Australian Government

AUSTRALIA'S BIODIVERSITY AND CLIMATE CHANGE

A strategic assessment of the vulnerability of Australia's biodiversity to climate change

Technical Synthesis

Technical synthesis of a report to the
Natural Resource Management Ministerial Council
commissioned by the Australian Government

thinkchange

Prepared for the Australian Government by the Biodiversity and Climate Change Expert Advisory Group:

Will Steffen, Andrew A Burbidge, Lesley Hughes, Roger Kitching, David Lindenmayer, Warren Musgrave, Mark Stafford Smith and Pat A Werner

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Suggestions and comments would be appreciated. They should be addressed to:

The Director
Biodiversity and Natural Resource Management Adaptation Team
Department of Climate Change
GPO Box 854, Canberra, ACT 2601

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Cover images:

Left – Billybuttons, Australian Alps (Graeme Worboys)
Centre – Boolcoomatta Reserve, South Australia (Wayne Lawler for Bush Heritage Australia)
Right – Rainbow over Brothers Point, Macquarie Island (Mike Preece)

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PREFACE

Since 2006, when the Natural Resource Management Ministerial Council (NRMMC) first identified climate change priorities, government focus on climate change adaptation has increased significantly. This is reflected, for example, in recent national activity to develop climate change action plans for fisheries and forestry, and the review of the National Agriculture and Climate Change Action Plan. The Council of the Heads of the Botanic Gardens have recently prepared a climate change strategy for Australia's botanic gardens and an assessment of the implications of climate change for Australia's World Heritage properties has been completed. There is also, under the National Climate Change Adaptation Framework, a nationally coordinated approach to adaptation research planning including for terrestrial, freshwater and marine biodiversity. Research planning is supported by the Australian Government's establishment of the National Climate Change Adaptation Research Facility and associated National Adaptation Research Networks.

The NRMMC recognises climate change as a key threat to the conservation of Australia's biodiversity, as highlighted through the terrestrial and marine biodiversity decline reports prepared in 2005 and 2008 respectively. Through the National Biodiversity and Climate Change Action Plan, agreed by NRMMC in 2005, the Australian Government in consultation with states and territory governments has led a suite of biodiversity-related climate change actions. A particularly significant activity commissioned by the NRMMC was a strategic assessment of the vulnerability of Australia's biodiversity to the impacts of climate change. To undertake this assessment, an Expert Advisory Group, chaired by Professor Will Steffen, was established.

This is the first such national assessment of the vulnerability of Australia's biodiversity to climate change. The assessment report has a stronger focus on terrestrial biodiversity for a number of reasons: there has been a recent analysis of the impacts of climate change on marine biodiversity generally1 and the Great Barrier Reef in particular[2]; while for freshwater systems, there has been relatively little research to date on the consequences of climate change for freshwater biodiversity, and relatively little literature to draw upon, although work is now underway to provide a preliminary assessment of implications for freshwater systems.

This Technical Synthesis has been presented to the NRMMC by the Expert Advisory Group as a summary of their findings. In its entirety it does not claim to represent the views of individual states and territories or the Australian Government. However, the insights gained through the biodiversity vulnerability assessment should provide a valuable source of direction and information for biodiversity practitioners in developing climate change adaptation strategies for Australia's biodiversity. Three products have been prepared:

- A short Summary for Policy Makers
- A Technical Synthesis (this document)
- A full report (published by CSIRO Publishing)

The NRMMC is continuing its effort to confront the challenges of climate change and has identified a broad ranging suite of climate change priorities to be addressed over the period 2009 to 2012. These priorities include a current review of Australia's biodiversity strategy, the *National Strategy for the Conservation of Australia's Biological Diversity*, Australia's premier biodiversity conservation policy statement, review of the *Environment Protection and Biodiversity Conservation Act 1999*, and review of the National Action Plan for Biodiversity and Climate Change.

Department of Climate Change

1 Hobday, A.J., Okey, T.A., Poloczanska, E.S., Kunz, T.J. & Richardson, A.J. (editors) 2006. *Impacts of climate change on Australian marine life*. Report to the Australian Greenhouse Office, Canberra, Australia.

2 Johnson J.E. and Marshall P.A. (editors) (2007). *Climate Change and the Great Barrier Reef*. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia.

1. The climate change challenge

Human-driven climate change is now widely acknowledged to be a reality. Effects on Australia's biota are already observable. Changes in species' distributions and abundances, and in community structure and composition, have already been detected that are consistent with recent changes in temperature, rainfall and sea level.

In terms of the future magnitude and rate of the climate change, Australia's (and the world's) biodiversity is facing a threat equivalent to those of the abrupt geological events that triggered the great waves of extinction in the past. Such rapid changes will put tremendous pressure on our biodiversity, especially those organisms that cannot disperse rapidly, and/or cannot adapt in their current location to rapid change. The species-level changes already observed, and ever more rapid changes in climate through this century and beyond, will undoubtedly cascade through to affect entire communities and ecosystems so that novel ecosystems will be formed. The services provided by these ecosystems will also be affected. While some of these impacts can be anticipated, cascading effects will produce many unanticipated and surprising outcomes.

The stress of rapid climate change is being imposed on top of existing stressors to biodiversity such as land use changes, altered disturbance regimes and species introductions. We are thus facing the climate change challenge with a biotic heritage that is already impoverished and which continues to face most of the historic stressors that have operated over the past two centuries.

Current policies and management strategies provide a foundation to address the existing array of stressors on Australia's biodiversity. However, our experience in biodiversity conservation over the past century may provide only partial or limited guidance for dealing with climate change. Although the future may appear bleak for some elements of Australia's biodiversity, the climate change threat provides an opportunity for innovative thinking and new resolve to secure our biotic heritage for the future. It is imperative that climate change is not viewed in isolation from the current status and trends in our biodiversity and reasons behind these trends.

To live in a more ecologically sustainable way will require changes in attitudes; innovative institutional arrangements, management skills and economic instruments; and a better understanding of Australia's (and the world's) species and ecological communities.

2. Australia's biotic heritage: valuable and worth conserving

The Australian continent has been isolated from other land masses for many millions of years. This isolation, together with a range of other factors such as its flatness and its nutrient-poor soils, has created an environment that supports large numbers of species found nowhere else (Table 1). Between 7 and 10% of all species on Earth occur in Australia. More than 4500 species of marine fishes – and the greatest number of species of red and brown algae, crustaceans, sea squirts, and bryozoans in the world – live in Australian inshore waters. Fifty-seven per cent of all mangrove species are found in Australian inter-coastal zones (Chapman 2005). The distribution and abundance of biodiversity is not even across the continent: some groups – such as birds and butterflies – are more species-rich in the tropics and high-rainfall areas; while others – such as lizards, scorpions and grasshoppers – are more species-rich in deserts.

Many of Australia's species, and even whole groups of species or taxonomic families, are endemic to this continent. About 85% of terrestrial mammals, 91% of flowering plants, 90% of reptiles and frogs, and 95% of ectomycorrhizal fungi are found nowhere else (Chapman 2005; Lindenmayer 2007). More than 50% of the world's marsupial species occur only in Australia. In addition, most Australian groups of plants and animals have particular features differentiating them from counterpart groups on other continents.

Table 1 – Australia's rich species diversity: global status for major animal, fungus and plant groups

Australia's species diversity on a global scale	
Marine fish	One of the most diverse fish faunas in the world, with more than 4500 species.
Sharks and rays	54% of the entire chondrichthyan fauna is endemic to Australia
Ectomycorrhizal fungi	95% endemic (22 genera and three endemic families)
Terrestrial vertebrates	1350 endemic terrestrial vertebrates, far more than the next highest country (Indonesia, with 850 species)
Terrestrial mammals	305 species, of which 258 (85%) are endemic; more than 50% of the world's marsupial taxa occur only in Australia.
Birds	17% of the world's parrots occur in Australia – more than 50 species (second-highest level of endemism after Brazil and the same as Colombia)
Reptiles	89% endemic; some groups such as front-fanged snakes (family Elapidae), pythons, and goannas are more diverse than elsewhere in the world. Australian deserts have the world's highest lizard species diversity.
Frogs	93% endemic (highest level of endemism of any vertebrate group in Australia); 220 species
Marine invertebrates	17.8% of the world's crustaceans, 22% of bryozoans and 29.4% of sea squirts occur in Australian waters
Vascular plants	91% of flowering plants are endemic; 17,580 species of flowering plants, 16 endemic plant families (the highest in the world) and 57% of the world's mangrove species
Butterflies and moths	Many groups are unique to Australia

Source: Modified and updated from Lindenmayer (2007, p. 33).

The structure and functioning of many Australian ecological communities also differs markedly from analogous communities on other continents (Orians and Milewski 2007). For example, extreme events and disturbances have a greater influence on most Australian communities than in the Americas, Europe, northern Asia and southern Africa, where biotic interactions such as competition and predation are more likely to control species abundances. In addition, whole trophic levels within Australian communities are occupied by different types of species compared with other continents. Many of the ecological niches occupied by placental mammals on other continents are filled by marsupials, birds, reptiles or insects in Australia.

The conservation of Australia's species-rich and distinctive biota is critically important for heritage, ethical, intrinsic and utilitarian values; and for the roles that it plays in the maintenance of ecosystem services (Table 2). At the planetary scale, biodiversity is crucially important for the maintenance of our own life-support system. Yet at the beginning of the 21st century, Australia's biodiversity remains under considerable pressure. The national *Australia State of the Environment 2006* report (Beeton *et al*. 2006) identified land clearing, altered fire regimes, total grazing pressure, weeds and feral animals, and changes to the aquatic environment as major pressures on biodiversity. Our continent's rate of extinctions is high in comparison with most other parts of the world, and many more species are on trajectories towards extinction. The flow-on effects of these changes in species diversity to the structure and functioning of ecosystems is equally serious.

Table 2 – Examples of ecosystem services from Australia's natural biodiversity

Type of service	Service	Examples from Australian natural biodiversity
Provisioning services	Food	Macadamia nut *Macadamia integrifolia*; bush food; meat and hides from kangaroos; honey; fisheries
	Fibre	Eucalypts provide timber and pulp
	Fuel	Wood; biofuels (e.g. ethanol from sugar cane)
	Genetic resources	Use of Australia's marine and terrestrial organisms for medical drug development; tree breeding for plantations.
	Biochemicals, natural medicines, etc.	Oil mallees; Kakadu plum *Terminalia ferdinandiana* has 50 times the concentration of vitamin C in oranges; anti-cancer drugs are being developed from wild plants
	Ornamental resources	Wildflower industry; shell collecting
	Fresh water	Naturally vegetated catchments provide millions of dollars worth of potable water for Australian cities and for irrigation each year; vegetation controls groundwater tables – its loss can lead to soil salinisation
Regulating services	Air quality regulation	Microbial immobilisation of sulphur compounds; plants absorb a variety of pollutants
	Climate regulation	Phytoplankton in the ocean absorb a significant amount of the CO_2 produced by human activities; changes in land cover can influence local temperature and rainfall; sequestration of greenhouse gases in trees, etc.
	Water regulation and purification	Vegetation and microorganisms remove pollutants from water; Naturally vegetated watercourses limit flooding; wetlands purify water
	Erosion control	Naturally vegetated watercourses show minimal erosion compared with cleared watercourses; mangroves prevent coastal erosion
	Disease regulation	Insects, birds and other predators naturally control disease-carrying insects.
	Pest regulation	Predation of pest insects by native animals; predation of house mouse by native carnivores; biological control
	Pollination	Insects, birds and mammals pollinate crops and native plant species that are utilised by people
Cultural services	Cultural diversity and heritage	Plants and animals are an integral part of Aboriginal culture
	Spiritual and religious values	The close association of Aboriginal Australians with country, including the Dreaming, in which ancestral beings, including animals, created the land and its biodiversity. Many non-Aboriginal Australians feel connected to plants, animals and the wild places they form
	Recreation and ecotourism	Australia's natural scenery and biodiversity are the major attraction for tourists visiting our country; amateur fishing; bushwalking; study of natural history

Type of service	Service	Examples from Australian natural biodiversity
	Aesthetic values	Australia's natural landscapes and biodiversity provide us with a sense of place
	Knowledge systems	Use of traditional and scientific knowledge systems for managing land and biodiversity
	Inspirational values	Australia's cultural identity is closely associated with the bush and its plants and animals; some Australian species are national icons; appreciation of the wonder of living things
	Educational values	Biodiversity helps us learn about the world and its complexity
Supporting services	Soils formation	The organic component of soil comes from biodiversity.
	Photosynthesis; primary production	Primary production via photosynthesis provides the basic building blocks for all carbon-based life forms on Earth, including *Homo sapiens*; natural vegetation and algae replenish the oxygen we breathe and require for energy utilisation
	Nutrient cycling	Symbiotic bacteria in many Australian plants fix nitrogen from the atmosphere, thus fertilising the soil
	Water cycling	Transpiration transfers groundwater to the atmosphere

Source: Millennium Ecosystem Assessment (2005); Wallace (2007).

Understanding why Australia is so species-rich, why our biodiversity is unique and why the conservation of our biodiversity is so important underpins the assessment. It is essential for understanding the profound implications of the European settlement of the continent and the looming challenge of climate change, both of which drive change of such magnitude and rate that Australia's biosphere is undergoing rapid and continuing transformation.

3. Australia's biodiversity in a changing world

The first humans – Indigenous Australians – arrived on the continent between 40,000 and 65,000 years ago. They came as hunters and gatherers, and had a relatively light ecological footprint, but they changed the landscape through hunting and by their use of fire.

European settlers arrived some 220 years ago and spread rapidly over the more productive parts of the country. The drivers of biodiversity change associated with European colonisation of Australia are unique in that the rate at which they operate is several orders of magnitude greater than the rates of change with which Australia's biota has evolved. The most important proximate drivers of change are:

- ***land clearing*** – has had the biggest impact of any driver on Australia's biodiversity. Landscape fragmentation interacts strongly with climate change by reducing connectivity; this driver will have an even greater effect as many species attempt to adapt by migrating to more suitable climatic zones
- ***introduction of new species*** – a major driver of biodiversity change. Climate change will create winners and losers among invasive species, with the impacts of the winners likely to exceed the direct impacts of climate change on biodiversity in many cases
- ***redistribution of water resources and changes in nutrient capital*** – this includes the wide application of fertilisers on crop and pasture lands, construction of watering points in grazing lands, and diversion of water for crop irrigation
- ***changes in fire regimes*** – the intensity, frequency and seasonality of fire has been significantly modified since European arrival which, when coupled with significantly reduced ranges for many species, can lead to disproportionately high impacts. Climate change may already be altering fire regimes and will certainly do so in future
- ***direct removal of species through hunting and fishing*** – particularly important in the decline of some of Australia's fisheries
- ***mineral extraction*** – primarily a localised driver, but can affect highly endemic species and rare ecosystems.

The ultimate drivers of biodiversity change include population growth, the amount of resources required to support individual consumption, the methods used to exploit these resources (e.g. primary industries) and a suite of global-scale phenomena such as economic globalisation. These drivers will continue into the future as climate change accelerates, but their pattern and intensity may change through some large-scale socio-economic trends that are sweeping across Australia (see section 7).

The historic drivers have led to profound changes to Australia's biotic fabric at the genetic, species and ecosystem levels. Much of the emphasis is on the species level, as this is the scale at which biodiversity conservation is often focused. The most prominent of these changes are:

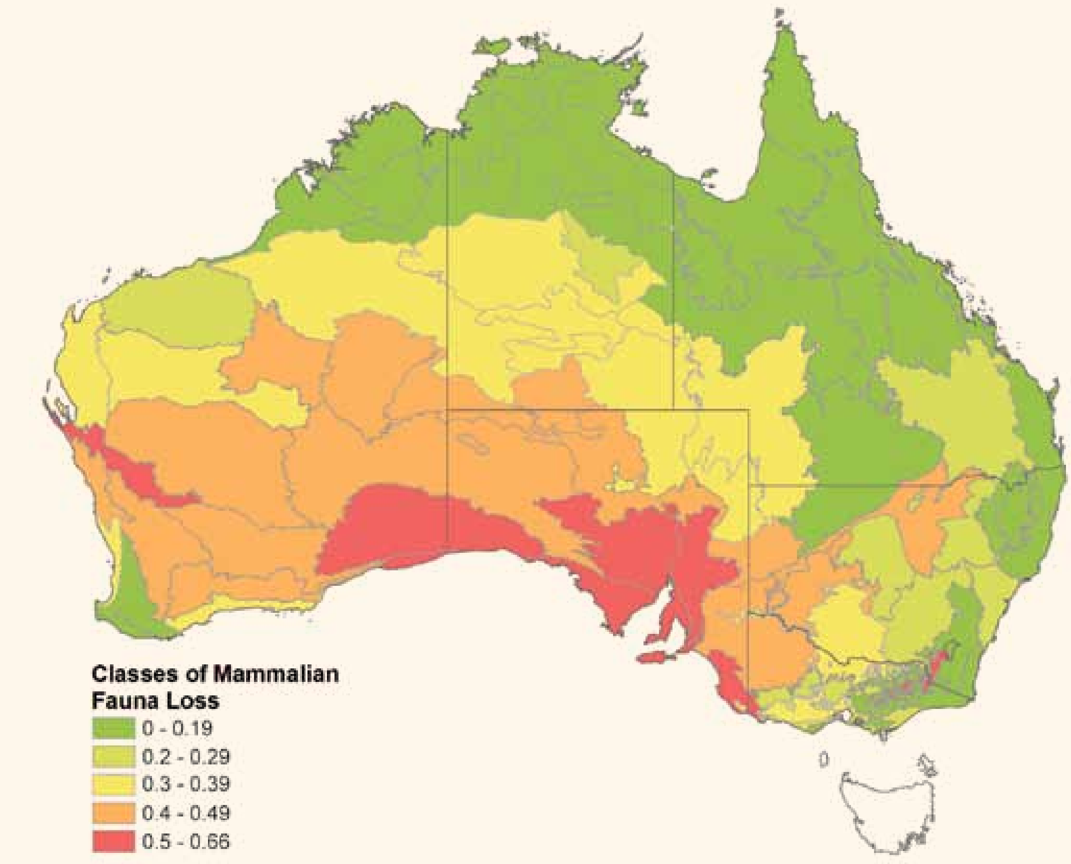
- ***extinction, functional extinction and threatened species*** – in addition to the well-known record of species extinctions in Australia, many others have reached such low numbers that they no longer play an effective role in the functioning of ecosystems and are thus functionally extinct. Many more species are threatened with extinction owing to massive and/or rapid declines in: (i) distribution and/or abundance; (ii) functional position within a community; or (iii) reproduction and recruitment
- ***changes in relative abundance and distribution*** – although not yet threatened with extinction, many other species have suffered large reductions in their ranges. For example, many of Australia's mammal species now have distributions covering less than 20% of their original range (Table 3; Figure 1)
- ***introduced species*** – many introduced plants and animals have had deleterious effects on biodiversity. These include mammals (e.g. cats, foxes, water buffalo, rats, rabbits, goats), marine and aquatic species (e.g. north Pacific starfish, European shore-crab, trout, water hyacinth, green alga), amphibians (cane toad), insects (e.g. honeybees) and many plants (prickly pear, mimosa, gamba grass, mission grass and many others).

