow trout, are unlikely to survive as the basis of recreational fisheries on mainland Australia, except in some high altitude areas.

Amphibians and reptiles are especially sensitive to climate change because of their dependence on water availability and temperature. Pronounced drying in south-eastern Australia since the mid-1990s along with over-extraction of water for domestic and agricultural use has led to widespread loss of breeding habitats for frogs. Temporary pools and ponds used for breeding have higher water temperatures and dry more rapidly, allowing few tadpoles to mature. Most reptiles are directly dependent on external temperatures, which may make them more active under increasing predicted temperature regimes, exposing them to greater predation and energy deficits. The sex of many reptiles is determined by thermal environment during development, and severe gender imbalances may arise.

Many terrestrial bird species that formerly migrated to avoid severe winter conditions now are year-round residents, increasing competition for resources, particularly food. This may perturb ecological relationships with non-migratory species, causing declines. Seabirds will be affected by climate change because as sea levels rise, nesting habitats will be lost and changes in food resources will lead to changes in reproduction.

Large declines of kelp forests in Tasmania have occurred over the last 50 years and have been attributed to sea temperature rise. Deterioration of coastal upwelling and interruption of nutrient-rich, subantarctic waters along Tasmania's east coast have occurred with weakening of westerly winds. This has the potential to further reduce photosynthetic capacity of kelp forests and reduce their viability. Many plants and animals of the coastal shores will be adversely affected by more extreme climate events, and episodes of die-back of seagrass beds will become more frequent. Increased frequency of days over the critical threshold for coral bleaching will lead to widespread bleaching and impaired recovery of coral symbiosis.

Climate change is likely to be most detrimental to species already under threat or declining because these species have evolved relatively specialised characteristics, such as narrow physiological tolerances, limited behavioural plasticity and often narrow food ranges.

6 Moving: dispersal and shifts in geographic range

Many plant and animal species depend on wide dispersal of individuals for both demographic processes and for interchange of genes to avoid inbreeding effects (e.g. young seeking new areas and mates, pollen and seed dispersal). Over large areas and long times, many species will respond and have responded to climate change by moving, resulting in geographic range shifts. However, some species will be unable to move as a consequence of their biology and/or environmental constraints. For these species, their geographic ranges will contract, heightening the risk of extinction.

Earth's climate has changed dramatically in the past, but rarely if ever as fast as the speed of current climate change. Plants and animals have responded by moving to new areas with suitable environmental conditions. In many cases, this is no longer possible due to massive, human-wrought changes in landscapes.

For terrestrial animals, climate projections suggest that many species will be negatively affected by thermal changes. For example, in one study more than 60 butterfly species are expected to decrease significantly in geographic range, with as little as 20% of climatically suitable area remaining under some scenarios. In the northern hemisphere, distributions of mobile animals are shifting polewards and to higher elevations. While also evident in Australia, these options are more limited because Australia lacks high mountain ranges and has little land further south than 40 °S, so effects are likely to be more severe. Two species of flying foxes have had significant southward range shifts, one of which (grey-headed flying fox, *Pteropus poliocephalus*) has retreated from its northern limit by 750 km since the 1930s.

Warming is likely to promote expansion of existing invasive freshwater species, such as mosquito fish (*Gambusia holbrooki*) and weather loach (*Misgurnus anguillicaudatus*). Native species such as the spangled perch (*Leiopotherapon unicolor*) may extend their ranges southwards. Warmer climate is likely to facilitate invasion in the south by disease-carrying mosquitos, with increased incidence of Ross River virus, Murray Valley encephalitis and Dengue fever. There are significant risks to freshwater ecosystems from warm water invasive plants including lippia (*Phyla canescens*).

Productivity of phytoplankton underlies marine food webs so effects of climate change on phytoplankton will affect abundance and distribution of a range of marine organisms. Increases in sea surface temperature combined with the strengthening southern flow of the East Australian Current will drive many tropical phytoplankton, zooplankton, seagrass and mangrove species southwards. Temperate species will retreat southwards, and in some cases, be lost due to lack of suitable conditions. The dangerous box jelly (*Chironex fleckerii*) causes problems for bathers and is likely to expand its range further south, and may occur earlier in the year, as oceans warm.