Table 3 – Examples of species collapse among Australian mammals, comparing their historical and current ranges

Common name (Scientific name)	Historic range (sq km)[1]	Current range (sq km)	Collapse (%)
Banded hare-wallaby (*Lagostrophus fasciatus*)	489,868	607	>99
Burrowing bettong (*Bettongia lesueur*)	4,371,154	607	>99
Greater stick-nest rat (*Leporillus conditor*)	1,325,043	607	>99
Rufous hare-wallaby (*Lagorchestes hirsutus*)	1,961,902	1,215	>99
Bridled nailtail wallaby (*Onychogalea fraenata*)	1,097,876	10,022	99
Northern hairy-nosed wombat (*Lasiorhinus krefftii*)	105,991	1,519	99
Brush-tailed bettong (*Bettongia penicillata*)	1,771,786	53,451	97
Hastings river mouse (*Pseudomys oralis*)	269,078	7,593	97
Numbat (*Myrmecobius fasciatus*)	1,924,243	58,918	97
Dusky hopping mouse (*Notomys fuscus*)	902,900	42,518	95
Heath rat (*Pseudomys shortridgei*)	235,975	14,881	94

[1] Historic range at the time of European settlement.
Source: Modified from Lindenmayer (2007).

Figure 1 – Proportion of loss of mammalian fauna in 76 bioregions of mainland Australia. The Faunal Attrition Index measures the status of a bioregion's fauna along a trajectory, from all species persisting throughout their original range in a region to a point at which all species are extinct. Shown are five classes: 0–0.19, 0.2–0.29, 0.3–0.39, 0.4–0.49 and 0.5–0.66; where 0 = all species persisting, through to 1 = all extinct.



Biodiversity change is also critical at the ecological community and ecosystem levels, as ecosystem functioning is largely dependent on the interactions among organisms within ecosystems, superimposed on the larger spatial scales of topography, soils, nutrients, hydrology and climate. The most significant changes at the ecosystem level are:

- ***species–species interactions*** – these include mutualism, competition and predation. Many invasive species affect biodiversity by outcompeting native species for resources or by direct predation on native species
- ***ecological cascades*** – these arise from second- and third-order effects when species interact, leading to the substantial modification of entire food webs and ecosystems
- ***novel communities and ecosystems*** – new combinations of species arising through human action and environmental change. Since the European settlement of Australia these have been produced primarily by invasions of new species, changes in fire regimes and landscape transformations.

The complexity of the historic changes in Australia's biodiversity, particularly at the community and ecosystem level, is already challenging enough for policy and management. Climate change adds a further degree of complexity, especially given its pervasive and fundamental nature for biological and ecological processes. Research on climate change and biodiversity, especially on the indirect, interacting effects at the community and ecosystem levels (which are the most important effects), is in its infancy. Thus, direct extensions of current policy and management will not be particularly effective in dealing with the climate change challenge, nor will adaptation measures based on the current generation of climate impact studies. Given this situation, the most effective way forward is to base policy and management on fundamental principles that describe the responses of biota and ecosystems to environmental change, and to use these to enhance the resilience and transformability of ecosystems in a highly uncertain and rapidly changing world.

Ten ecological principles that are relevant to environmental change, such as could be expected occur under a changing climate, are identified in Table 4. These ecological principles provide some guidance in developing management responses, as they identify the key ecological drivers of change that can result in changed species distribution and abundance. The principles describe: (i) the relationships among individual species, which are often the focus of biodiversity conservation; (ii) the role of individual species in communities and ecosystems; (iii) the structure and functioning of ecosystems, important for the provision of ecosystem services; and (iv) phenomena associated with environmental change that are applicable to all ecosystems at all levels. At larger scales, these principles underpin the understanding of interactions among ecosystems, particularly the nature and strength of the connections among them, which become very important as rapid environmental change drives differential responses of individual species and groups of species.

Table 4 – Ecological principles relevant to environmental change

Subject	Ecological principles	Explanation	Relevance to environmental change excluding climate change
1. Species differences	Every species is different. Species distributions and abundances reflect individual responses to their environments.	• Environmental determinants include the physico-chemical environment and the biological environment • These define their fundamental and realised niches • Species-specific features such as dispersal ability, reproductive rate and competitive ability affects their spatial and temporal dynamics	Responses to human-induced changes on terrestrial native species differ widely in response to urbanisation, land clearing, and native marine species' responses to over-fishing or water pollution Dispersal ability affects the ability of species to respond to landscape or seascape modification

Subject	Ecological principles	Explanation	Relevance to environmental change excluding climate change
2. Scale (time and space)	Species abundances and distributions are responses to drivers at different scales.	• Species respond differentially to drivers at different scales • Key scales are both spatial and temporal, including local to continental, and immediate to geological	Some exotic predators operate on widely different scales, while other impacts are location-specific
3. Life histories and population genetics	Life history attributes determine the ability of species to respond to change. Population genetic variability and breeding systems also determine ability to respond.	• Attributes include reproductive rates, longevity, dispersability, genetic variability and phenotypic plasticity • These occur in repeated sets, organising species into a manageable number of functional groups • Species that adapt well to change have high reproductive rates, short longevity and high mobility	Native species that become agricultural 'pests' are pre-adapted to rapid responses. Some native species cope with radical change better than others because of life-history and/or genetic plasticity.
4. Species interactions	No species exists in isolation from other species.	• Species interact in pairs, trios and so on • Interactions include competition, predation and mutualism • Interacting sets make up ecological communities; when considered with their abiotic components, they are called ecosystems	Introduced food plants change distributions of native herbivores. Introduced animals change whole communities.
5. Species' roles	Some species affect ecological structure and processes more than others within communities and ecosystems.	• Single species may determine the state of entire communities • These include, for example, key structural species, foundational species, keystone species, and ecological engineers	Forestry management practices affect whole local communities of plants and animals. Marine communities can be vastly changed by the alteration of single species, especially the primary producers or top predators. Some exotics have far more impact than others.
6. Trophic structures and ecosystems	Species are structured by their means of obtaining food into a larger trophic structure, or food web, of an ecosystem. The interaction of biota and physico-chemical environment yields ecosystem-level processes.	• Changes at the species level can cascade through trophic levels to produce a change in the entire system • Changes in geological time and those due to human activities have produced novel ecosystems	Changes in plants through fertilisation or grazers have cascaded through ecosystems to produce tree dieback, or changes in primary productivity or fire regimes, with further consequences.

Subject	Ecological principles	Explanation	Relevance to environmental change excluding climate change
7. Multiple drivers of ecological change	Communities and ecosystems change in response to many drivers, and these drivers themselves may interact.	• Communities and ecosystems respond to drivers of change in different ways. The timing and relationships among the drivers can also affect outcomes. Hence, when there is more than one driver present, the responses can be complex, sometimes leading to unpredictable outcomes	Major drivers have included land clearing, exotic species, urbanisation and pollution. Some regional ecosystems have changed due to land clearing, others due to exotic predators, urbanisation, etc. These changes are evident at the individual species levels as well (above).
8. Non-linearity	Changes can be non-linear.	• Changes in species abundances and distributions, community structure, or ecosystem functioning may be proportional to changes in the drivers (even those that are linear) **but**: • There may be thresholds where rates of change alter or even jump to different levels (i.e. non-linear response) • As a consequence, this inherently increases uncertainty in predictions	Native communities can absorb small numbers of exotics, beyond which radical change occurs. Vegetation clearing can gradually reduce native populations to a point where mating encounters become infrequent and/or offspring survival plummets – then the species collapses rapidly (non-linearly).
9. Heterogeneity	Variations in time and space (heterogeneity) enhance biotic diversity.	Because different species are different sizes, have different home ranges and dispersal abilities, and interact with other species at different times and distances, then the greater the variability of resources and habitat, the greater the number of species.	Variability of rainfall and resources – as well as disturbances by storm, drought, insect outbreaks, and traditional fire practices – has been a fundamental feature of Australian landscapes. Recent changes to these, especially fire regimes in terrestrial systems, have reduced biodiversity.
10. Connectivity	Connectivity among resources and habitat required by species determines the longer-term patterns of species distributions and abundance, and ultimately longer-term landscape-scale biodiversity.	Connectivity is an entirely relative term to the individual species or community type under consideration. It refers to the location of resources and habitat that are conducive to survival and reproduction, in close enough proximity to be available through dispersal of individuals, offspring or reproductive units (e.g. seeds, pollen). What might appear as a highly fragmented landscape to one species might also be one of high connectivity to another species.	Changes in land use and land management have been the main causes of changes in connectivity in terrestrial systems. Fragmentation of previously continuous landscapes, sea bottom types or vegetation may have changed connectivity for many species and communities.

Source: Expert Advisory Group.

4. Climate change: magnitude and rates

4.1 Global climate change

The mean temperature and atmospheric CO_2 concentrations of the Earth have been positively correlated over geological time. During the past 2.5 million years, the rate of change during successive cooling (glacial) periods has been slow compared with the rate of subsequent warming. For example, during the most recent ice age, both temperature and CO_2 concentration declined steadily for more than 100,000 years but were restored to interglacial values within the relatively short succeeding time span of 5000 to 10,000 years (Lorius *et al*. 1990). However, the current atmospheric CO_2 concentrations (>380 parts per million (ppm)) are far above those found during the most recent interglacial warm period of approximately 300 ppm. Furthermore, CO_2 concentrations are currently rising faster than expected on the basis of the IPCC emissions scenarios (IPCC 2007a; Figure 2). Global mean temperature is currently tracking within the range of IPCC projections (Figure 3), and sea-level rise is tracking at the upper limit of the range of projections (Figure 4).

Figure 2 – Observations of anthropogenic CO_2 emissions from 1990 to 2007. The envelope of IPCC projections is shown for comparison. Source: Raupach *et al*. (2007) with additional data points from Canadell *et al*. (2007) and Global Carbon Project annual carbon budgets.

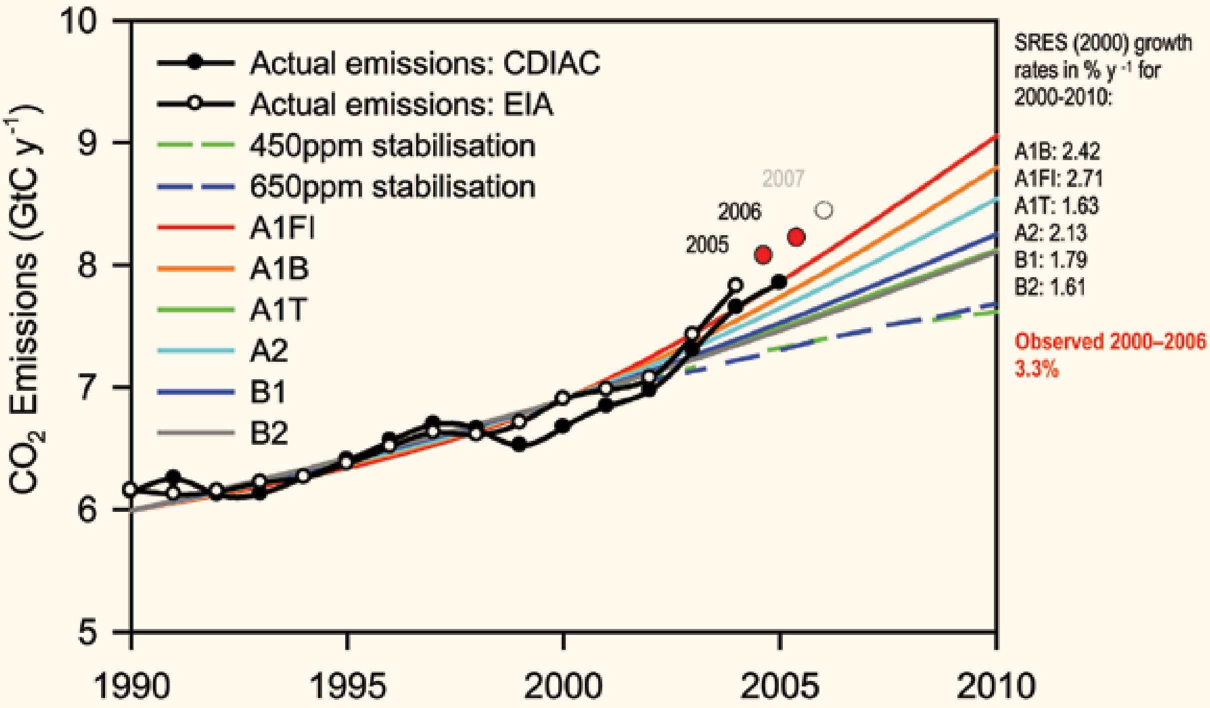


Figure 3 – Changes in global mean surface temperature (smoothed over 11 years) relative to 1990. The blue line represents data from Hadley Center (UK Meteorological Office); the red line is GISS (NASA Goddard Institute for Space Studies, USA) data. The broken lines are projections from the IPCC Third Assessment Report, with the shading indicating the uncertainties around the projections. Source: Rahmstorf *et al*. (2007), with data for 2007 and 2008 from S Rahmstorf.

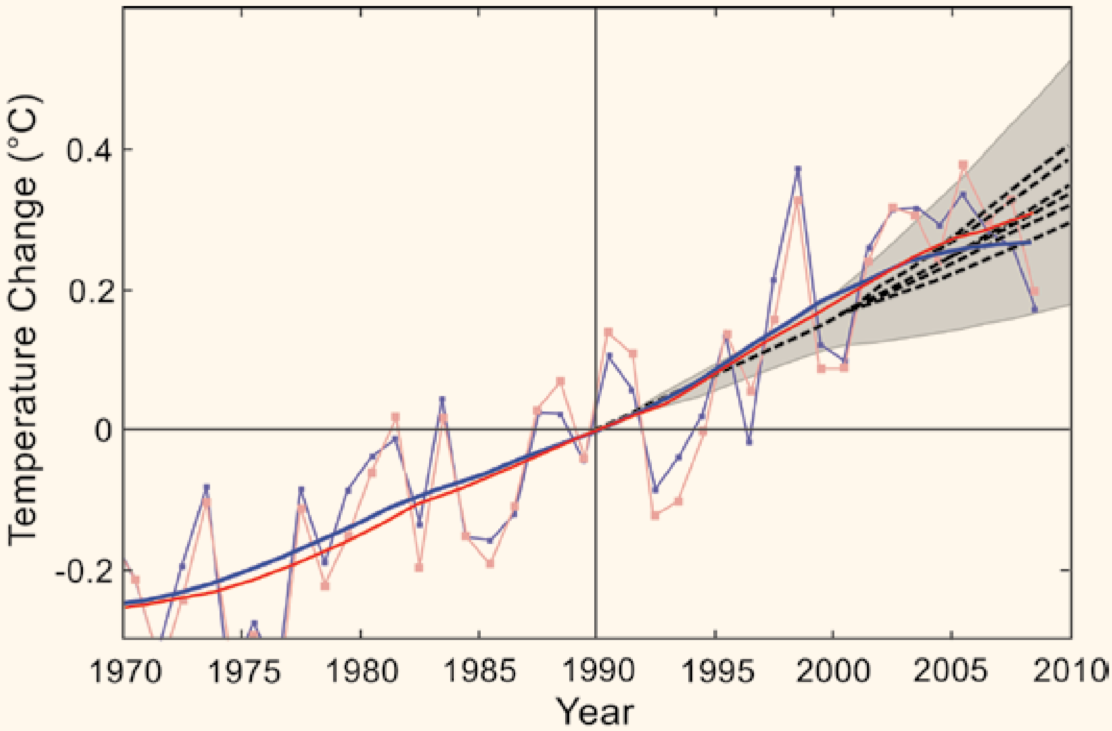
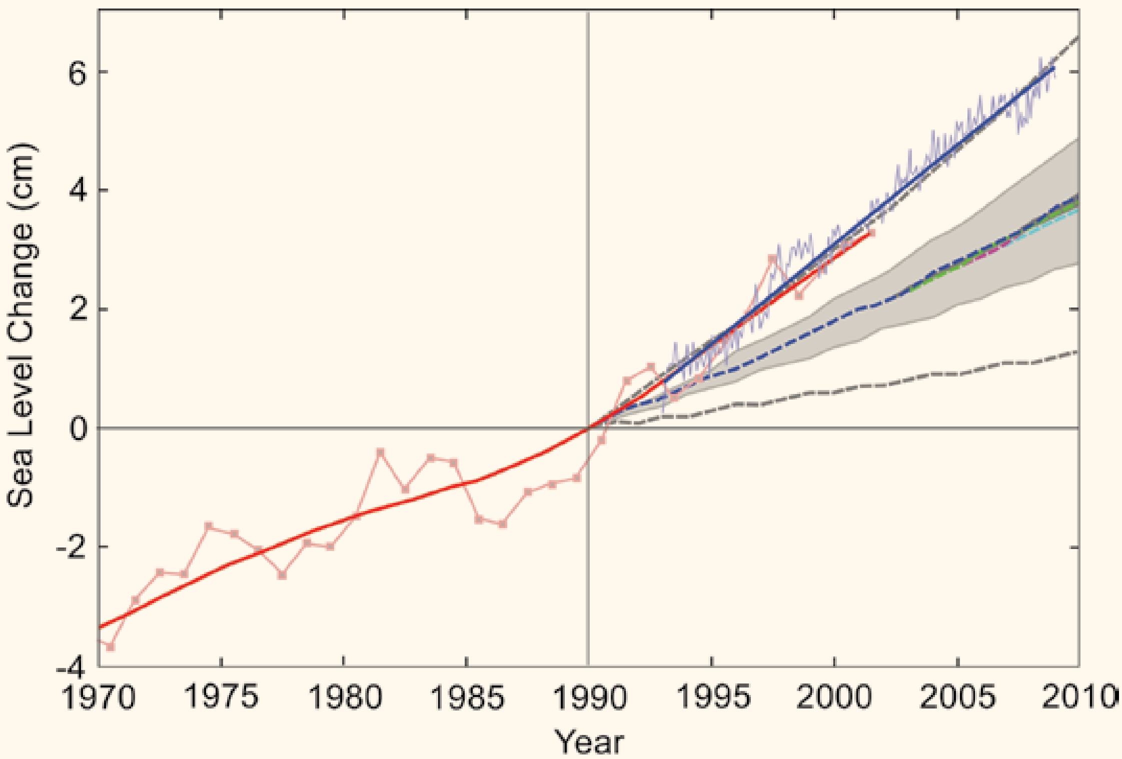
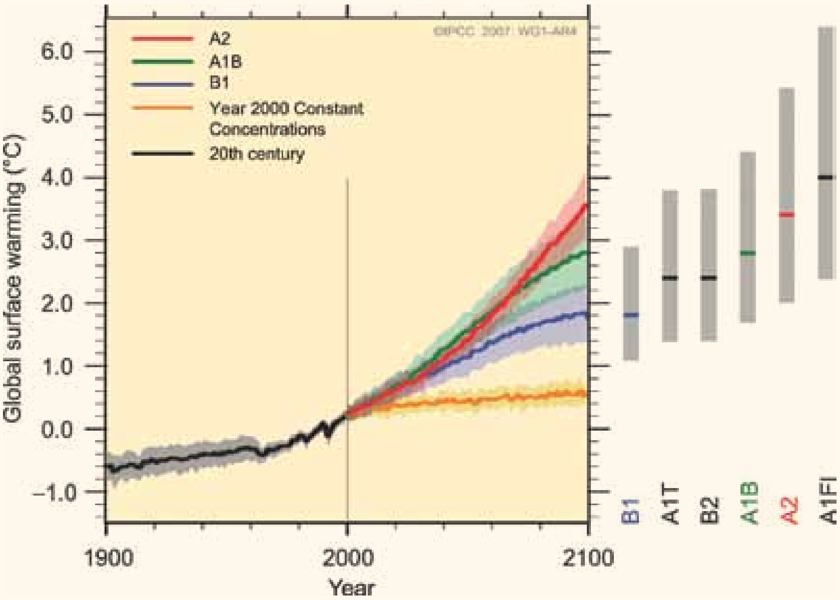


Figure 4 – Change in sea level from 1970 to 2008, relative to the sea level at 1990. The solid lines are based on observations, smoothed to remove the effects of interannual variability. The envelope of IPCC projections is shown for comparison (broken lines with grey shading showing the uncertainty levels). Source: Rahmstorf *et al*. (2007), based on data from Cazenave and Narem (2004); Cazenave (2006) and A Cazenave for 2006–2008 data.



Global average temperatures have increased 0.74°C from 1906 to 2007, with 12 years of a recent 13-year period (1995–2005) ranking among the 13 warmest years in the instrumental record since 1850. The IPCC also concluded that it is *very likely* that anthropogenic greenhouse gas increases have caused most of the observed increase in globally averaged temperatures since the mid-20th century. Figure 5 shows a near-2000 year reconstruction of northern hemisphere surface temperature with the instrumental record of the past 150 years superimposed (red line). This puts the observed 0.7°C increase in global mean temperature over pre-industrial values into a longer time perspective. The figure shows that anthropogenic climate change is moving the Earth's system out of the envelope of natural variability that the world's ecosystems have experienced over the past two millennia at least, and probably much longer (Steffen *et al*. 2004).

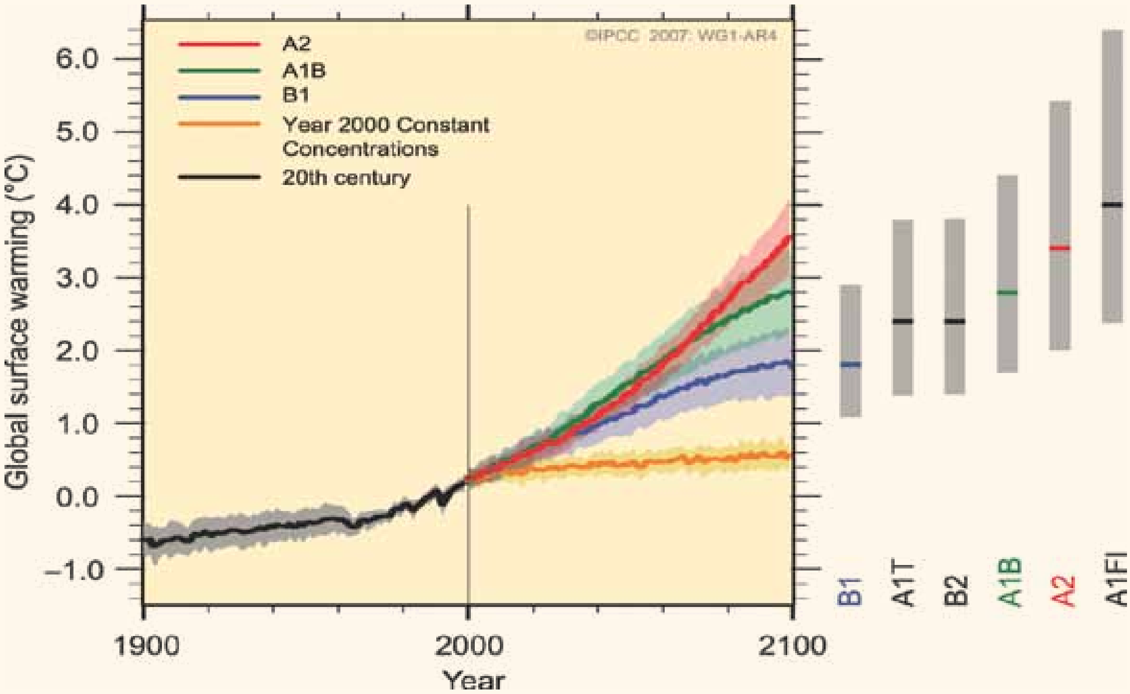
Figure 5 – Reconstructions of northern hemisphere surface temperature for the past 1800 years compared to the instrumental record of the past 150 years (red line). Source: Mann *et al.* (2003).



Global average sea levels are rising at a rate consistent with the warming trends, increasing 1.8 mm/year in the period 1960–1983 and 3.1 mm/yr since that time (Figure 4). Thermal expansion, melting glaciers and polar ice sheets have all contributed to the rise. It is unclear whether the apparent acceleration in rate since 1983 is due to decadal variability or to a longer-term trend (IPCC 2007a).

It is very likely that the climate system will continue to warm through the rest of the 21st century and beyond, with associated changes to wind patterns, precipitation, sea level, extreme events and many other aspects of weather and climate. Figure 6 shows the range of model projections of global mean temperature through the rest of the century. Three features are particularly important. First, the momentum in the climate system means that the Earth is committed to a further warming of at least 0.4°C regardless of human actions. Second, there is a high probability that the Earth will warm beyond the 2°C level (compared with pre-industrial levels), which is sometimes considered to be the threshold of 'dangerous climate change'. Finally, significantly higher temperature rises cannot be ruled out, and will become more probable if deep cuts in global emissions of greenhouse gases cannot be achieved in the next decade or two. As noted above, the current global emissions trajectory is tracking at or near the upper limit of the IPCC suite of projections (Raupach *et al*. 2007), increasing the risk that a 2°C rise in global mean temperature will be exceeded during this century.

Figure 6 – Projections of increases in global mean temperature to 2100, relative to 2000. Source: IPCC (2007a).



Some of the difficulty in developing adaptation approaches for climate change is due to the uncertainty within climate change projections (grey bars at the side in Figure 6). Box 1 discusses areas of uncertainty in climate change science; however, it is worth noting that one of the greatest sources of uncertainty about the state of the world's climate by 2100 is the extent to which nations act to limit CO_2 emissions in the coming decades.

Box 1 – Assumptions and uncertainties

There are four main areas of uncertainty in climate change projections: (i) the projected rate of increase in greenhouse gases (emissions scenarios); (ii) the relationship between the rate of greenhouse gas emissions and their atmospheric concentrations; (iii) the magnitude of the global warming for a given change in concentrations; and (iv) identifying how global climate change plays out regionally.

The emissions scenarios depend on assumptions about future demographic changes, economic development and technological improvements. These uncertainties become greater further into the future, but the emissions scenarios are fairly similar up to 2030.

Greenhouse gas concentrations in the atmosphere depend not only on the emissions, but also on the rates at which the gases are removed from the air by various processes. Most gases are removed by chemical reactions or ultraviolet radiation, but carbon dioxide is removed by absorption into the ocean and terrestrial biosphere, e.g. forests. Higher carbon dioxide concentrations and larger changes in climate tend to reduce the absorptive efficiency of these sinks, resulting in a positive feedback that has been observed in recent years (Canadell *et al*. 2007).

Increasing concentrations of greenhouse gases and changes in aerosol emissions affect the thermal radiation balance of the Earth and the average surface temperature. The radiative forcing due to greenhouse gases is well understood. The contribution from aerosols (microscopic particles in the air) is relatively poorly understood, but the net effect is a cooling (IPCC 2007a). Climate feedbacks are also important, such as: ice-melt, which will lead to more absorption of solar radiation and greater warming; the ability of warmer air to hold more moisture (water vapour being a greenhouse gas); release of methane from melting permafrost in tundra regions; and changes in cloud properties (the largest source of uncertainty in the climate response). Global warming projections take account of these uncertainties.

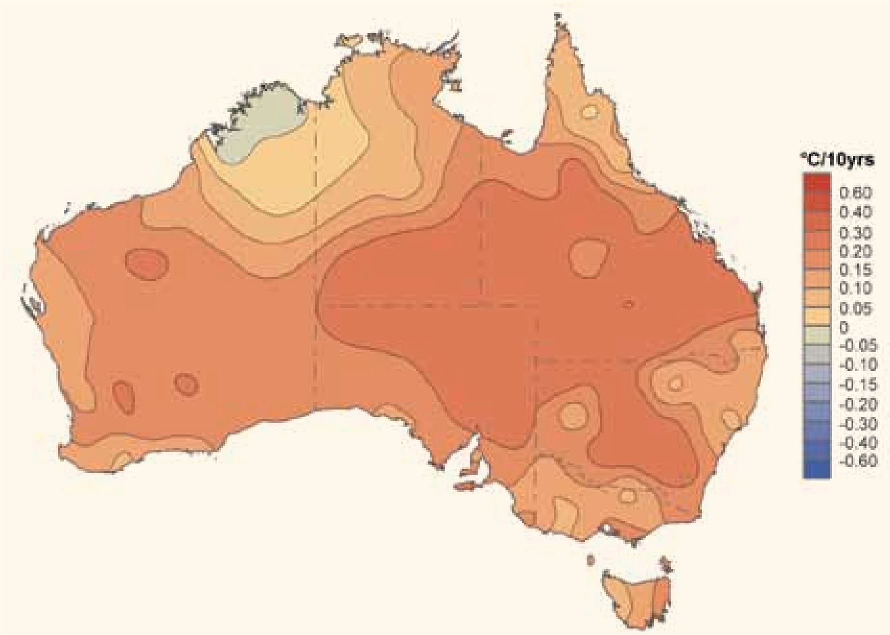
Source: Modified from Hennessy *et al*. (2008).

4.2 Climate change in Australia

Australia is experiencing climate trends consistent with the global picture of increasing temperatures and rising sea levels. Concomitant changes in intensity, distribution and seasonality of rainfall, snow cover and precipitation runoff; increasing acidity of oceans; and changes in extreme events such as floods, droughts and fire have also been documented.

Australian average temperatures on land have increased 0.9°C since 1950, although with significant regional variations (Figure 7), which is slightly faster than the global average of 0.74°C. The warmest year on record in Australia was 2005, with an average temperature over 1.0°C above the long-term mean. 2007 was the sixth warmest year on record, and the warmest ever in southern Australia. Within this framework of increasing mean temperatures, minimum temperatures have been increasing faster than maximum temperatures (Nicholls 2006).

Figure 7 – Trend in mean temperature in Australia, 1950–2007

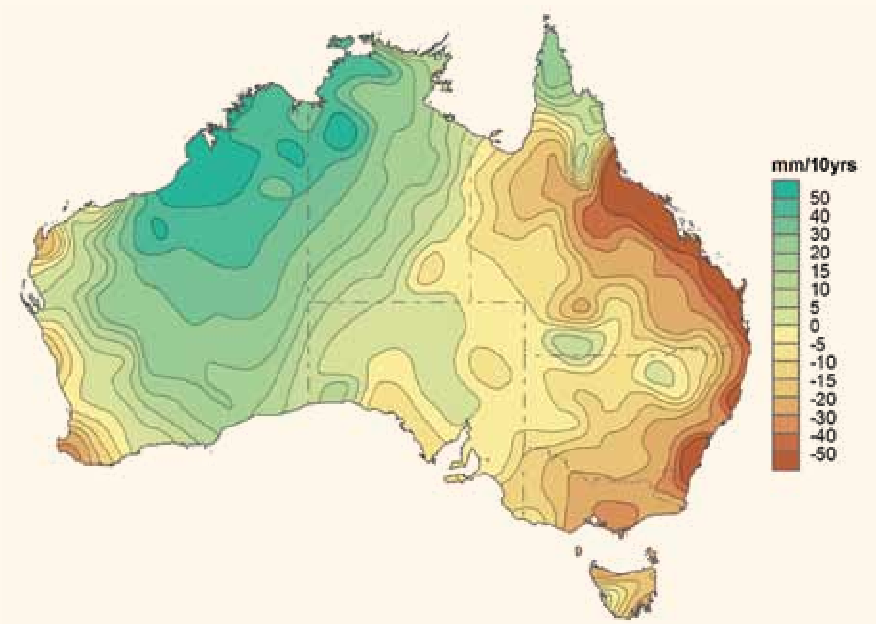


Source: Australian Bureau of Meteorology.

The frequency of extreme hot and cold temperatures has also been changing. There has been an increase in hot days (over 35°C) since the late 1950s, as well as an increase in hot nights (>20°C), and a decrease in cold days (<15°C) and cold nights (<5°C) (CSIRO and BOM 2007).

Significant changes in regional rainfall patterns have occurred over the past century, especially when comparing the period 1910–1950 and the period since. Since 1950, rainfall has increased over the north-western regions and has declined in the south-west and along the eastern seaboard (Nicholls 2006) (Figure 8). From 1950 to 2005, extreme daily rainfall intensity and frequency increased in central Australia and the north-west (mainly during the summer) and over the eastern tablelands of New South Wales, but it has decreased substantially in south-eastern and south-western Australia, and along the central east coast.

Figure 8 – Trend in annual total rainfall in Australia, 1950–2007



Source: Australian Bureau of Meteorology.

Extreme climate and weather events are infrequent events at the high and low range of values of a climate or weather variable (Nicholls 2008). Trends in extremes are highly correlated with trends in means for both temperature and precipitation in Australia. However, the trend for daily rainfall extremes is often greater than the trend for the mean, indicating the frequency of extreme rainfall events is changing faster than the mean (Alexander *et al.* 2007). Projections for the future suggest increases in the frequency and intensity of many extreme events such as drought, tropical cyclones, storm surges and fire. There is also evidence that trends in the most extreme events of both temperature and rainfall are changing more rapidly, in relation to corresponding mean trends, than are the trends for more moderate extremes (Alexander *et al*. 2007).

Droughts in Australia have become more severe, with higher temperatures and increased evaporation (Nicholls 2004). The most recent drought has placed considerable stress on water resources in many regions. Declines in winter rainfall by 10–20% in the south-west have resulted in a 50% reduction in flows to the Perth water supply dams (Pittock 2003); streamflow into Perth dams since 2001 has been only 16.5% of the 1911–1974 mean.

The effects of reduced rainfall and hotter droughts on fire frequency, duration and seasonality have not yet been detected although hotter and drier years are generally associated with increased fire risk (Hennessy *et al*. 2005). Mean snow cover on the Australian Alps has declined significantly between the periods 1960–1974 and 1975–1989. Maximum winter snow depth has declined by about 40% since the 1960s (Nicholls 2005).

Substantial warming has also occurred in the three oceans surrounding Australia, particularly off the south-east coast and in the Indian Ocean (CSIRO and BOM 2007), and the East Australian Current (EAC) has penetrated further to the south and increased in strength by about 20% since the late 1970s. The region has become both warmer and saltier over the 1944–2002 period, which corresponds to a poleward advance of the EAC of 350 km (Cai 2006; Ridgway 2007). Sea level at sites monitored around the Australian coast from 1920 to 2000 rose by about 1.2 mm/year (Church *et al*. 2006), with large regional variation due in part to different rates and directions of land movement. Sea levels across northern Australia are rising at 7.8–8.3 mm/year (National Tidal Centre 2006), about four times the global average.

The acidity of marine waters around Australia is increasing (lower pH). There is a north-south gradient in the rate of change in acidity, with southern seas becoming more acidic faster than northern because cold water absorbs more CO_2 (Hobday *et al*. 2007).

While there have been increases in the frequency of intense cyclones in both the Pacific and Atlantic oceans (Easterling *et al*. 2000), the total number of tropical cyclones along the east coast of Australia has declined since the 1970s. However, there has been an increase in the number of very intense systems (Kuleshov 2003).

4.3 Projections of future climate

The projected rate of temperature increase for the rest of this century far exceeds that experienced during the past several million years. The transition from the Last Glacial Maximum (about 20,000 years ago) to the present (Holocene) climate took over 5000 years, compared with a potential recent change of similar magnitude in only 100 years. The degree to which Australia's biodiversity will be affected by climate change will depend on the magnitude and rate of climate change that is realised this century and beyond.

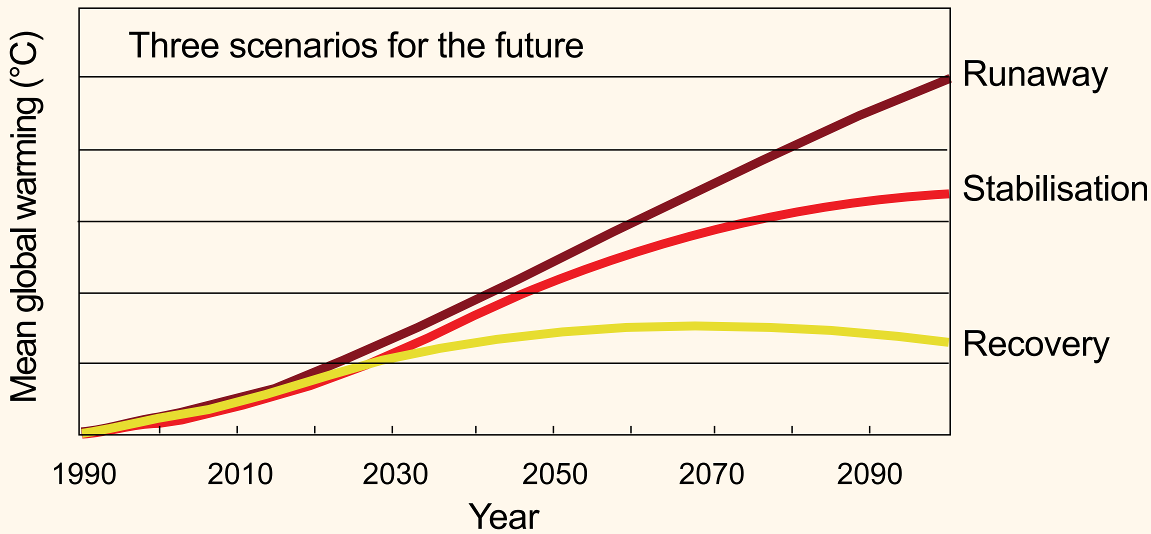
One of the greatest sources of uncertainty around what the global climate might be in the year 2100 is the extent to which nations act to limit CO_2 emissions in the coming decades. The range of model projections of global mean temperature through the rest of the century shown in Figure 6 can therefore be schematised as three contrasting climate scenarios related to this degree of mitigation response. These scenarios (Figure 9), which provide the basis in this assessment for analysing future responses of

Australia's biodiversity to climate change, are:

- 'recovery', assuming that vigorous global mitigation efforts will succeed in limiting climate change to a temperature rise of 2°C or less, with a recovery towards the pre-industrial climate within 100–200 years
- 'stabilisation', assuming that the climate is eventually stabilised but at a significantly higher level than pre-industrial levels (ca. 3–4°C) and with a much longer time to return to pre-industrial values
- 'runaway', assuming unmitigated climate change, with accelerating change through this century and no stabilisation in sight. In this scenario the global mean temperature would be ca. 5–6°C higher than pre-industrial levels by 2100 and still rising.