As Australian life forms shift their distributions with climate change, tropical and sub-tropical species will claim large areas of the south and higher elevation regions. Species-specific tolerances to changing climatic conditions will lead to range shifts at different rates and with differing degrees of success. Given that entire assemblages will not 'migrate' together, novel assemblages will form that have no current analogues, with unpredictable consequences.

7 Dying-out: extinction of native biodiversity

Many species will not be able to migrate or adapt to climate change because they lack suitable habitat to move into, have limited or impeded mobility or do not possess sufficient and necessary genetic diversity to adapt. These species are at the greatest risk of dying-out. Extinction risk under climate change scenarios will be highest for those species with restricted distributions, small population size and long generation times, and those already under threat or in decline. 'Hotspots' of biodiversity and endemism (species found nowhere else) in Australia, south-west Western Australia, the Wet Tropics of Far North Queensland, and the alpine region of south-eastern Australia, will be severely affected by climate change.

Australia's high-altitude species are particularly at risk. These species are already at their range limits due to the low relief of Australia's mountains, and lack suitable habitat to which to migrate. For example, a 1 °C temperature rise will eliminate 100% of the mountain pygmy possum's (*Burramys parvus*) habitat. This species cannot move to higher mountains because such mountains do not exist, and will not be able to stay where it is because it does not have the capacity to adapt to warmer temperatures. Aquatic fauna restricted to high altitudes will become less abundant, with some species facing extinction. Groups particularly at risk include freshwater crustaceans and some temperate fish. Hotspots of fish endemism in the highlands of Tasmania and in south-western Australia are likely to be particularly vulnerable to extinction with increased temperatures. The Wet Tropics of Far North Queensland will face high levels of extinctions. A 2°C rise in average temperatures will force all endemic (i.e. unique to the region) Australian tropical rainforest vertebrates to extinction. Many of Australia's plant species will be similarly affected.

The risk of extinction that climate change poses to Australia's biodiversity cannot be over-stated. The lack of extensive pole-ward land in Australia (compared with the northern hemisphere and South America) and the continent's generally low relief have profound implications for species adapted to temperate and cooler climates. There are few geographic refuges available for such species, and the potential for large numbers of extinctions is high.

8 Interactions among species and changes in assemblage composition

Many interactions among species have evolved over thousands of years, and there will be profound disturbances to these relationships. For example, suitability of leaves as food for herbivores (insects and mammals, including the koala, *Phascolarctos cinereus*) is likely to be affected directly by increasing CO₂ concentrations. Leaves will be more difficult for herbivores to digest (i.e. easier for plants to defend themselves), which in turn will reduce growth rates, individual sizes, reproduction and population sizes of herbivores. Plant protein contents typically are lower under elevated CO₂ concentrations. The cascading effects are potentially dire: many birds depend on foliage-eating invertebrates for food, so reductions in invertebrates will flow-on to greater mortality, lower reproductive output, and reduced population sizes of such birds. Native ecosystems rely on the timely provision of resources (e.g. leaves, nectar, pollen) from terrestrial plants. In recent decades, plants have been observed to shoot and flower at different times of the year leading to disruption of timing between herbivore and host plant, and pollinators and plants.

Although the current distribution of plant species is broadly controlled by climate, plants generally are restricted at the edge of their distributions by competition, soils and disturbance (e.g. fire). While plant species may be able to physiologically tolerate new climates, species with broader environmental tolerances will dominate. Animal species differ greatly in the range of ecological resources (e.g. food types) they use. Assemblages usually consist of a mix of generalist species, with broad tolerances, and specialists, with relatively narrow resource use. Extinction of more specialised species across broad areas is likely, and would disproportionately reduce biodiversity and lead to large areas occupied by similar sets of generalised species.

Interactions between freshwater and marine environments will be strongly influenced by changes in sea level and changes in patterns of rainfall. Alterations to the balance between marine and freshwater influence will affect estuaries, coastal lakes, wetlands and mangroves, which are characterised by high levels of endemism. In the south-east, reduced rainfall together with sea level rise will exacerbate the ongoing salinisation of coastal lake and estuarine systems, leading to a much-altered species mix.

Phytoplankton distributions are likely to change in response to increases in sea surface temperatures. Declines in phytoplankton production in the southern Coral Sea and northern Tasman Sea may reduce productivity of fisheries, especially in conjunction with existing fishery pressures (e.g. long-line fishing). Lower abundances of zooplankton resulting from reduced phytoplankton abundance may cause an increased incidence of jellyfish blooms that could have dramatic effects on higher food-web levels and humans.

Novel combinations of species and altered 'balance' in assemblages of plants and animals are among the most complex and unpredictable outcomes of climate change. Removal of single species can have drastic effects on the functioning of an ecosystem. Loss or reduction of predators can allow species, such as sea urchins, to defoliate stressed kelp forests. This may cause collapses or shifts to a degraded state of much-reduced biodiversity. On Australia's Christmas Island, structure and native biodiversity of its unique rainforest is threatened following decimation of a 'keystone' native land crab by just one introduced ant species. This sent an unforeseen 'shockwave' through the ecosystem, slowing litter decomposition, spawning insect outbreaks and tree deaths and threatening endemic birds.

9 Ecosystem processes

Altered physiologies under climate change will lead to new rates of resource production and use. As species alter their behaviour and interactions in response to climate change, the flow of energy and nutrients through food webs will change. With loss of diversity and the formation of novel assemblages, these changes will drastically alter fundamental ecological processes, such as carbon storage and nitrogen dynamics.

Australian soils have diverse but poorly understood biological communities. Soil biodiversity has been linked with soil structure, function and fertility, and is therefore intimately tied to the sustainability of natural and production ecosystems. Many soil processes are mediated by microbes, which respond rapidly to changes in temperature and moisture. Under a warming climate scenario, the rates of some important microbially mediated processes may increase (e.g. decomposition and nutrient cycling), particularly where soil moisture is not a limiting factor. Soils contain arguably the largest pool of actively cycling carbon in terrestrial ecosystems. Maintenance of 'recalcitrant carbon', which takes millennia to break down, may be especially important to the long-term sequestration of carbon in soils. The availability of nitrogen in soils is in large part regulated by microbial processes. This is likely to be critical under future climate scenarios, due to reduced nitrogen content of biomass under elevated CO₂.

Productivity of terrestrial vegetation is unlikely to increase under elevated CO₂ due to limitations of increased temperature, reduced rainfall and generally infertile soils. Nonetheless, forests are currently significant sequestrators of atmospheric carbon. In drought years, this uptake of carbon is much reduced—by as much as 90% in temperate forests. Reduced decomposition under elevated CO₂ and drier conditions will further reduce productivity of terrestrial vegetation and provide a poorer resource for terrestrial and aquatic animals. Terrestrial vegetation maintains water quality by reducing erosion and controlling saline groundwater tables. Therefore, widespread dieback of vegetation under drier and/or hotter scenarios would lead to a significant reduction in quality of the limited water supply.

Terrestrial vegetation has a substantial potential to ameliorate climate change. In medium rainfall areas (500–800 mm p.a.), which have been extensively cleared for agriculture, plantations are predicted to sequester substantial amounts of carbon while producing similar runoff to agriculture and reducing salt and nutrient inputs to streams. Conversion of native vegetation to agriculture leads to changes in the amount of heat absorbed and water released from the land, which may lower regional rainfall and alter surface temperature. This can affect patterns of atmospheric pressure leading to deflection of rain-bearing fronts from southern Australia.