More detailed information on the projections of Australia's future climate is given in the full assessment.

Figure 9 – Three scenarios of future climate: recovery, stabilisation and runaway. Drawn using the IPCC suite of scenarios (IPCC 2007a) as driven by different assumptions about how humanity responds to the challenge of mitigating CO_2 emissions over the coming century. The shorthand names range from the most optimistic 'recovery', through the more realistic 'stabilisation' to the pessimistic 'runaway' (along which the world is currently tracking).

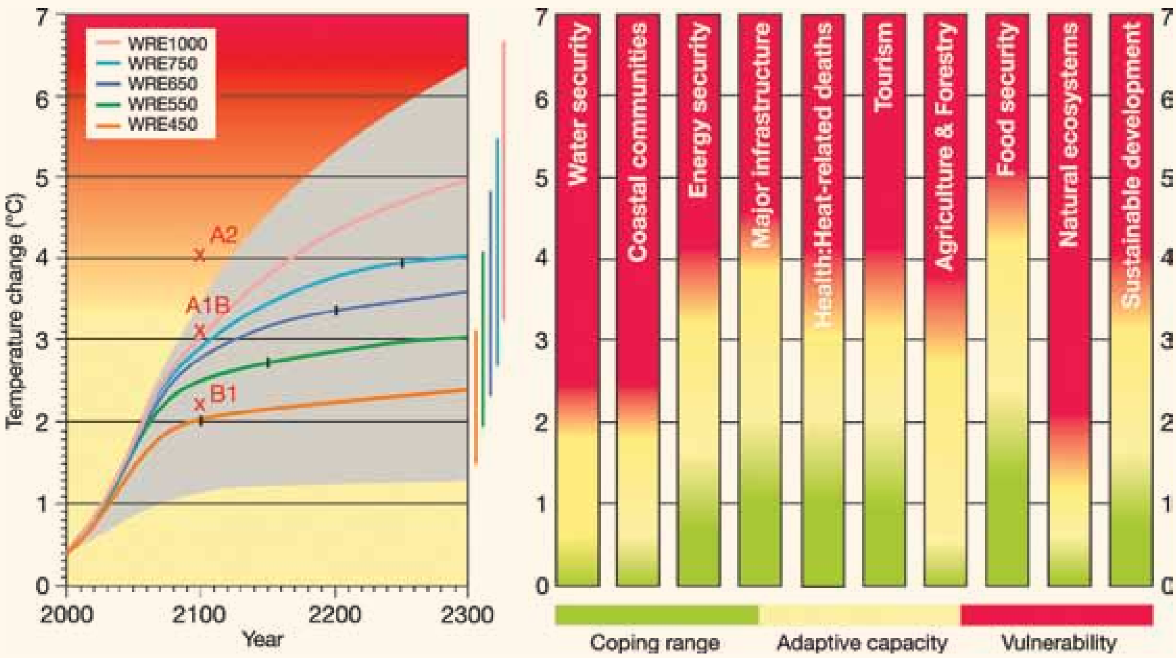


Source: Mark Stafford Smith (CSIRO Sustainable Ecosystems).

5. Biodiversity and climate change: impacts and responses

The IPCC (2007) has highlighted that biodiversity is likely to be the most vulnerable sector for the Australian and New Zealand region (as it is in general around the world), largely reflecting the very low adaptive capacity of natural ecosystems compared with other sectors (Figure 10). This section describes the vulnerability of Australia's biodiversity, documents observations of how the Australian biota is already responding to a climate change signal and outlines potential changes that may occur in the future.

Figure 10 – Vulnerability to climate change aggregated for key sectors in the Australian and New Zealand region allowing for current coping range and adaptive capacity. The right-hand panel is a schematic diagram assessing relative coping range, adaptive capacity and vulnerability. The left-hand panel shows global temperature change taken from the synthesis report of the IPCC Third Assessment Report. The coloured curves in the left panel represent temperature changes associated with stabilisation of CO_2 concentrations at 450 ppm, 550 ppm, 650 ppm, 750 ppm and 1000 ppm. Year of stabilisation is shown as black dots.



Source: IPCC (2007b).

The ecological principles of Table 4 are directly applicable to an assessment of biodiversity vulnerability and responses to climate change. In applying these ecological principles to consider environmental change that may result, it is important to understand that:

- the threats to biodiversity from climate changes arise from changes in the basic physical and chemical environment underpinning all life – especially CO_2 concentrations, temperature, precipitation, and acidity – unlike other threats such as land clearing and introduced species
- the *rate* of current warming and other associated changes in climate is unprecedented since the last massive extinction event 60 million years ago.

Identifying and predicting the effects of such rapid climate change on biodiversity is complicated by the fact that many of Australia's species and ecosystems are already under great pressure from other drivers of change. Indeed, it is often difficult to attribute the recently observed changes in species characteristics and ecosystems to a specific cause, such as climate change. Nevertheless, scientists and managers have already documented changes in species, communities and ecosystems that carry a 'climate signal', being consistent with recorded changes in temperature, precipitation, CO_2 concentrations and/or sea level.

5.1 Australia's biodiversity: already responding to climate change?

Observed changes in Australian species and ecological communities

On other continents, particularly in the northern hemisphere, the availability of long-term biological datasets has enabled the extensive documentation of recent climate and biological trends. The clearest evidence for such changes comes from observations of phenology (mostly advances in life cycle events) and geographic range shifts (mostly northwards and to higher elevations (many reviews cited in full assessment). To the extent that similar organisms respond to climate change in similar ways in Australia, we have confidence that many changes in species' life cycles and distribution recently observed in Australia are also consistent with having a climate change signal, mainly due to changes in temperature and rainfall.

Most of the recently observed changes in biodiversity have been at the species level, due partly to the visibility of larger mobile species such as birds, and partly to the nature of biological organisation itself. 'Fast' processes such as dispersal, migration and population growth in small organisms are more obvious in many species, with greater time lags predicted in responses of 'slow' processes such as vegetation change, reef building, or reproduction and recruitment in large, long-lived organisms.

Table 5 provides some examples of recently observed changes in Australia that are consistent with having a climate change 'fingerprint'. This is not an exhaustive list, but highlights the wide range of responses, taxa and communities that appear to be responding to recent changes in climate. What is most remarkable about these observations and those globally, is that in many cases significant impacts are apparently occurring with extremely modest increases in temperature compared with what is expected over the coming decades.

Table 5 – Examples of observed changes in Australian species and communities consistent with a climate change signal

Type of change	Observations
Geographic ranges	Increased penetration of feral and native mammals to higher elevations in alpine and sub-alpine areas and prolonged presence of macropods in winter; range shifts and expansions of several bird species to higher elevations or higher latitudes; southerly range shifts of both black and grey-headed flying foxes; southern range extension of the barrens-forming sea urchin from the mainland to Tasmania, associated with increased southerly penetration of the East Australian Current; coral reefs establishing at higher latitudes at Rottnest Island in Western Australia, attributed to both warmer temperatures and lack of competition from macroalgae; changing composition of phytoplankton blooms off Tasmania and southerly range extensions of many fish species
Life cycles	Earlier arrival and later departure times of migratory birds in Australian breeding and feeding grounds; changes in number of breeding seasons per year and altered patterns of overwintering in birds in south-east Queensland; earlier mating and longer pairing of the large skink
Populations	Reduced reproduction in wedge-tailed shearwaters on Great Barrier Reef islands associated with higher sea temperatures; higher sea surface temperatures and recent El Niño events also associated with population declines in northern Australian birds; declines in mountain pygmy possum and broad-toothed rat associated with declining snow cover, drought effects on food supply, loss of habitat after fire and increased predation (feral cats and foxes); significant changes in growth rates of long-lived Pacific fish species; mortality of montane and central plateau eucalypts in Tasmania linked to a 30-year rainfall deficit
Ecotonal boundaries	Expansion of rainforest at the expense of eucalypt savanna woodland and grassland in the Northern Territory, Queensland and New South Wales associated with increases in rainfall and changes in fire regimes; encroachment by snow gums into sub-alpine grasslands at higher elevations; woody shrub expansion into alpine heathlands and grasslands; saltwater intrusion into freshwater wetlands since the 1940s in the Northern Territory has been accelerating since the 1980s, possibly associated with changes in sea level and rainfall, but also with impacts of introduced buffalo; plant colonisation of areas exposed by glacial retreat, and changes in competitive relationships in plant communities on Heard Island; decline in area of sphagnum moss since 1992 on Macquarie Island associated with drying trend
CO_2-related impacts	Woody 'thickening' of vegetation in some parts of northern Australia, consistent with a trend observed throughout the world's savannas and grasslands
Ecosystems	Eight mass bleaching events since 1979 on the Great Barrier Reef triggered by unusually high sea surface temperatures; no serious events known prior to 1979. Most widespread events occurred in the summers of 1998 and 2002, affecting up to 50% of reefs within the Great Barrier Reef Marine Park; declines in live coral cover followed by declines in obligate coral-feeding fish
Disturbance regimes	Fire regimes have changed over the past two decades throughout Australia, consistent with drier and hotter climate in the southern part of the country

Source: Lesley Hughes (Macquarie University).

Observed changes in Australian ecosystems

At the ecosystem level, observed changes in Australia cannot be attributed definitively to climate change to date, largely because of the many significant changes to the structure and functioning of ecosystems caused by the range of natural and human drivers of change. However, there is one notable exception – coral reefs. Although reefs are subject to a number of direct human stressors – such as fishing, and nutrient and sediment runoff from adjacent coastal regions – climate change has produced multiple, discernible impacts on the reefs, leading to overall decline in reef health and resilience (Box 2).

Box 2 – Climate change and the Great Barrier Reef

The Great Barrier Reef World Heritage Area is one the most biologically diverse regions in the world. Climate change is now recognised as the greatest long-term threat to the Great Barrier Reef (GBR), with implications for nearly every part of the ecosystem. Coral reefs are among the most vulnerable of all ecosystems to climate change, due in large part to the high sensitivity of corals to small increases in water temperature. When sea temperatures exceed the long term summer maximum by only 1–1.5°C for as little as six weeks, extensive coral bleaching occurs, leading to widespread coral mortality if temperatures do not return to normal levels. Unusually warm sea temperatures have now caused serious and lasting damage to 16% of the world's coral reefs. While the Great Barrier Reef has fared well by comparison, major bleaching events in 1998 and 2002 saw over 50% of reefs bleached and up to 5% seriously damaged in each year.

However, the impacts of climate change extend beyond the immediate effects on corals: a vast array of organisms depend on corals for habitat and food, and many more will be affected directly or indirectly by shifts in environmental conditions brought about by climate change. In an effort to understand the full implications of climate change, the Great Barrier Reef Marine Park Authority (GBRMPA) coordinated the *Climate change and the Great Barrier Reef: a vulnerability assessment*. This collaboration between over 80 leading climate and marine experts presents climate projections for the GBR region to 2100, assesses how these changes will affect the GBR and identifies strategies that can minimise climate change impacts.

Climate projections for the GBR region show that sea and air temperatures will continue to increase, sea level will continue to rise, the sea surface waters will continue to become more acidic, ocean currents will change, and intense storms and rainfall will become more frequent. The vulnerability of different species groups to these changes varies widely; hard corals are extremely vulnerable to changes in sea temperature and ocean acidification, whereas many fleshy and turf macroalgae are likely to benefit from increased substrate and nutrient availability. An overwhelming conclusion of the GBR vulnerability assessment is that key components of the GBR are highly vulnerable to climate change, and signs of this vulnerability are already evident. Some further degradation is inevitable as the climate continues to change, but the extent of the decline will depend on the rate and magnitude of climate change and the resilience of the ecosystem.

Adaptive, resilience-based management offers the best hope of limiting the impacts of climate change on the GBR. Management and governance systems need to be flexible so that managers can respond rapidly to opportunities to reduce local stresses, to protect sites with favourable characteristics or modify management practices as ecosystems change. Understanding the social and economic implications of climate change for communities and industries that depend on the Reef, such as fisheries and tourism, will also be important to assist with adaptation and ensure sustainable industries into the future. The focus must be on facilitating adaptation to bring about positive changes in the interactions between people and the Reef.

Source: Paul Marshall, Great Barrier Reef Marine Park Authority.

5.2 What does the future hold for Australia's biodiversity?

Predicting the *future* effects of climate change on Australia's biodiversity is complicated for a number of reasons, including the following:

- Climate change will interact with other drivers that are currently affecting biodiversity.
- Responses to physical and chemical changes will be individualistic – they will occur at the level of the individual, and be reflected in population dynamics of individual species. The component species or functional groups within an ecosystem will therefore not respond as a single unit, and interactions among species will have the potential to modify outcomes, sometimes in unpredictable ways.
- Even with application of general principles (Table 4), some properties of biological and ecological systems are inherently difficult to track. For example: (i) a change in the average value of a continuous

environmental variable (such as temperature) may not be as important biologically as a change in variability or extremes of that variable; and (ii) responses of biological systems may be non-linear, with thresholds or 'tipping points' not yet identified.

- Basic knowledge about limiting factors, genetics, dispersal rates and interactions among species that make up Australian communities and ecosystems is generally lacking.
- Management actions taken to adapt and/or mitigate the impacts of climate change on human systems could have further adverse impacts on biodiversity.

Underlying physiological processes

Changes in the physical environment affect physiological processes in plants and animals such as respiration, photosynthesis, metabolic rate and water use efficiency. Individuals may also respond to environmental change by altering their behaviour or the timing of life cycle events (phenology) such as flowering, dispersal, migration and reproduction. All organisms are able to cope with some degree of variability in their environment, and to maintain homeostasis and reproduction within the bounds of that variability. Beyond some physiological threshold, however, responses change quite dramatically and death may result.

The response of plants to rising CO_2 is also important, especially coupled with warming and/or altered rainfall patterns, as any differences among plant species could have large secondary impacts on plant community structure, animals that use plants as habitat or food, and even nutrient cycles in ecosystems.

Will species stay or move?

Organisms experiencing environmental change may tolerate the change *in situ* (i.e. individuals acclimatise or adapt at the site) and/or disperse away from their current location. The rate of environmental change is crucial in determining which response (that is, *in situ* adjustment versus dispersal) is more likely and/or more successful for any species. All *in situ* and dispersal responses have the potential to change the population size (abundance) and/or distributional range of a species, either positively or negatively.

Individualistic responses of species to climate change mean that many communities and ecosystems could change from current compositions. Differential rates of dispersal as climate zones shift, for example, mean that communities will not 'move' as units across a landscape. With the current rapid rate of climate change, novel combinations of species will most certainly appear in the future, creating communities that have no present day analogue (Hobbs *et al*. 2006; Lindenmayer *et al*. 2008).

Which species will be 'winners' and 'losers'?

Responses of species to rapid climate change will vary, with some species potentially advantaged ('winners'), and others disadvantaged ('losers') (Figure 11). The vulnerability of an individual species will depend on: (i) life history traits and other traits (Thuiller *et al*. 2005); (ii) degree of exposure of the habitat and region where the species lives; and (iii) capacity of the species to adapt, either genetically or behaviourally.

Life history traits

The suite of traits that predispose a species to being vulnerable to disturbance and threats, such as land clearing or invasive species, overlap with the suite of traits that predispose species to risk from rapid climate change (Figure 10). Those species with traits that may advantage them in a rapidly changing climate may also be advantaged in disturbed areas, and may be successful invaders and colonists. Indeed, many species, both native and exotic, that are not currently considered to be invasive may expand their ranges and increase in abundance to such an extent that they have transforming, and negative, impacts on other species and ecosystems. Within wide-ranging species, individual populations may be affected differently, either because of ecotypic differences (i.e. local adaptations) or regional variation in climate, or both (King *et al*. 1995).

Figure 11 – Physiological and life history traits of species that influence vulnerability or resilience in response to climate-related disturbance

Species least at risk	Species most at risk
• Physiological tolerance to broad range of factors such as temperature, water availability and fire • High degree of phenotypic plasticity • High degree of genetic variability • Short generation times (rapid life cycles) and short time to sexual maturity • High fecundity • 'Generalist' requirements for food, nesting sites, etc. • Good dispersal capability • Broad geographic ranges	• Narrow range of physiological tolerance to factors such as temperature, water availability and fire • Low genetic variability • Long generation times and long time to sexual maturity • Specialised requirements for other species (e.g. for a disperser, prey species, pollinator or photosynthetic symbiont) or for a particular habitat that may itself be restricted (e.g. a particular soil type) • Poor dispersers • Narrow geographic ranges

Source: Lesley Hughes (Macquarie University).

Of particular concern is that many species of Australian flora and fauna are endemic, with restricted climatic and geographic ranges. For example, over 50% of Australian eucalypt species, the tree genus that dominates all but the most arid landscapes, have distributions that span less than 3°C of mean annual temperature, with 25% spanning less than 1°C (Hughes *et al*. 1996). However, many of Australia's endemic species have adapted to a highly variable climate, especially in arid and semi-arid regions, and thus may have greater resilience to climate variability than their narrow ranges might otherwise suggest. In addition, their narrow ranges may be due to species–species interactions rather than to their fundamental environmental niche.

The ability to disperse, particularly across fragmented landscapes, will be a crucial factor determining a species' capacity to adapt to shifting climate zones. Plants with small, numerous seeds dispersed by wind will be better able to disperse to new sites, although they may be at a disadvantage during their establishment phase if they have to compete with existing vegetation. Plants with seeds dispersed by vectors that are themselves capable of long-distance movement, like birds or bats, may also be advantaged. Animals capable of flight will also disperse faster, and many observed range shifts attributed to climate change are in such species (birds, butterflies, flying foxes). In marine environments, the length of the larval development time is positively correlated with dispersal distance. There appears to be a bimodal distribution of dispersal with some species tending to develop quickly (sometimes in just minutes to hours), and disperse less than 1 km during this time. Other species may spend weeks to months in the dispersive phase, and be able to dispersal many kilometres (Shanks *et al*. 2003). Warming temperatures will tend to reduce development time and thus reduce dispersal distance (O'Connor *et al*. 2007). Species confined to freshwater lakes and waterways may only be able to disperse along temperature gradients if the geography permits, and may otherwise be trapped within increasingly hostile environmental conditions.