The current composition of most Australian plant assemblages is determined by fire regime. Fire frequency is predicted to increase under hotter and drier conditions, which could lead to conversion first from forest to shrubland and then to grassland. Many already threatened plants and animals would be lost.

Aquatic vegetation influences nutrient and carbon cycling within freshwater and marine ecosystems. Increased water temperatures and reduced amounts of water in rivers and lakes under warmer, drier conditions may increase the likelihood of blue-green algal blooms, which can make water toxic to native aquatic plants and animals, livestock and humans. Drying of waterways ultimately will kill freshwater organisms and prolonged dry periods will reduce their capacity to recover. Productivity of aquatic vegetation (e.g. mangroves and seagrass) may not increase under elevated CO₂ due to increases in sea temperatures, radiation and natural disturbances such as storms and cyclones.

The oceans are the largest carbon sink globally, and oceans will become more acidic as more CO₂ is absorbed. Continued acidification of the oceans will lead to the extinction of organisms that produce calcareous structures (e.g. corals, molluscs and some crustaceans). As sea surface temperatures rise toxic algal blooms may become more frequent and cause widespread impacts on marine fisheries.

Climate-change effects on ecosystem processes are likely to be the most confronting and evident effects on Australian ecology. These effects are to be understood by tracing responses of individual species and altered interactions among species to climate change.

10 Biodiversity ‘currencies’ of climate change effects

The range of biodiversity consequences arising from climate change can be envisaged by considering four key ‘currencies’: (1) **extinction** (elimination preceded by population decline), (2) **invasive species** (emergence of new invaders), (3) **ecosystem processes** (loss of key ecological functions) and (4) **‘ecological surprises’** (unanticipated changes).

Extinction. When organisms are unable to adapt to climate change, genetic, individual, and population processes will be eroded. Genetic diversity will be lost, populations number and sizes will decline, geographic ranges will contract, ecological interactions will be severed, and entire biological assemblages impoverished. These effects will emerge long before actual extinction because long declines in species abundance typically precede what often is interpreted as a ‘sudden collapse to extinction’. They will harm the functioning of declining populations, reduce biodiversity at all its levels and negatively affect human use of biological resources. The ultimate endpoint of these effects is irreversible species extinction.

Invasive species usually comprise introduced (exotic) species that adversely affect the native ecosystems they invade, often with economic and social consequences. Climate change, by setting in train rapid and large scale movements of native species, means that many natives will move into new areas to become invaders themselves. Just like exotic species, native species in these new contexts may have consequences for various components of biodiversity (e.g. genetic diversity and ecosystem processes). Climate change will favour expansion of many current exotic invasives, but it will also create new invasives. Some existing, cool-adapted invasives (e.g. carp, *Cyprinus carpio*) may be disadvantaged with temperature increases.

Ecosystem processes and ‘services’. The cycling of energy and materials through the global ecosystem is fundamental to maintaining biodiversity at all levels. These processes contribute directly or indirectly to human health and well-being, and have been termed ‘ecosystem services’. Ecosystem services are the transformation of a set of natural assets (soil, plants and animals, air and water) into things that we value. The vast majority of ecosystem services are far too sophisticated and expensive to implement by engineering, even with the most advanced technologies, yet the benefits are returned to humans with minimal investment. Human-induced environmental change has already disrupted ecosystem processes. Climate change will further degrade the services provided. Existing assemblages are being disrupted and new, unforeseen combinations of species will emerge. The complex biotic machinery that provides ecosystem services is being jumbled, the consequences of which are impossible to predict accurately.

Ecological surprises. Biological systems, like climate systems, are driven by complex interactions among diverse elements. Most estimates of the biological and ecological consequences of climate change focus on the average response of individuals, populations, and assemblages under average conditions described in each climate change scenario. However, biological systems may change in unexpected ways at unexpected times for unanticipated reasons. As species differentially move and others die out, novel assemblages will be generated that may be unstable and very difficult to manage. This complexity makes it difficult to predict the nature of future changes. We must be prepared for significant ecological surprises, most of which will be detrimental to our natural biological heritage and many will have adverse effects on economic productivity and human well-being. The list from the 20th century and earlier already is long. Expect more under climate change.

11 What will be the biodiversity effects of the different climate scenarios?

Biodiversity consequences following climate change vary, depending on the scenario. The severity of impacts are shown by using projections of relative impacts on the four 'currencies' (figure), and illustrated in case studies for three key ecosystems (Boxes 1–3). The severity of effects on the four biodiversity currencies are rated from LOW to VERY EXTREME using a graduated scale similar to the familiar fire danger signs used throughout Australia (figure).

Recall that the scenarios (by 2100) can be characterised as:

(R1) +4.5 °C mean temperature, -25% water availability

(R2) +4.5 °C mean temperature, +15% water availability

(A) +1 °C mean temperature, -25% water availability

(B) +1 °C mean temperature, +15% water availability

(C) +0.55 °C mean temperature, -7% water availability

(+3) +3 °C mean temperature, -7% water availability.

In most instances, these ratings are likely to be conservative because they do not account for interactions between climate change and other human-induced impacts. For example, a -25% change in water availability probably will induce extreme water-harvesting behaviours that will magnify (possibly many-fold) the purely climate-based sources of change.

Extinction ratings. The effects on species extinctions are likely to be VERY EXTREME for R1, with no moderation of temperature rises by water availability. R2 may engender almost as severe effects but there will be a slight amelioration by greater water availability. The +3 scenario is less severe than either R1 or R2 but still would lead to widespread loss of native species. Scenario A is likely to be next most deleterious given the loss of water availability. Scenario C, the most moderate of the scenarios, will generate widespread extinctions but to a much lesser extent than the other scenarios.

Invasives ratings. Invasive species, including pests, weeds and pathogens, will be a prominent part of the Australian ecological landscape under all scenarios, as they have been for over a century. It is probable that Scenario B will produce the worst outcomes given the relatively moderate increase in temperature (although still roughly twice the current increase) coupled with greater water availability. Scenario B is likely to be very favourable for spread of tropical and sub-tropical invasives (both exotic and native). Scenario R2 will produce conditions almost as suitable as Scenario B, but moderated somewhat by the very high temperature change. The hot, dry reference Scenario R1 is much less likely to engender problems with invasive species because species adapted to such conditions generally do not have irruptive life-histories and the landscape is unlikely to provide easy movement (low river flows).

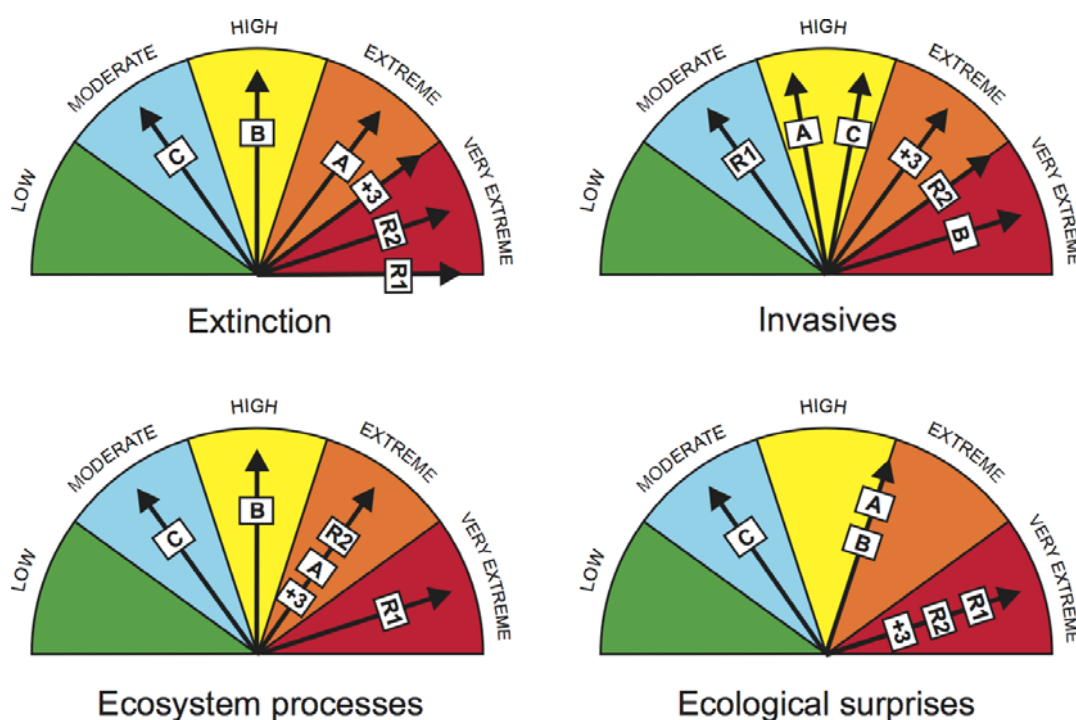
Ecosystem processes ratings. Scenario R1 is likely to be disastrous for all ecosystem processes, such as plant production, biogeochemical cycling and natural decomposition rates, due to precipitous declines under high temperatures and low water availabilities. Three other scenarios will be almost as bad (R1, +3, A), while C represents the only scenario in which ecosystem processes (and hence dependent services) will not be altered out of all historical recognition.