Degree of exposure

The degree and rate of climate change in the future will vary from region to region. Relatively more warming is expected for the inland, compared with coastal regions. Australian arid-zone species, however, have evolved in a habitat with both great climatic extremes and high inter-annual variability, and may therefore be better equipped than mesic or coastal species to cope with rapid change. Many species have reproductive strategies that are highly opportunistic, being cued to occasional rainfall events. Australia also has a high proportion of species that are facultatively migratory, especially butterflies and birds; these species are able to migrate relatively long distances to take advantage of favourable conditions. Warming is also expected to be relatively less at lower latitudes, so tropical species may be affected more slowly by warming trends than temperate species (CSIRO and BOM 2007; IPCC 2007a). These species, however, may have less intrinsic capacity to withstand even fairly modest changes, having evolved in a region with a more predictable environment. Predicted rainfall changes in northern regions are also relatively small compared to present patterns of temporal and spatial variability. These regions, however, may well bear the impact of rising sea level sooner than many other parts of the continent.

Within a habitat, some species may have more opportunity than others to take advantage of differences in microhabitats. Regions with high topographic relief, such as dissected plateaus with cool, moist gorges, may continue to provide refugia for some species as the regional climate warms. Species restricted to high elevations or high latitudes, to low-lying islands (see Box 3) or to ephemeral habits such as intermittent streams and inland wetlands will be particularly at risk in the near term.

Box 3 – Australia's islands and sea level rise: Houtman Abrolhos Islands example

Thousands of islands occur within Australia's jurisdiction including oceanic islands that are volcanic in origin such as Christmas Island in the Indian Ocean, continental islands that were isolated from the mainland by rising sea levels during the Pleistocene, and coral and sand cays that have accumulated on reefs. Many of these islands are extremely important for biodiversity.

Low-lying islands are often important seabird nesting sites and sea turtle rookeries. As is the case elsewhere in the world, Australia's low-lying islands will be significantly affected by sea level rise. Examples include the Houtman Abrolhos Islands off the west coast, the islands of the Capricorn group at the southern end of the Great Barrier Reef (including Heron, Lady Musgrave and North West islands), cays in the Coral Sea and islands in the Torres Strait.

The Houtman Abrolhos comprises about 120 small, low-lying islands, and has the greatest species diversity and largest concentration of breeding seabirds in the eastern Indian Ocean. It also provides a base for rock lobster fishers each year during the lucrative Abrolhos season and is a significant tourist destination. The mixture of species is unique, as the breeding islands are shared by subtropical (cool water) and tropical species, and littoral and oceanic foragers. One listed threatened seabird, the lesser noddy *Anous tenuirostris melanops*, breeds only in three small areas of white mangrove *Avicennia marina* on three low Houtman Abrolhos islands.

Source: Andrew Burbidge.

Capacity to adapt

Some species may adapt genetically, or have sufficient phenotypic plasticity to tolerate new conditions *in situ.* Others may be able to cope, at least in the short- to medium-term, by altering their use of microhabitats or by shifting their geographic range. For mobile species physically capable of travelling some distance to more suitable areas, their capacity to do so will depend on the 'permeability' of the landscape matrix between suitable habitats. Some species, although capable of shifting their range, will be prevented from doing so by physical barriers such as coasts or extensively cleared agricultural land. Species that are currently restricted to Tasmania or southern parts of the continent, to isolated lakes and waterways or to mountain tops, will simply have nowhere to go. Marine species confined to the continental shelf (waters <200 m) will also run out of habitat in the south of Australia, because warming will continue to occur from the north along both east and west coasts.

5.3 Predicted general trends

Species

From an assessment of the part played by species life histories, degree of exposure and capacity to adapt, we can make broad predictions as to what general trends to expect in species responses to climate change over the next few decades:

- local extinctions of populations may occur at the lower elevations and northern or hottest edges of species ranges as individuals become progressively more stressed by increasing temperatures and/or physiological thresholds are exceeded on hot days
- colonisation of new sites at higher elevations and at the southern or cooler edges of species ranges as establishment success increases due to reductions in frosts or limiting cold days
- continued observations of range expansions of the more mobile species to the south or at higher elevations
- progressive decoupling of present-day interactions between species as species respond at different rates to climatic and atmospheric changes
- spread of ecological generalists (both native and exotic) at the expense of native specialists via competition, predation and/or disease
- possible global extinctions of narrow ranged endemics, especially species with low dispersal ability, and species already confined to the highest elevations of montane areas, southern coastal areas and low-lying coastal habitats
- geographical ranges of widespread species will become fragmented with smaller, patchily distributed populations.

Species interactions

Climate change is affecting and will continue to affect interactions between species. As any one species becomes advantaged or disadvantaged, all species with which it interacts (e.g. pollinators, competitors, predators) will likely be affected. Indeed, such indirect biotic effects will almost surely have greater impacts than the direct impacts of changes in temperature and rainfall. Potential changes in species interactions include the following:

- changes in the synchrony of life cycles because one partner in an interaction is cued differently by warming temperatures from the other. This type of change may be particularly important for species whose successful reproduction relies on seasonal food supplies, such as fledgling birds which rely on a spring flush of emerging insects and plants that rely on a small number of insect pollinators. In some interactions, photoperiod may be a cue for the behaviour of one partner, while temperature may trigger behaviour in the other
- changes in plant–herbivore interactions mediated by changes in the chemical composition of plants as atmospheric CO_2 increases. Plants grown at elevated CO_2 are generally less nutritious due to increased C–N ratios and reductions in digestibility. The performance of insect and other herbivores feeding on plants grown at elevated CO_2 is generally reduced. Despite increased consumption rates, these insects often develop more slowly, have reduced body size and fecundity as adults, and are more vulnerable to parasitism and predation. All herbivores may potentially be affected, but impacts may be particularly severe for arboreal vertebrates (folivores) that may not be able to increase their consumption sufficiently to compensate for reductions in nitrogen content and digestibility (Kanowski 2001)
- changes in competitive interactions between plant species with different growth forms, different carbon-fixing pathways (C3 vs C4) or nitrogen-fixing capabilities (legumes vs non-legumes)
- differential dispersal rates under the influence of shifting climate zones may result in the geographic ranges of species that currently interact no longer doing so. For example, flying herbivorous insects may shift their ranges faster than the host plants on which they currently feed, potentially resulting in colonisation of new hosts.

- changes in the virulence of parasitic infections and diseases and in the susceptibility of hosts may have large impacts. In particular, vector-borne diseases may spread upwards in elevation and southwards as mosquitoes and other vectors respond to warming. The potential impact of climate change on the incidence and distribution of the chytrid fungus may have significant impacts for the already threatened Australian amphibian fauna (Pounds *et al*. 2006)
- differences in the growth rates of coral species will affect their response to rising sea levels, with the faster-growing species expected to take advantage of new colonisation sites, and cascading impacts expected for the structure and composition of reef communities
- changes in interactions between humans and other species, for example, if human-adaptive responses result in further modification of natural landscapes.

The general species-level predictions outlined above can be extended to further predictions about the vulnerability of particular taxa (Table 6). Of the taxa listed in the table, only birds have received any systematic attention in Australia to identify particular species at risk (Olsen 2007).

Table 6 – Examples of factors that will increase vulnerability to climate change of particular taxa

Taxa	Potential vulnerability
Mammals	Narrow-ranged endemics (particularly in montane regions) susceptible to rapid climate change *in situ* (Williams *et al*. 2003); changes in competition between grazing macropods in tropical savannas mediated by changes in fire regimes and water availability (Ritchie *et al*. 2008); herbivores affected by decreasing nutritional quality of foliage as a result of CO_2 fertilisation
Birds	Changes in phenology of migration and egg-laying; increased competition of resident species with migratory species as the latter species staying at breeding grounds for longer periods; breeding of waterbirds susceptible to reduction of freshwater flows into wetlands; top predators such as some sea birds vulnerable to changes in food supply as a result of ocean warming; rising sea levels affecting birds that nest on sandy and muddy shores, saltmarshes, intertidal zones, coastal wetlands and low-lying islands; saltwater intrusion into freshwater wetlands, especially in northern Australia, affecting breeding habitat
Reptiles	Warming temperatures may alter sex ratios of species with environmental sex determination (ESD) such as crocodiles and turtles; some species likely to modify use of microhabitats to cope with warming *in situ*
Amphibians	Frogs may be the most at-risk terrestrial taxa. Altered interactions between frogs and the pathogenic chytrid fungus *Batrachochytrium dendrobatidis* may occur, with changes in both host susceptibility and pathogen activity; higher temperatures shift the growth optimum of the fungus, encouraging outbreaks; susceptibility to competition and predation by cane toads as their range expands with warming; threatened alpine species such as the southern Corroboree frog *Pseudophryne corroboree*, at risk from drying and fire impacts on bogs used as breeding sites
Fish	Freshwater species vulnerable to reduction in water flows and water quality; limited capacity for freshwater species to migrate to new waterways; all species susceptible to flow-on effects of warming on the phytoplankton base of food webs
Invertebrates	Expected to be more responsive than vertebrates due to short generation times, high reproduction rates and sensitivity to climatic variables. Flying insects such as butterflies may be able to adapt by shifting range, as long as they are not limited by host plant distributions; non-flying species with narrow ranges susceptible to rapid change *in situ* (e.g. estimated that 25% of insect diversity in the Wet Tropics may be threatened this century); genetic changes already observed in some widespread species such as *Drosophila* spp.; invertebrate herbivores also affected by reduced foliar quality under elevated CO_2

Taxa	Potential vulnerability
Plants	Longer-lived plants such as trees may be very vulnerable if climate change 'moves' suitable establishment sites for seedlings beyond seed dispersal distance at a rate exceeding generation time. Narrow-range endemic plants requiring very specific set of environmental characteristics (such as specific soil types) will have limited capacity to disperse to similar, rare sites. Elevated CO_2 will increase photosynthetic rates, as long as other factors such as water and nutrients are not limiting. There is potential for productivity to be boosted in some regions by a combination of increased CO_2 and longer growing seasons. This effect however, may not occur in regions where drying occurs. Increasing CO_2 will increase water use efficiency at an individual plant level, especially in C3 plants, but at an ecosystem level total water use may not necessarily decrease due to decreased total leaf area, and increased evaporation from soil as a consequence of warmer temperatures. Competition between C3 and C4 plants may be affected by elevated CO_2 due to differential responses but soil moisture may be a stronger influence than photosynthetic pathway. Any changes in productivity and foliar nutrients will have flow-on effects to herbivores. Changes to fire regimes will have significant impacts on vegetation; increases in frequency and intensity of fires may disadvantage obligate seeders relative to vegetative resprouters. Changes in the timing of plant phenology and insect life cycles will affect pollination and some forms of dispersal

Source: Lesley Hughes (Macquarie University).

Communities and ecosystems

Table 7 summarises how some of the most important Australian ecosystems might be expected to respond as both biotic and abiotic components of the system undergo change. For a few of the ecosystems, the interaction of climate change effects with the ongoing impacts of current stressors is described. However, in general this is a largely unknown area of understanding, and thus constitutes one of our major knowledge gaps (next section). Closing this gap is especially urgent, given the importance of ecosystem functioning for the provision of ecosystem services.

Table 7 – Projected impacts of CO_2 rise and climate change on key Australian ecosystems

Key component of environmental change	Projected impacts on ecosystems
Coral reefs	
CO_2 increases leading to increased ocean acidity	Reduction in ability of calcifying organisms, such as corals, to build and maintain skeletons
Sea surface temperature increases, leading to coral bleaching due to the death of symbiotic algae in coral polyps	If frequency of bleaching events exceeds recovery time, reefs will be maintained in an early successional state or be replaced by communities dominated by macroalgae; warming will increase susceptibility of corals to diseases such as white syndrome, leading to outbreaks in locations of high coral density; potential for new reefs to develop at higher latitudes where suitable substrates are available and until light becomes limiting; potential decrease in beta diversity of coral communities as tropical-adapted taxa expand their range to the south, amplified by differential survival of different taxa
Increase in cyclone and storm surge	Increased physical damage to reef structure
Rising sea levels	Fast-growing corals advantaged over slow-growing species, leading to changes in structure and composition of reef communities

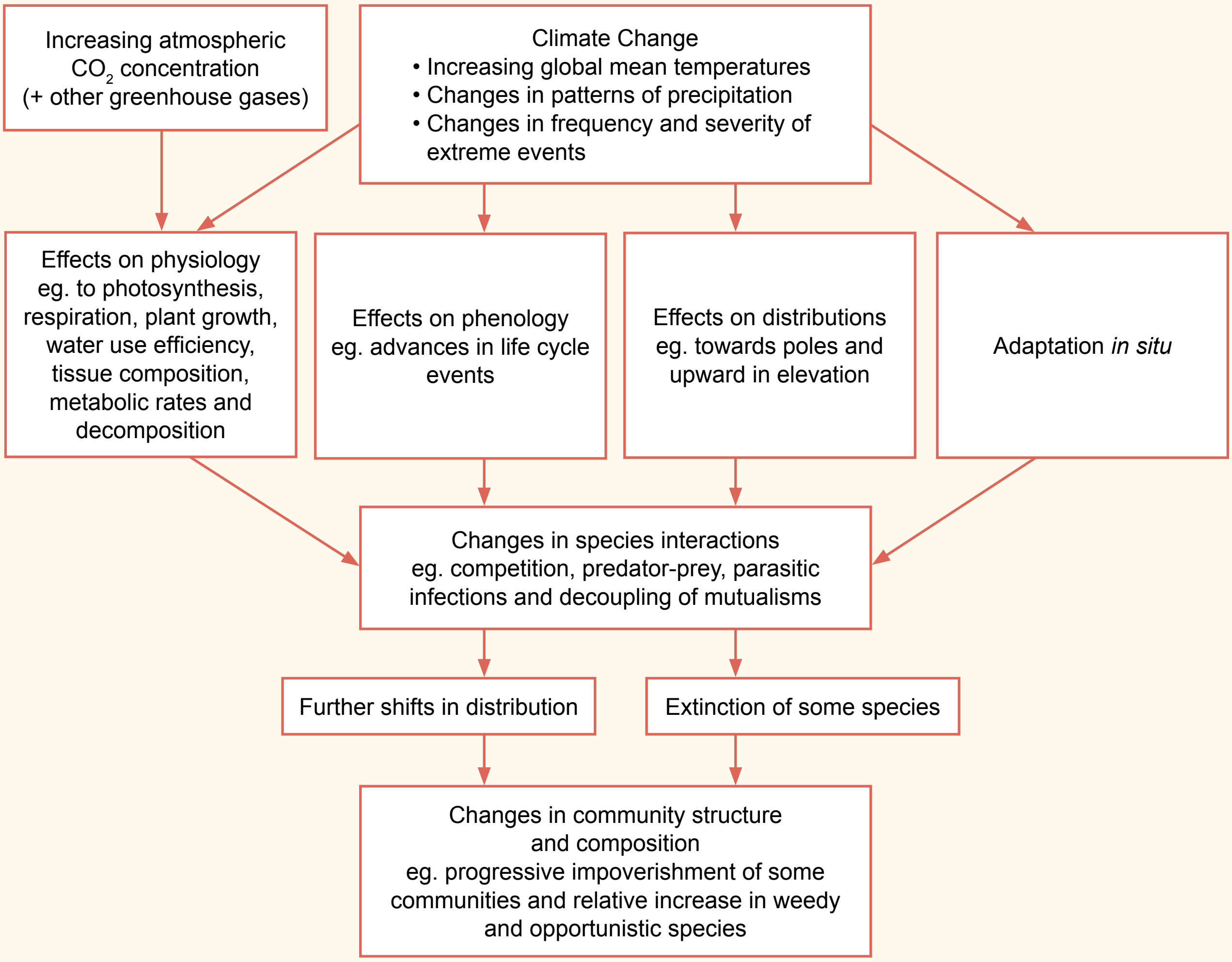
Key component of environmental change	Projected impacts on ecosystems
Oceanic systems (including planktonic systems, fisheries, sea mounts and offshore islands	
Ocean warming	Many marine organisms are highly sensitive to small changes in average temperature (1–2°C), leading to effects on growth rates, survival, dispersal, reproduction and susceptibility to disease; in particular, increasing temperatures reduce larval development time, potentially reducing dispersal distances during this phase; warm-water assemblages may replace cool-water communities, with coastal species endemic to the south-east most at risk; little is known about potential impacts on fish populations due in part to limited baseline information on fish stocks
Changed circulation patterns, including increase in temperature stratification and decrease in mixing depth, and strengthening of East Australian Current	Distribution and productivity of marine ecosystems is heavily influenced by the timing and location of ocean currents; currents transfer the reproductive phase of many organisms, thus playing a key role in dispersal and maintenance of populations; currents also play a role in nutrient transport, by bringing cooler, nutrient-rich waters to the surface through upwelling, and thus increasing productivity; climate change may suppress upwelling in some areas and increase it in others, leading to shifts in location and extent of productivity zones
Changes in ocean chemistry	Increasing CO_2 in the atmosphere is leading to increased ocean acidity and a concomitant decrease in the availability of carbonate ions, the building blocks of calcium carbonate skeletons; many planktonic species and other species will be affected, as well as corals; increased dissolved CO_2 may increase productivity
Alterations in cloud cover and ozone levels, which alter solar radiation reaching the ocean surface	Potential negative impacts on phytoplankton production
Changes in timing of major climate phenomena such as El Niño events	Changes in seasonal cycles of plankton abundance, with potential for mismatch between phytoplankton blooms and zooplankton growth, leading to cascading effects to the rest of the marine food chain
Sub-antarctic islands	
Extension of ice-free season for lakes and pools on Macquarie, Heard and MacDonald islands	Increased length of the stratified period with deeper mixing
Warming associated with glacial retreat on Heard Island	Exposure of previously ice covered ground, colonisation by plants and invertebrates
Estuaries and coastal fringe (including benthic, mangrove, saltmarsh, rocky shore, and seagrass communities)	
Sea level rise	Landward movement of some species (especially mangroves) as inundation provides suitable habitat, which may be at the expense of other communities such as saltmarsh and freshwater wetlands; changes to upstream freshwater habitats will have flow-on effects to species such as wetland birds; rocky shore and saltmarsh species in areas of low topographic relief will be vulnerable to complete loss of habitat, especially when bounded by cliff lines or coastal development
Increased storm surges	Physical damage (erosion, slumping, rockfalls) to coastal zone, including beaches and rocky shores; changes to timing and magnitude of wrack (decaying plant material) washing up on estuarine and ocean shores
Increases in water temperature	Impacts on phytoplankton production will affect secondary production in benthic communities
Human adaptive responses to sea level rise and beach erosion, including artificial beach nourishment	Changes in composition of soft-sediment communities with cascading impacts to higher trophic levels