Ecological surprises ratings. Scenarios R1, R2 and +3 will produce unexpected ecological outcomes because we have little knowledge of climates with such extreme temperatures. Scenarios A and B probably will induce fewer surprises and possibly of lesser impact, but for disparate reasons. This is because the same temperature increase with very different water availabilities will produce quite different but equally severe surprises. Scenario C once again is least likely to generate unexpected outcomes, but there still will be many, diverse consequences of such a change in climate superimposed on changes that have already occurred.

12 Key steps to ameliorating adverse biodiversity change

Proactive investments now will be much more effective and more economical than delaying responses to climate-change effects. The following actions will improve the nation's capacity to buffer our biodiversity against climate change:

- Broad-scale restoration of native vegetation through strategic actions such as 'biolinks' (Gondwana Link, Alps2Atherton)
 - benefits include significant new habitat for native plants and animals, carbon sequestration, improved ecosystem processes and services, local climate amelioration, and infrastructure for species' movements through landscapes.
- Restitution of substantial amounts of water to natural ecosystems, including sympathetic management of riparian zones
 - benefits include sustainable aquatic ecosystems, fisheries, self-sustaining floodplain vegetation, infrastructure for species' movements through landscapes.
- Reduce and avoid 'over-engineering' and 'over-management' of all natural biological resources
 - benefits include re-introduction of natural variability and natural disturbance regimes to native ecosystems, sustainable ecosystem processes and services, and greater resilience to ecological surprises, including invasives.



Relative ratings of impacts on four biodiversity currencies in relation to six climate-change scenarios.

Box 1 The climate change threat to Australia's 'food-bowl'—the Goulburn-Broken Catchment

The Goulburn-Broken Catchment (GBC) forms part of the Murray-Darling Basin, covering 2.4 million hectares of Victoria. The GBC has many land-uses, from horticulture to cropping to irrigated dairy pasture. The landscape has been much influenced by human impacts on vegetation cover, hydrology, nutrient cycling and invasive species. The GBC has warmed 0.1°C per decade since 1950, and predictions for climate change in the GBC are for higher temperatures and reduced precipitation, with fewer frosts, and more hot summer days. Droughts will become more frequent, widespread and intense, while rainfall events will become more pulsed and flashy. Increased evaporation will lead to drier soils and reduced run-off into streams of 35% by 2030. With greater drying, the thousands of existing farm-dams will intercept an increased proportion of run-off, further reducing yields to streams. Pressures on already over-harvested waterways will reduce opportunities for environmental flows for rivers, particularly as demand increases from urban centres, especially Melbourne. Major readjustments in patterns of land-use are required. Water markets will lead to even greater allocation of water to high value/high intensity land-uses, such as dairying and horticulture. This will put pressure on water quality because these uses contribute substantially to nutrient and agrochemical pollution. New land uses such as biofuel crops and carbon farming are likely to become important, generating more pressures on already degraded biodiversity. Floodplain plant communities, which evolved under and rely on regular flooding, will become even more degraded, further reducing the health of the iconic river red gum (*Eucalyptus camuldensis*) forests over the GBC. Many of the rare or threatened species occur in montane and sub-alpine ecosystems. Increasing temperatures will place pressure on threatened species in montane and subalpine ecosystems, forcing a retreat to higher altitudes or extinction.

Box 2 Kakadu—a northern internationally renowned icon under threat

The wetland system at **Kakadu National Park** depends on a finely balanced interaction between freshwater and marine environments. Kakadu is an important hotspot for Australian biodiversity and attracts more than 200,000 visitors annually, spending more than \$122 million. The area is the cultural homeland and source of sustenance for indigenous groups who have occupied Kakadu for at least 50,000 years. In places the natural levees that act as barrier between Kakadu's freshwater and saltwater systems are only 20 cm high. Sea levels rises of another 18–59 cm by 2100 will adversely affect 90% of the Kakadu system. Under climate change scenarios, Kakadu will be subject to a warmer and wetter climate placing pressure on the levees from the freshwater side. Rising sea levels will erode the levees from the seaward side and make the freshwater sections vulnerable to storm surges. Salt water has intruded into the freshwater wetlands so much over the past 50 years that tidal creeks have moved inland four kilometres in the East Alligator River. Bare and saline mud flats have grown nine-fold (2000) and two-thirds of the *Melaleuca* forest has been killed by increased salinity. Valued freshwater plants, such as lotus lilies, wild rice and native water chestnuts, have been lost over large areas. The area also supports more than 60 species of water birds, which congregate around freshwater pools in the wetlands. The coastal wetlands are important nursery areas for barramundi, prawns and mud-crabs, and are key breeding habitats for crocodiles, turtles, crayfish, water snakes and frogs. Woody vegetation in the park is increasing, which will make the park more vulnerable to fire. Fundamental changes in ecological function of the national park will place severe pressure on many species of both plants and animals.

Box 3 Australia girt-by-sea—threats from sea-level rise and storm surge

Australia's marine environment covers 8.1 million km² of ocean and provides \$A52 billion p.a. of ecosystem goods and services. Given the economic value of the marine system, there will be flow-on effects for Australia's people. Increases in atmospheric CO₂ levels will make the ocean more acidic, adversely affecting the many organisms that use calcium carbonate for their skeletons and shells, including corals, molluscs and phytoplankton. Climate change will increase sea surface temperatures, with the greatest warming to occur in the southern hemisphere. The Eastern Australian Current will strengthen and deliver warmer waters to the Tasman Sea to a depth of 500 m. The productive temperate phytoplankton area may shrink to an area west of Tasmania by 2100. Storm events are likely to increase with climate change, and will adversely affect coastal areas. Toxic algal blooms may become more frequent in coastal areas because these are driven by warm sea temperatures and by storm-driven re-suspension of algal cells. Degradation of kelp forests has the potential to lead to collapse of whole assemblages and have a large impact on biodiversity of kelp and nearby assemblages. Kelp forests provide key ecosystem services, acting as a nursery for many marine species considered to be of commercial value. These marine environments are diverse and influence coastal nutrient and carbon cycles, playing a vital role as CO₂ sinks. Severe or intense storms can cause significant shifts in community abundance and composition on rocky shores. Australia's marine biodiversity has high endemism—species found nowhere else (fish 85%, sea-stars and their relatives 90%, molluscs 95%, and temperate seaweeds 62%). Climate change will adversely affect marine biodiversity as tropical species move southwards, and temperate species retreat.