Key component of environmental change	Projected impacts on ecosystems
Changes in upstream river flows	Alteration in quality and quantity of detritus flowing into estuaries and near-shore communities, leading to disruption in detritus-based food webs; patterns of primary production in estuaries may shift from light-dependent nutrient-intolerant seagrasses to fast-growing macroalgae; distribution and transmissability of many marine diseases closely linked to water temperature and salinity
Savannas and grasslands	
Elevated CO_2	Shifts in competitive relationships between woody and grass species due to differential responses
Increased rainfall in north and northwest regions	Increased plant growth will lead to higher fuel loads, in turn leading to fires that are more intense, frequent and occur over large areas (compared to small-scale mosaic burning promoted by traditional Aboriginal practices) and occur later in dry season; synergistic impacts of introduced grasses such as gamba grass, which are intensifying fire regimes in general, and leading to hotter late season fires in particular; change to ecotonal boundaries between savanna woodlands, grasslands and monsoonal rainforest patches; increased rainfall may increase overall productivity and shift productivity belts southwards but predicted changes are small relative to the present degree of temporal and spatial variability
Tropical rainforests	
Warming and changes in rainfall patterns	Increased probability of fires penetrating into rainforest vegetation resulting in shift from fire-sensitive vegetation to communities dominated by fire-tolerant species; cool-adapted species forced to higher elevations, altering competitive interactions; potential for reduced population sizes as area of potential habitat decreases; changes in distribution of different rainforest types; rise in basal altitude of orographic layer will reduce occult precipitation (cloud stripping) in cloud forests, exacerbating effects of long-term drought
Change in length of dry season	Altered patterns of flowering, fruiting and leaf flush will affect resources for animals
Increased incidence of storms/ tropical cyclones	Increased physical disturbance to forests, altering gap dynamics and rates of succession; shallow-rooted tall rainforest trees particularly susceptible to uprooting, breakage and defoliation
Rising atmospheric CO_2	Differential response of different growth forms to enhanced CO_2 may alter structure of vegetation; growth of vines potentially enhanced proportionally more than trees, leading to increased tree mortality; enhanced CO_2 will increase overall productivity but decrease the digestibility and nutritional value of foliage for herbivores; reduced stomatal conductance under elevated CO_2 will reduce rates of transpiration and alter catchment water balance – this may in turn affect runoff to estuaries and coastal ecosystems, including coral reefs
Temperate forests	
Potential increases in frequency and intensity of fires	Changes in structure and species composition of communities with obligate seeders may be disadvantaged compared with vegetative resprouters
Warming and changes in rainfall patterns	Potential increases in productivity in areas where rainfall is not limiting; reduced forest cover associated with soil drying projected for some Australian forests
Increasing atmospheric CO_2	Overall increases in productivity and vegetation thickening

Key component of environmental change	Projected impacts on ecosystems
Inland waterways and wetlands	
Reductions in precipitation, increased frequency and intensity of drought	Reduced river flows and changes in seasonality of flows, exacerbated by competition with needs of agriculture and urban settlements; reductions in area available for waterbird breeding; increased rainfall in the catchment of Lake Eyre could transform it from an ephemeral to a permanent wetland; 55% of Australia's wetlands of international importance and 26% of wetlands of national importance are considered at high to very high risk in the near term; changes in species composition and community structure; more intense rainfall events will increase flooding, affecting movements of nutrients, pollutants and sediments, riparian vegetation, and erosion; groundwater-dependent ecosystems, such as cave streams and mound springs, may be negatively affected; organic wetlands likely to suffer more frequent burning of peaty sediments
Changes in water quality, including changes in nutrient flows, sediment, oxygen and CO_2 concentration	May affect eutrophication levels, incidence of blue-green algal outbreaks; loss of cool-adapted aquatic species, increase in populations of warm-adapted species; increased eutrophication at permanent water holes will have negative consequences for dependent fauna including grazing animals
Sea level rise	Saltwater intrusion into low-lying floodplains, freshwater swamps and groundwater; replacement of existing riparian vegetation by mangroves
Warming of water column; increase in depth of seasonal thermoclines in still water	Changes in abundance of temperature-sensitive species such as algae and zooplankton; reduction in depth of lowest, oxygenated zones in some cases, leading to local extinction of some fish and other vertebrates
Arid and semi-arid regions	
Increasing CO_2 coupled with drying in some regions	Interaction between CO_2 and water supply critical, as 90% of the variance in primary production can be accounted for by annual precipitation; competition between C3 and C4 grasses in sub-tropical regions; increased productivity
Shifts in seasonality or intensity of rainfall events	Any enhanced runoff redistribution will intensify vegetation patterning and erosion cell mosaic structure in degraded areas; woody vegetation may be favoured, leading to encroachment of unpalatable woody shrubs ('woody weeds') in many areas; changes in rainfall variability and amount will also have important impacts on fire frequency that greatly increases after wet periods; dryland salinity could be affected by changes in the timing and intensity of rainfall
Warming and drying, leading to increased frequency and intensity of fires	Reduction in patches of fire-sensitive mulga in spinifex grasslands, potentially leading to landscape-wide dominance of spinifex
Alpine/montane areas	
Reduction in snow cover depth and duration	Potential loss of species dependent on adequate snow cover for hibernation and protection from predators; increased establishment of plant species at higher elevations as snow pack is reduced; potential displacement of high-elevation species by competition as lowland species shift upwards; potential extinctions of summit-restricted species; changes to composition of snowbank/snow patch communities; changes in hydrology will affect distribution and persistence of fens and bogs, and their dependent species; potential increases in fire frequency following prolonged dry periods in non fire-adapted vegetation types; changes in timing of acclimation and deacclimation rates of snow gums to freezing temperatures; increased predation pressure on small mammals at higher latitudes from foxes and cats as snow declines; early spring thaw may advance phenology of many species including emergence of insects, flowering and bird migration; increased growth rates of extant shrubs may promote expansion of woody vegetation into areas currently dominated by herbaceous species; reduction in extent of persistent summer snowdrifts may allow shrubs, grasses and sedges to expand at the expense of cushion plants and rushes; potential increases in mammalian herbivory at higher elevations (macropods and feral horses), where herbivory has previously been dominated by invertebrates.

Source: Lesley Hughes (Macquarie University).

Figure 12 – Example of the potential pathways of community change flowing on from individual responses to climate change. Increased CO_2 concentration will act on species directly (via physiology) and indirectly (via climate changes) (first tier). Individual species might respond in four ways (second tier), resulting in changes in species interactions (third tier). These changes might then lead either to extinctions or to further shifts in ranges (fourth tier), ultimately leading to changes in the structure and composition of communities.



Source: Redrawn from Hughes (2000).

6. Dealing with complexity, uncertainty and knowledge gaps

It will be very important for biodiversity managers to focus on the biological and ecological qualities that give biodiversity (at all levels) increased resilience, i.e. the capacity to experience shocks while retaining essentially the same functioning, structure, feedbacks and therefore identity. This can apply to an individual species, or to a community or ecosystem, where the resilience refers to particular trophic structures or functioning. It also applies to maintenance of evolutionary processes through preservation of genetic diversity. Preservation of heterogeneity and diversity of environments is particularly important in providing avenues for resilience of biodiversity. In turn, society will be required to take appropriate action, in the face of uncertainty, that will increase the resilience of biodiversity. Current conservation policies and practices, although useful to some extent, are not yet fully adequate, given the continuing documented species losses and communities at risk.

Large and rapid changes in both climate and Australian biodiversity are taking place, implying that in many cases facilitating transformation of ecosystems may be a more appropriate response than trying to maintain the resilience of existing ecosystems. The degree to which society can predict transformations and assist ecosystems to transform to new states beneficial to both natural biodiversity and human society thus needs to be addressed with urgency. As indicated earlier, even predicting change at the level of individual organisms and populations is difficult, due to the lack of basic knowledge about the biology of Australian species and, in particular, about what currently limits their distributions. The following complex issues affect our ability to predict change at all levels of biological organisation.

6.1 Non-linearity, time lags, thresholds, feedbacks and rapid transformations

Biological systems, from individuals to ecosystems, generally respond to environmental changes in a non-linear fashion. Time lags also play a large role, mainly due to development times and life spans of individual organisms. Rapid transformations after a long period of no or little change are more the rule than the exception in populations, communities and ecosystems, perhaps due to complex internal interactions that are non-linear. These rapid transformations relate to 'tipping points' or 'critical thresholds' and occur when a relatively small perturbation qualitatively alters the state or development of a system (Lenton *et al.* 2008). Examples are numerous and found at all levels of the biological hierarchy (Box 4), although few have been described in Australia other than coral reef dynamics.

Box 4 – Examples of ecological 'surprise' following otherwise sensible management decisions. Both result from temperatures exceeding previously unknown thresholds, which allowed two generations of insects to be produced in a single year.

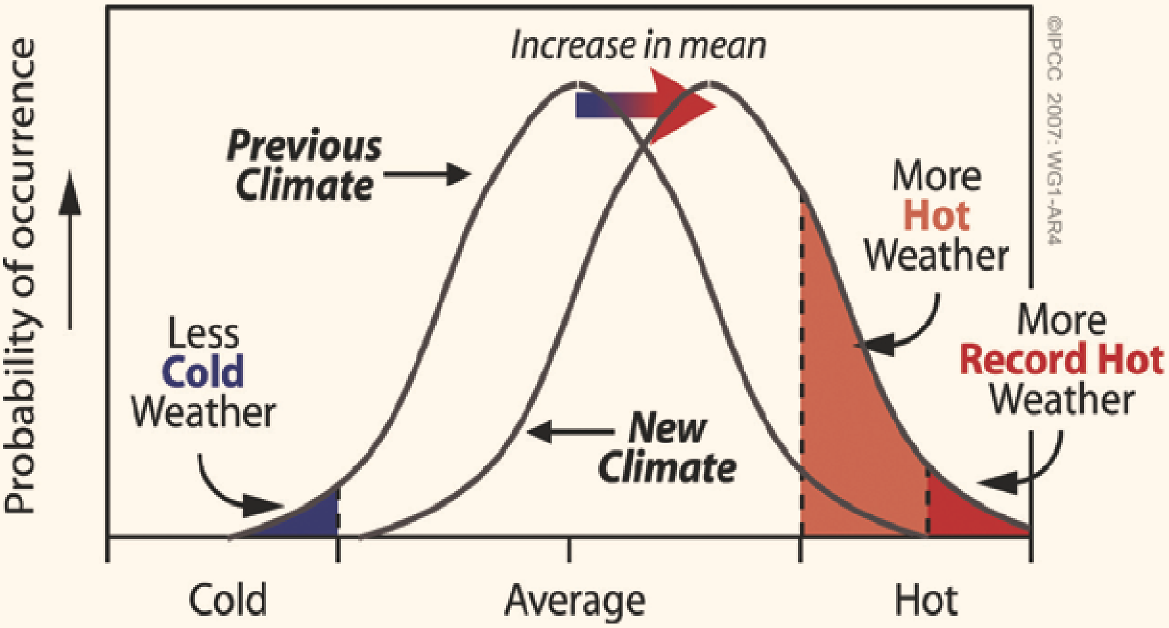
Wildfire management of coniferous forests – The issue of wildfires in spruce forests in Alaska has been a long-standing one (predating concern about climate change) and, as in many parts of the world, fire suppression has been practised in forests near human settlements to safeguard property and lives. Suppressing fires has led to stands of old growth/very mature forests that have not been subjected to a natural disturbance (fire) for unusually long periods of time. About a decade ago, under the influence of a warming climate, a herbivore in the forests, the spruce bark beetle, passed a threshold in which it could complete two life cycles in one growing season rather than one. This resulted in a population explosion of beetles that quickly devastated the very old and vulnerable trees. The result was the death of most of the trees that had been protected from fire and, ironically, wildfires then quickly spread through the stands, threatening lives and property. A grassland has now replaced the forest. Frequent fires in this community are preventing the re-establishment of the spruce trees and the conversion from forest to grassland appears permanent (Walker *et al*. 1999).

Immunisation campaign against tick-borne encephalitis – In the mid-1990s the county of Stockholm (Sweden) initiated an immunisation campaign to protect the population against tick-borne encephalitis. The immunisation campaign was highly successful in terms of the proportion of the population that was immunised, but yet the incidence of the disease did not decrease as expected. During the time that the immunisation campaign was being implemented, the climate in the Stockholm region warmed significantly and the tick that carries the disease now began to complete its life cycle in one rather than two years. Tick numbers exploded. In addition, the number of roe deer, the major host of the tick, had increased greatly due primarily to land cover changes around the region. The two processes – the immunisation campaign and the tick population explosion – offset each other. There was no change in the incidence of the disease (Lindgren 2000).

Source: Will Steffen (Australian National University).

Increasing frequency and intensity of extreme climate events also has the potential to more readily breach tipping points and thresholds. While community attributes like productivity are likely to change in response to changes in average values (means) of environmental variables such as temperature or precipitation, many aspects of species responses will be primarily affected by changes in the extreme values of a climatic variable (Parmesan *et al*. 2000) (Figure 13). The boundaries of a species' distribution may be determined by the maximum summer temperature in a location, or by the minimum winter temperature. For example, the green ringtail possum *Pseudochirops archeri*, a species endemic to the Queensland Wet Tropics, cannot tolerate more than 4–5 hours above about 30°C ambient temperature. Its geographic range is thus limited to cool montane rainforest uplands above 600 m where temperatures meet this requirement. Extreme, high temperatures also caused a significant number of deaths of Cape Barren Geese *Cereopsis novaehollandiae* on islands in the Recherche Archipelago, Western Australia, in 1991.

Figure 13 – Means vs extremes: the relationship between a shifting mean and the proportion of extreme events when extreme events are defined as some fixed physiological or life history threshold. Here the environmental variable is temperature. When the mean becomes warmer (for example, under climate change), the frequency of warm days past the threshold shows a disproportionate shift.



Source: IPCC (2007a).

An important limitation in our ability to predict future distributions of species is that most current projections of future climatic conditions are couched in terms of average temperature and rainfall. There is thus a mismatch between the output of climate models and the needs of researchers assessing impacts on particular systems and species. Furthermore, it is well known that while means and extremes of climatic factors such as temperature are correlated, the relationship is often highly non-linear. This problem is becoming increasingly well recognised but is likely to remain a stumbling block in predicting impacts for some time to come.

Potential large-scale 'surprises' in the Earth system, including climate, have been acknowledged for some time, and would have significant implications for biodiversity. They include abrupt changes (e.g. shutdown of the North Atlantic thermohaline circulation), gradual but irreversible changes (e.g. the melting of the Greenland ice sheet) and positive feedbacks such as the large discharge of methane from warming permafrost. In reality, if we can anticipate such events, they are not really surprises, but nevertheless they are low-probability, high-impact events that are not expected or not well predicted in models of the Earth system. In addition, novel climates will almost surely emerge in the future; that is, combinations of temperatures, precipitation and seasonality that have no current analogues (Williams and Jackson 2007). Novel climates are particularly likely at regional scales where human modification of land cover also has an influence. Indeed, novel climates may have already emerged in some regions, such as south-west Western Australia.

Ecological surprises are also increasing, with unexpected outcomes becoming more common. The surprises are not just due to lack of specific experience and knowledge about systems (which do contribute), but also because individuals and populations have physiological and life history thresholds, communities exhibit keystone effects and ecological cascades, and because both deterministic (in principle, predictable) and stochastic (chance) processes are involved in any environmental change. Some surprises will arise as climate change impacts on key species that structure habitats (like deep-rooted trees) or are important for ecosystem processes (mycorrhizae or symbionts involved in nitrogen fixation). Other surprises arise when species encounter environmental conditions for which they have no previous experience; outcomes are virtually impossible to predict (Box 5).

Box 5 – Climate, fire and the little penguin *Eudyptula minor*

In coastal regions, misty rain or fog following long spells of hot, dry and dusty weather can result in the ignition of power-pole crossarms, due to a build-up of salt and dust on the insulators. The red-hot salt crust can fall from the pole and ignite vegetation at its base. Corrosion of high-voltage power lines can also cause breakage and then fire when they fall to the ground. In recent years a number of such fires have occurred on Phillip Island, home to a large colony of little penguins *Eudyptula minor*.

These fires, as well as a lightning-initiated fire late in 2005 on Seal Island in Victoria, have caused the death or injury of many little penguins. In each case the penguins did not avoid the fire, suggesting that their responses to fire are surprisingly inappropriate and maladaptive. In many cases, dead penguins were found either in their burrows (often collapsed) or within metres of burrows. Birds nesting under vegetation appeared to remain until they were severely burnt or killed. Penguins were also observed standing beside flames preening singed feathers, rather than moving away. Most live penguins suffered debilitating injuries including burns to their feet and legs, scorched feathers and blistered skin, swollen eyes, and many had difficulty breathing.

The synchronised breeding of seabirds such as penguins when large numbers are present in a colony, makes them particularly vulnerable to such fires during their nesting seasons. This is particularly true for burrow-nesting species, such as the little penguin, which are disinclined to abandon eggs or chicks or emerge from their burrows during daytime.

Increased occurrence of hot, dry and dusty weather is projected for the future and may result in increased fire-related risk of little penguin death and injury on Phillip Island if these periods are followed by rain or fog. As coastal development encroaches on little penguin colonies throughout south-eastern Australia, this risk is heightened. Risk reduction options include running the power underground, more regular pole inspections, improved insulator design and cleaning of the insulators. The risk can be reduced further by appropriate habitat management such as the planting of fire-retardant vegetation and quick response by agencies when a fire does occur.

Source: Lynda Chambers (Centre for Australian Weather and Climate Research, Bureau of Meteorology), and Leanne Renwick and Peter Dann (Research Department, Phillip Island Nature Parks).

6.2 Understanding the complexity

The previous sections have outlined the many complexities and uncertainties we face in trying to better predict the responses of the Australian biota to climate change. One method that has been proposed to assist in understanding outcomes of ecological complexity is a 'functional analysis' approach. This is commonly used in analyses of ecological communities facing disturbance (Noble and Slatyer 1980). It uses a functional classification of individual species (or species groups) based on species characteristics, the range of their possible physiological states or life history stages, and then analyses the potential impacts of the disturbance on those classifications and states (Box 6).

Box 6 – An example of the functional analysis approach: assessing the likelihood of insect outbreaks under climate change

Landsberg and Stafford Smith (1992) used a functional analysis approach to make predictions about the potential outbreak of herbivorous insects under global atmospheric change. They started with critical functional attributes of plants, insects and insect 'enemies', as well as possible states of each attribute (e.g. dormant, active). For each attribute/state, the direct effects of climate change were derived from published literature, with added notes as to which were temperature-sensitive, rainfall-sensitive or CO_2-sensitive.

From their analyses, they concluded global changes that increase environmental stress on host plants are most likely to favour sap-feeding insects. They also concluded that elevated CO_2 was not likely to have a major influence on probability of devastating insect outbreak, except possibly in systems where nitrogen-based defensive compounds are produced by plants (e.g. on all other continents). Thus, because Australian plants tend to use carbon-rich defensive compounds, increased outbreaks of herbivorous insects (above the already-high levels) will not likely happen as a consequence of demonstrated effects of higher CO_2 on plants on this continent.

In sum, the analysis yielded critical insights that were not immediately obvious, simplified the complex interaction without compromising any scientific knowledge or principles, and provided guidance and a framework for setting priorities for research and management.

Source: Patricia Werner (Australian National University).

6.3 Improving modelling and monitoring capabilities

In Australia, most projections of impacts on species and communities have involved the use of bioclimatic models to predict changes in geographic range. These are mainly correlative models that relate occurrence of a species or community to climate. Modelling of individual species distributions to date has generally indicated that as the climate continues to change rapidly, most species will suffer reductions and/or fragmentation to their current geographic ranges. Bioclimatic modelling of weed species has also indicated that some may expand their ranges (e.g. prickly acacia *Acacia nilotica*, and rubber vine *Cryptostegia grandiflora*). However, modelling efforts need to be much better integrated with observations and experiments. Currently, we are a long way from routinely incorporating biological information such as life history and species interactions into these models, even for individual species.

Although many qualitative predictions have been made of the vulnerability of certain systems (e.g. Wet Tropics, alpine zones, coral reefs) quantitative, community- and ecosystem-level projections for Australian systems are rare. One exception is the work by Hilbert *et al*. (2001), who used artificial neural network techniques to model potential changes in rainforest types in North Queensland under various combinations of temperature and rainfall; large changes in rainforest types were predicted with relatively small climatic changes. Modelling effort to project changes in vegetation types in Australia is gearing up but preliminary results may still be a year or more away. This is in contrast to research in the northern hemisphere where modelling of changes in major vegetation types/biomes has been underway for at least 10–20 years.

Dunlop and Brown (2008) provide a preliminary regional assessment of biodiversity impacts under climate change based on agro-climatic zones. This ecosystem-based approach assesses how seasonal patterns in plant growth and therefore productivity may vary, and how these changes in growth may drive or contribute to a range of other changes affecting species and ecosystems. Ten agro-climatic zones were used (Hobbs and McIntyre 2005), and each of the 85 Interim Biogeographic Regionalisation for Australia (IBRA) regions were placed in a zone based on seasonal growth and moisture indices. The CSIRO and BOM (2007) projections were then used to predict environmental changes. The zones identified as most likely to experience significant ecosystem-level changes were the 'Temperate cool-season wet' (southern Victoria and north-eastern Tasmania) and the 'Temperate subhumid' (north-eastern New South Wales). Both zones currently have limited growth in winter due to cool temperatures, despite available moisture; warming is therefore expected to lead to marked changes in vegetation structure and composition. These zones are also likely to be affected by changes in fire regimes (Box 7) and are already subject to extensive habitat modification (see Dunlop and Brown 2008 for more detail).

Box 7 – The impact of climate change and fire for biodiversity conservation

The impact of climate change on the management of fire in areas managed for biodiversity conservation will be a function of direct impacts of climate change on fire regimes (the pattern of recurrent fire in the landscape), ecological functional types, the responses of species and ecological functional types to climate change itself (extinction, migration, persistence, adaptation in response to changing patterns of temperature, rainfall and CO_2), and the choices society makes in dealing with climate change. Thus it is a highly complex and poorly understood problem.

A preliminary assessment of climate change–fire–biodiversity interactions has been undertaken, and considered how climate change may affect fire weather and fuels, how this may alter fire regimes, and how this in turn might affect the dynamics and management of biodiversity. The predicted impacts of climate change on fire, weather and fuels were reviewed and a broad, national framework for addressing the issue proposed. Additionally, climate change–fire regime–biodiversity interactions for four selected vegetation types/regions were investigated (alpine ash forests, sclerophyllous vegetation of south-eastern and south-western Australia, and the tropical savannas).

Historical trend analysis of weather data over the period 1973–2007 suggests a change towards increased fire danger, with an increased incidence of days of extreme fire weather. Further increases in the intensity and frequency of extreme fire weather events are likely. However, translating these projected climate trends into changes in local and national patterns of fire regimes is complex, because of the uncertainties surrounding the impact of climate change on other critical drivers of fire events (such as fuels and ignitions) and the effects of increased CO_2 on vegetation.

A sensitivity analysis at a national, broad-biome scale – and via select regional case studies in vegetation types in south-eastern, south-western and northern Australia – showed that the likely increases in fire danger indices in these regions may result in shorter intervals between fires, particularly in southern Australia. The risk to biodiversity as a consequence of changing fire regimes is not equal across the country. In particular, the biodiversity values of sclerophyllous vegetation of south-eastern and south-western Australia appear to be at higher risk than those of the savanna woodlands of northern Australia. In all settings, pockets of vegetation that are sensitive to higher-intensity fires, and occur within flammable matrices, will also be at risk.

Further research is required to clarify risk and vulnerability of biodiversity to altered fire regimes at the landscape, regional and national scales. There is some evidence that the risk to biodiversity values posed by some current or proposed land use changes (e.g. more frequent prescribed burning in sclerophyllous vegetation in south-eastern Australia; the spread of exotic pasture grasses in the savannas) is greater than the risk posed by altered fire regimes as consequence of climate change. However, there will be complicated and poorly understood interactions among these variables and fire activity.

The primary implication for the management of protected areas is that fire management, an already complex issue, will become more complex in the coming decades. This will be due to both the potential trade-offs that will be required to manage biodiversity values in the face of (either perceived or actual) potentially more frequent and/or intense fires; and the need to account for fire regime effects on additional values such as carbon abatement, smoke management and water yield, in the matrix of protected area management objectives.

In the face of such complexity and potentially competing demands on resources, it is vital that adaptive management systems for fire management be developed.

Source: Dick Williams (CSIRO Sustainable Ecosystems) and Ross Bradstock (University of Wollongong).

Monitoring of biodiversity is a critically important and urgent need to inform research, policy and management. On-site monitoring projects need to distinguish between monitoring to inform and adapt management (a form of hypothesis testing) and monitoring to simply watch species go extinct and ecosystems fail. A national framework to identify suitable species and sites, and to execute appropriate monitoring – building on any long-term records where useful – would greatly assist both researchers and managers. It is also important to increase the role of the community in monitoring; a side-effect is increased awareness of the sensitivity of biological systems to relatively small amounts of climatic change. Phenological monitoring is particularly well-suited to community involvement.

6.4 Ecological knowledge gaps and research questions

There are substantial gaps in our ecological knowledge and many research questions of direct relevance to the climate change challenge. The types of knowledge gaps and research questions described in Table 8 present a serious challenge to the research community. Some questions have been tackled, and key knowledge gaps recently identified for specific biomes and geographical areas of Australia (e.g. forests – Lindenmayer and Franklin 2002; arid zone – Stafford Smith and McAllister 2008; Great Barrier Reef – Johnson and Marshall 2007). There does not appear to be a general set of guidelines for identifying knowledge gaps in the face of climate change applicable to Australia, although a number of publications have identified many areas worthy of research (e.g. Hilbert *et al*. 2007); this may be a task for the National Climate Change Adaptation Research Facility. The principles set out in Table 4, and the analysis of observed and projected climate change impacts outlined above, provide a framework within which to build a coherent, integrated research program to eliminate these knowledge gaps. Table 8 is certainly not an exhaustive list, but serves to highlight the wide range of issues requiring more information.

Table 8 – Some key knowledge gaps and research questions

Species
Knowledge gaps
Genetic structure and ecotypic variation within species/populations
Extent of phenotypic plasticity in populations, especially with regard to physiological temperature responses and behaviour
Key threshold values for keystone and habitat-structuring species in relation to the changing climate
Dispersal mechanisms and dispersal rates (capabilities) for most organisms
The role of biotic vs abiotic factors in controlling species distributions and population dynamics
Research questions
To what extent will species be able to cope with regional climatic changes by altering use of microhabitats *in situ*?
What is the level of ecotypic variation in key life history traits and physiological tolerances for Australian species in general? Are there discernible relationships between ecotypic variability and present-day geographic range size and if so, are these relationships consistent among different functional groups?
What will be the role of genetic adaptation relative to phenotypic plasticity and behavioural responses in different functional groups or different taxa in adaptation to climate change?
How can we link bioclimatic models with demographic and population viability models to better predict future responses?
Communities
Knowledge gaps
How changes in temperature, CO_2 and water availability affect key structural and key functional (e.g. keystone) species, and how will these changes flow on to affect species interactions such as competition
How to develop community assembly rules that will be useful predictors for assessing responses to rapid climate change
Research questions
Are some taxa/functional groups more likely to be limited by biotic interactions than others? i.e. can we begin to generalise as to how closely the fundamental and realised niches correspond in relation to other characteristics?
What are the physiological thresholds of temperature and water availability (and pH for marine organisms) of key species (e.g. keystone and habitat structuring species)?
Which key species and ecotones should be targeted for monitoring effort to best inform future management and provide information about the rate of important changes?

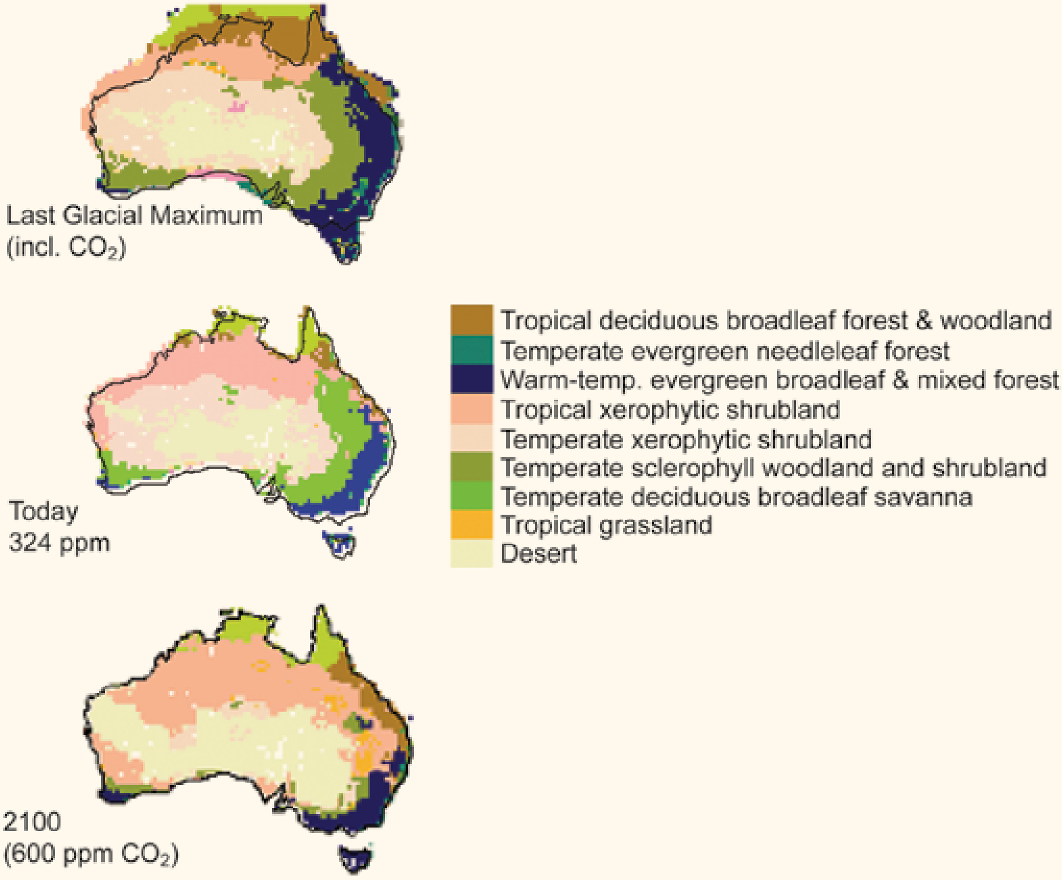
Ecosystems
Knowledge gaps
Ecological cascades and trophic structures within ecosystems
Key physical elements in ecosystems (e.g. water holes)
The extent to which can species be lost and/or substituted in an ecosystem without affecting ecosystem function
Magnitude of interaction and synergies with existing stressors such as fire, clearing, grazing, invasive species, salinity, disease and water extraction
Research questions
Ecosystem functioning rules: what basic components are required to ensure sustained ecosystem function?
Ecosystem services: what are these in each type?
What will be the role of fire management in mitigating threats including climate change?
Palaeoecology
Knowledge gaps
Biotic responses to past climate change, particularly periods of rapid or abrupt climate change
Location and role of refugia in the past, especially in areas of high topographic relief (e.g. the Wet Tropics)
Role of multiple localised refugia in terms of resilience
Research questions
How can we better identify past climatic refugia and use this information to target conservation planning?
Will climate change differentially affect known centres of endemism compared with other regions?

Source: Roger Kitching.

6.5 A long-term perspective

A long-term, continental-scale perspective on the relationship between biota and climate provides an overview of the potentially profound changes that await Australia's biodiversity; knowledge that, in a broad sense, compensates for the almost bewildering complexity of ecosystem-level questions and uncertainties described in the previous subsections. Figure 14 compares the equilibrium distribution of biomes at the Last Glacial Maximum to the present distribution, and then to the simulated equilibrium biome distribution with a 2100 climate associated with a CO_2 concentration of 600 ppm. Over the next 100 years Australia could well experience changes in ecosystem type and distribution at least as great as those associated with the transition from the Last Glacial Maximum to the present, a period of at least 5000 years. The rate of climate change – a similar transition in only 100 years – is almost surely unprecedented for the last several million years (Steffen *et al*. 2004). Selective pressure on many organisms, particularly long-lived organisms, will be extreme – particularly as the incidence and severity of extreme events will increase even more rapidly than climatic means. Such dramatic rates of change have prompted assessments that the Earth will experience a massive wave of extinctions this century, with rates of species loss about 1000 times background levels (MA 2005).

Figure 14 – Australian biome distribution at the Last Glacial Maximum, present and at 2100 using BIOME 4.0, a dynamic global vegetation model. Results of such simulations are sensitive to both the climate and vegetation models used.



Source: Sandy Harrison, University of Bristol, UK.

The above analysis provides the basis for an overall strategic framework for reducing the risk of climate change to Australia's biodiversity and sets the context for the next section on management approaches to conserving Australia's biodiversity under a rapidly changing climate. The framework has two major components:

- If Australian society wishes to minimise the risk of an unprecedented wave of extinctions over the next 100–200 years, mitigation of climate change must be undertaken vigorously and rapidly. Mean temperature above the 1.5–2°C level, with the associated changes in other aspects of climate, will lead to escalating loss of biodiversity with little or no chance of avoiding or reducing losses via adaptation.
- Second, even under the most modest climate change scenario, the potential impacts on biodiversity will increase through most of this century. Formation of novel ecosystems, abrupt changes in ecosystem structure and functioning, and surprising, counterintuitive outcomes will become more common. Coupled with the existing stressors on biodiversity, these climate-related complications challenge the policy, management and governance communities to develop and implement innovative, adaptive and resilient (or transformative) regimes for the conservation of Australia's biodiversity under rapid change. Thus, investing in adaptation is not an 'optional extra' but is central to *any* strategy to minimise the impacts of climate change on Australia's biodiversity.

The relationship between adaptation and mitigation is thus not an 'either-or' question but rather a 'both-and' imperative. That is, with agile, innovative and better-resourced conservation policy and management *now,* the current degradation of Australia's biodiversity and the impacts of modest climate change can be reduced. With rapid and effective global mitigation of climate change, the probability of more severe climate change and the associated risk of unavoidable, much higher rates of biodiversity loss in the coming decades and centuries can be reduced significantly.

7. Platform for biodiversity and climate change adaptation

Historical stressors on biodiversity, such as landscape fragmentation and invasive species, still dominate as drivers of biodiversity change that are observable now. However, as noted above, the potential for accelerating change due to climate is large and growing. As global emissions of carbon dioxide continue to rise at or near the upper bounds of projections (Figure 2), the resulting rate and magnitude of climate change will place ever more severe pressure on biodiversity in Australia and worldwide. Is Australia ready to meet the climate challenge?

An adaptation strategy for biodiversity is required, which covers the following broad elements:

- understand what we are managing for – the rate of change within natural systems could be very swift compared with the past and the magnitude of change could be large. Management approaches that seek to maintain current spatial arrangements of species will be very difficult to implement under a changing climate
- transform our biodiversity management policies, legislative frameworks and institutional structures to provide the flexibility that will be required to respond to rapid change and to align with a changed emphasis in management objectives
- prepare and implement specific climate change regional adaptation planning using risk management frameworks and scenario planning to inform management strategies and guide research needs.

7.1 Biodiversity policies, management strategies and tools for climate change adaptation

There is a growing awareness that management objectives need to be reoriented from preserving all species in their current locations towards an overarching goal of minimising the loss of biodiversity. Two principles become very important in this context:

Maintain well-functioning ecosystems

With decades or centuries of projected climatic change that is significant in magnitude but uncertain in detail, the single most important principle guiding the management of biodiversity is the maintenance of well-functioning ecosystems. This is, in fact, a two-way principle. Maintenance of high levels of biodiversity is a good strategy to ensure the adequate functioning of an ecosystem. However, this is not a simple principle to implement under a changing climate. Maintaining or enhancing the resilience of ecosystems is crucial to ensure the continuation of adequate functioning; but when, under climate change, does maintenance of resilience of existing ecosystems become counterproductive and facilitation of transformation into new ecosystems become more appropriate? As transformation becomes more common later this century, monitoring the functioning of these ecosystems and their ability to deliver the services on which society depends will be critical for implementing this principle.

Protect a representative array of ecological systems

Not only is it important to have well-functioning ecosystems, but the full diversity of these systems needs to be included in areas managed for conservation. This basic principle of conservation needs renewed emphasis and re-interpretation under climate change. The principle of representativeness – representing all biodiversity in appropriately managed systems – remains essential under climate change. However, the purpose is now to represent as many different combinations of underlying environments and drivers, rather than specific arrays of current species. While the particular assemblages of species or genes in a single location may change, aiming to encompass diversity provides the best likelihood of having favourable conditions for all biodiversity somewhere. This applies at all scales from local through regional to national, in that a diversity of several stages (e.g. time since fire) should be maintained locally; all environments should be represented in regional reserve systems, and a diversity of landscape architectures in terms of the arrangements of patches and connecting habitats should be represented in regional on- and off-reserve landscapes.

In addition to the above principles, there are a number of other principles that will be important in guiding how we manage to achieve well-functioning ecosystems and protect a representative array of ecological systems.

Remove or minimise existing stressors

The biggest threat to Australia's biodiversity continues to be a number of existing stressors, such as the direct human modification of ecosystems (e.g. land clearing) and the introduction of exotic species. These will continue to be important, but climate change presents a 'double whammy', acting as an additional, direct stressor on species and ecosystems as well as exacerbating the effects of many of the existing stressors. Thus, as a management principle, it will become even more important to minimise or remove existing stressors, with particular attention given to those stressors that might benefit from climate change. Many of these activities offer 'no regrets' solutions; that is, the activity will benefit Australia's biodiversity irrespective of the new, additional stress of climate change. Accelerating the implementation of 'no regrets' activities offers an extremely low-risk, high-payback starting point in building resilience of natural systems to climate change.

- ***Land clearing and degradation –*** Land clearing has been the single greatest cause of biodiversity loss in Australia and even if no further clearing takes place, losses will continue because of habitat fragmentation and extinction debts. (These are extinctions that are sure to occur over coming decades due to irrecoverably small and fragmented populations of some threatened species.) The resulting loss of connectivity will exacerbate climate change effects on biodiversity. Many current responses to degradation should be intensified, especially as they often benefit both production and conservation.
- ***Invasive species –*** Some invasive species will be 'winners' from climate change. For example, feral cats are known to have caused extinctions of indigenous mammals on arid islands but not on high-rainfall ones. Decreasing rainfall will change this balance. Some 'sleeper' weeds will expand their range, and some new weeds may emerge. Some pathogens and their hosts will extend their range as temperatures increase. Increases in fuel loads due to introduced species such as gamba grass and buffel grass will alter fire regimes. These impacts are already being observed. Quarantine and biosecurity frameworks will need to be proactive in managing for new climate change-related invasive species. This will need improved bioclimatic modelling to predict the effects of climate change on distributions of invasive species, increasing investment in invasive species control technologies (including biological control) and managing connectivity carefully with a view to minimising dispersal of invasive species into new areas.
- ***Fire regimes –*** Increases in temperature, longer and more intense dry periods, more extreme fire weather, more storms and lightning strikes, changing vegetation, and invasion by weeds will affect fire regimes and consequently biodiversity. A recent synthesis of our current understanding of the consequences of climate change for fire regimes provides important insights for biodiversity conservation strategies and indicates that changes to fire regimes will need to be understood at a regional level (Box 7). In terms of biodiversity, the most important features of managing fire regimes include limiting the extent and intensity of post-fire salvage logging, adapting biodiversity management to account for changes in fire regimes, protecting refugia, and managing the cumulative effects of fire and other stressors.
- ***Climatic extremes –*** Changes in climatic extremes are likely to affect many species more than a change in mean temperature and rainfall. Arguably the most important of the climatic extremes for biodiversity is the likely change in water availability, implying a focus on areas where a combination of elevated temperatures and reduced rainfall will impose water stress on ecosystems and species. Therefore, it is critical that water allocation frameworks include a consideration of biodiversity requirements under a changing climate. Those species forced out of their tolerable environmental envelope by climatic extremes and unable to migrate to suitable habitat will need translocation, captive breeding, germplasm storage and biobanking programs. More generally, there is a need to plan and develop post-disturbance management actions, such as controlling grazing pressure by domestic livestock after a drought, and determining which species are encouraged to re-establish after a disturbance.

Enhance the capability of ecosystems to self-adapt and reorganise

With increasing pressure on species to migrate in response to a changing climate, and for ecosystems to disassemble and reassemble, there is a greater focus on achieving appropriate types of landscape and seascape connectivity to 'give space for nature to self-adapt' (Mansergh and Cheal 2007). The concept of 'landscape fluidity', defined as the ebb and flow of organisms within a landscape (or seascape) through time (Manning *et al*. 2009), provides a more appropriately dynamic underpinning to biodiversity conservation in a rapidly changing world. Here, marine ecosystems may have some advantage, in that many (but not all) organisms may be able to change their geographical position in response to changes in the abiotic environment around them. Terrestrial ecosystems face more severe challenges, because most terrestrial organisms are less mobile, and they are subject to more direct and pervasive human modification. Freshwater organisms may face the greatest barriers to dispersal of all, given that they may need to move between catchments.

Such an emphasis on the landscape as an integral part of biodiversity management indicates the need, in principle, to move from simplistic, polarised patterns of landscape structure and use – 'fortress agriculture' and 'fortress conservation' – to more fluid, multiple-use landscapes with space for self-adaptation of ecosystems in the landscape. Support for such adaptation must come from those who live in and on the landscape, and who must therefore be productively engaged in policy formulation and implementation.

Increasing connectivity is, in many cases, an appropriate response to achieve these goals. However, there is a need to define 'connectivity for what', and a need to determine why and where increased connectivity will be needed. In some cases, increasing connectivity may be counterproductive. Appropriate connectivity will be achieved through enhancing both the National Reserve System and off-reserve conservation, building on specific strategies to integrate them.

- ***National Reserve System (NRS) –*** The NRS remains a very useful framework for conserving biodiversity under a changing climate (Dunlop and Brown 2008). Resources for managing protected areas are inadequate under current conditions, and will need significant increases to deal with the additional climate change stress. Key areas of focus include:
  - expansion of the NRS to meet CAR (Comprehensive, Adequate, Representative) objectives
  - integration of all types of protected areas into a single national system
  - promoting larger reserves that provide larger buffers spatially and through larger populations
  - use of adaptive management within the NRS.
- ***The National Representative System of Marine Protected Areas (NRSMPA) –*** The NRSMPA is as yet poorly developed and needs urgent attention, using CAR principles, before it can contribute effectively to conserving a greater array of Australia's marine biodiversity. Under a changing climate, the identification and protection of refugia will be increasingly important.
- ***Off-reserve conservation –*** While protected areas will remain a cornerstone of conservation policy and practice, they will, on their own, be inadequate to conserve biodiversity under climate change. Off-reserve conservation will assume growing importance as the 21st century progresses, and will need to be enhanced through:
  - adequate funding or incentives for off-reserve conservation schemes
  - use of regional-scale planning to integrate off-reserve conservation with the NRS and NRSMPA
  - establishing extension-style education to promote voluntary self-management for biodiversity by landholders, for example, in the growing area of amenity landscapes.

The challenge of climate change will require an increasing emphasis on principles that have generally not had a strong focus in biodiversity conservation under a more stationary climate.

Eco-engineering to assist adaptation

Driven somewhat by the growing interest and experience in restoration ecology, as well as the improved understanding of ecosystem structure and functioning, there will be cases where a passive 'let nature adapt' approach can and should be augmented by more proactive measures to conserve biodiversity (e.g. Hoegh-Guldberg *et al*. 2008). This principle invariably involves the direct and substantial modification of ecosystems in directions consistent with the impacts of climate change. Although costly and not always successful (especially in a rapidly changing environment), eco-engineering may nevertheless constitute a necessary response principle in a few specific cases. Eco-engineering should be focused on places where the best return on investment (both financially and in terms of biodiversity conserved) can be obtained. For example, re-establishment of keystone or structuring species may allow ecological systems to self-organise around such critical elements; or the use of provenances and species for the anticipated climatic conditions may help forests to regenerate after logging or fire. Translocations may become critical for island ecosystems, especially low-lying islands that are threatened by sea level rise. Sea turtles and other reptiles will be particularly impacted as the sex of hatchlings is determined by incubation temperature; translocations may be required to promote establishment of new populations in cooler environments. Similarly, focusing on environments that have flow-on effects on other parts of the landscape (e.g. restoration of riparian areas or building artificial reefs, which provide a key structural element around which new ecosystems may develop) is likely to provide disproportionate benefits. More generally, however, research is needed to identify such critical intervention points in the context of climate change.

Genetic preservation must be considered in some cases

As a last resort approach, some species may need to be preserved outside of an ecosystem context, whether it is an existing or transformed natural ecosystem or a human-engineered ecosystem. However, such last-resort, *ex situ* methods should be seen in no way as substitutes for well-functioning ecosystems. Examples of *ex situ* conservation include:

- cryogenic seed bank for food species being established in Svalbard, Norway
- refrigerated seed stores and cryogenic germplasm stores at Australian herbaria and botanic gardens
- potential role of zoos in conserving a very small number of charismatic and highly valued species
- breeding and maintenance of near-extinct species in isolated or quarantined areas, such as remote islands.

The above strategies will almost surely fail in achieving widespread, effective implementation unless they are supported by a set of more general strategies that transform the way that societies think about and value the biotic world around them.

Understanding and consensus-building is vital to bring the Australian community along with change

The public, as well as political and institutional leaders, will need to recognise that climate change is driving the natural world into uncharted territory in the 21st century. Innovative approaches to assisting nature to deal with the interacting set of new and existing stressors will be required. Social and political support is necessary for these new approaches to succeed. This may require re-examination of some strongly-held views on biodiversity and its conservation (Hobbs *et al*. 2006). One such view is the need to preserve what we have now. The Australian community will need to learn to value new, unique, diverse ecosystems over individual species that may no longer inhabit them. In a rapidly changing abiotic environment, landscapes will change; species will be lost and others will not persist in their current location. In general, the current emphasis on species will need to be balanced by an increasing focus on ecosystem services, processes and diversity. Managing for resilience of existing ecosystems (a preservation strategy) may work to a point, but there will also be a need to manage for transformation of ecosystems, landscapes, seascapes and perhaps even whole biomes. Such a wide-ranging remit for biodiversity management will, in turn, pose challenges to existing governance arrangements and administrative institutions. The increasing urbanisation of the Australian (and global) population also means that most of the public know less and less about the significance of biodiversity in providing services to their everyday lives. Engaging their interest in maintaining biodiversity is critical for long-term human well-being.

Seize opportunities and minimise threats

Biodiversity conservation must look towards new opportunities, and more creative strategies and tools. Many of the socio-economic trends described below offer opportunities for new conservation approaches and tools. Others, however, could prove maladaptive for the biodiversity sector. Carbon trading and offsets schemes, probably the most common climate mitigation approach in landscapes, offer an opportunity to promote sequestration in biomass while simultaneously benefiting biodiversity. On the other hand, there is the distinct possibility of perverse outcomes, depending on the design of the sequestration scheme. Creating such synergies among ecosystem services should become a central organising principle for all proposals to use landscapes for climate change mitigation. Market-based instruments and other incentive approaches, such as a system of biodiversity credits linked to Australia's emissions trading scheme, could be established to deliver win-win outcomes for biodiversity conservation and climate mitigation.

Apply a risk management approach to deal with irreducible uncertainties

Significant uncertainties surround critical features of climate change science, such as how the hydrological cycle will change, and the consequences of these changes for water resources and water availability. Strategies and tools for biodiversity conservation under a changing climate must therefore embrace uncertainty as a central underpinning principle. A greater emphasis on risk management, scenario planning and adaptive management approaches is essential. The linear approach of research–policy–management–outcome needs to be replaced by an iterative, cyclical approach in which biodiversity outcomes are appraised, leading to new research, and adjusted policy and management. Such an adaptive, cyclical approach needs high-quality information, based on monitoring and experimentation. Australian society may need to accept some initial failures in policy and management approaches to deal with such a complex stressor as climate change. However, 'failures' are only true failures if management and policy fail to learn from them, adapt their approaches and do better the next time (Lindenmayer and Franklin 2002).

7.2 Innovative, adaptive governance systems

Even without climate change, agencies and organisations are challenged to deliver effective, integrative management approaches to conserving Australia's unique biodiversity, within current resource constraints. Climate change will also exacerbate existing challenges to institutional capacity. The most important of these challenges include the historical dominance of production industries, resource constraints, institutional constraints, key knowledge gaps and socio-economic trends.

Historical dominance of production over conservation

Agriculture, forestry, water provision, mining and other resource-oriented sectors all affect terrestrial and aquatic biodiversity. Because of their economic importance, these sectors have traditionally taken precedence over biodiversity conservation in terms of land use planning and resource allocation. If landscape goals are not reconciled between the different natural resource sectors, principally between biodiversity and primary production, a changing climate could amplify perverse outcomes.

Resource limitations

For most societies, the historical flow of ecosystem services has been so abundant as to not cause concern. In many cases, they have been treated as free goods, which did not warrant priority treatment in state budgets. Consequently, much of the wealth generated by the consumption of ecosystem services has been invested in the provision of (non-ecosystem) services perceived to be scarce. Comparison with investment in physical capital such as roads and buildings, as well as in human and social capital, through health, education and governance, would probably show that Australian investment in 'natural' capital is tiny, even when private investment by landowners, NGOs and industry research bodies is added. The reasons for this reflect the inability to establish markets for many ecosystem services and, as a consequence, the need for the public sector to ensure ecosystem services. Today, natural capital is struggling to continue to provide adequate delivery of these non-substitutable services. Under a changing climate, a major reappraisal is required of the strategically appropriate level of public and private sector investment in natural capital.

Institutional constraints

Ecosystems and bioregions do not respect jurisdictional boundaries, creating management challenges even without climate change. As more species move at increasing rates in response to a changing climate, cross-jurisdictional issues will become even more pervasive and complex. Policies in other areas of climate change can also have impacts on biodiversity through so-called perverse incentives or unintended impacts. One very specific area of interest is Indigenous land management, especially in relation to institutional arrangements, and to what extent the absence of private property rights will meet the challenges of rapid climate change.

Knowledge gaps

Biodiversity management agencies need strong science groups within them to conduct high-priority research, taking care to increase research capacity internally, while also taking advantage of research conducted by or in collaboration with others. Given the large uncertainties associated with the future trajectory of climate change and the equally large uncertainties associated with the ecological responses, adaptive management is the only way forward. Yet many management agencies are risk-averse, being reluctant to use adaptive management for fear of it being perceived as a policy failure rather than as a learning-by-doing approach (Lindenmayer and Franklin 2002).

Biodiversity policy and management initiatives in response to climate change will involve the expanded use of some existing strategies and tools, and will further complicate an already complex policy scene. The increased demands on the institutions and organisations responsible for policy and management may lead to a lack of trust and confidence in these existing or future structures – as is already evident, for example, in the attitude of many farmers, who have been bruised in the past by the poor application of environmental policy (Productivity Commission 2004). The challenge of regaining and maintaining the public's trust will be made greater by the highly uncertain nature of climate change. The Australian community will need to accept the need for a changing policy and institutional landscape, just as they will need to accept novel, self-adapting ecosystems rather than the preservation of existing ecosystems in their present location.

Three important features of the current policy and institutional landscape, which provides the base on which governance changes need to build, are:

- robust, cooperative arrangements between the Australian (Commonwealth) Government and the states and territories, most recently implemented through the Council of Australian Governments (COAG)
- a more complex institutional architecture at the sub-state level, with local governments, regional natural resource management bodies and Landcare groups all playing particularly important roles in environmental management
- increasing fiscal and policy dominance of the Australian Government (Connell 2007), often expressed through purchaser-provider funding arrangements and the use of the private corporation model for public sector operation.

The need to integrate production, biodiversity and cultural values and objectives in landscape management, within the context of accelerating climate change, presents unprecedented challenges to the institutional architecture developed since Federation. Advocates of integrated catchment management have long argued for a more 'bottom-up' system while, more recently, there have been advocates for alternatives to conventional 'top-down' governance (Marshall 2005). The concepts of 'subsidiarity' and 'polycentricity' (Box 8) are central to building more effective and responsive environmental governance structures for the 21st century, particularly those focused on a regional scale. Embedding these concepts in a regionally oriented governance structure supports the retention of local ownership and cooperation (crucial for trust and legitimacy) while helping to develop integrated solutions adapted to the particular knowledge, preferences, capacities, socio-economic trends and biophysical characteristics of a region. Such structures are likely to involve lower transaction costs and to be more effective than present and currently proposed arrangements (Connell 2007; Marshall 2008).

Box 8 – The concepts of 'subsidiarity' and 'polycentricity'

The concepts of subsidiarity and polycentric governance are increasingly appearing in discussions about environmental management in Australia. The principle of subsidiarity requires each governance function to be performed at the lowest level of governance with capacity to implement it effectively. This capacity involves both the representation of all parties with a substantive interest in the function of a body, and the availability of sufficient physical, financial, human and social capital to perform that function.

A polycentric system of governance comprises multiple decision-making centres that retain considerable autonomy from one another. A monocentric governance system may comprise more than one organisation, but coordination occurs through a single, integrated (often linear) command structure. To meet both polycentric and subsidiarity design principles, then, a governance system needs to comprise not only multiple organisations and levels, but also to afford these multiple organisations real autonomy in how they perform the functions assigned to them.

In practice, this would mean central government agencies permitting a much greater degree of autonomy in both the design and performance of local natural resource management (NRM) bodies. In particular, information flow would be multi-directional rather than primarily top-down, and decision-making would be interactive and collaborative involving multiple centres in the system. Today's regional NRM system has taken a step in this direction, but remains largely monocentric with limited subsidiarity. Other NRM arrangements (e.g. many regional water planning processes) similarly retain a strong element of central decision-making.

Source: Warren Musgrave and Graham Marshall (University of New England).

A future system might look more like a series of diverse, local, community-based NRM groups (perhaps growing from current non-governmental organisations) that send their chairpersons to a regional NRM body with greater autonomy than in most jurisdictions today. A hands-off central government role would focus on ensuring regional groups met basic standards of local representativeness and accountability, facilitating learning between regions, and distributing un-tied central funding on the basis on minimal financial accountability requirements.

A regional governance system based on subsidiarity and polycentricity principles has the benefits of: (i) capitalising on the local knowledge needed to identify community-owned environmental solutions; (ii) responding in a more timely manner to local and regional issues; (iii) gaining cooperation with governance decisions (or at least weakening opposition); (iv) allowing the reconfiguration of institutional arrangements and organisational structures to suit the different population densities in peri-urban through to remote regions, and as problems evolve; and (v) motivating institutional learning and innovation (Marshall 2005, 2008). The last point is crucially important in implementing an adaptive management approach, which is required to deal with the complexities and uncertainties of the climate change challenge. Additionally, where an individual body within a polycentric governance system fails, this is likely to have only local effects rather than pervading the whole system.

Possible or perceived disadvantages include: (i) less 'tidy' governance arrangements than those of a monocentric 'one size fits all' design (Ostrom 2005); (ii) new kinds of transaction costs to which all players must become accustomed; and (iii) potential lower capacity to access scientific knowledge. Appropriate support from higher levels of government can mitigate the effects of all of these problems.

In addition to reorienting our institutional architecture, more effective collaboration among the policy, management and research communities is required. One possible foundation could involve partnership arrangements for sharing the costs of NRM investments among communities, governments, the private sector and other expected beneficiaries (Musgrave and Kingma 2001). A new national institution, which would also review the status of the Australia's natural resources and advise relevant bodies from the Natural Resource Management Ministerial Council down, could provide the guidance, monitoring and auditing functions necessary for this to work effectively. The institution could play a particularly crucial role in fostering polycentricity by ensuring arrangements exist for accountability both upwards and downwards through the governance system.

In addition to supporting a more polycentric approach to institutional architecture, the proposed new national instititution would focus on some functions required for effective biodiversity conservation that could be most effectively carried out at the national level. These include audits of climate mitigation activities that can affect biodiversity, assessment of the state of and trends in Australia's biodiversity and the implications for ecosystem services, and the design and oversight of a biodiversity monitoring system; many of these functions are currently either non-existent or are fragmented and uncoordinated. The institution would need to work closely with the policy sector at the national and state levels, yet be at 'arms length' from government to be effective and independent. The Reserve Bank of Australia, the Australian Competition and Consumer Commission, the Productivity Commission and the former Resource Assessment Commission provide possible models for such an institution.

7.3 Implications for management of long-term climatic trends

Further insights towards innovative and creative approaches to adaptation can be gained by an integrated analysis of both climatic and socio-economic trends for the 21st century. The legacy of past changes to biodiversity may set the initial condition; however, the nature of climatic and socio-economic changes over the next several decades will set the dynamic boundary conditions for future change.

The three contrasting climate scenarios introduced earlier (Figure 9) – recovery, stabilisation and runaway – provide a framework for adjusting long-term management approaches to account for contrasting possible climatic futures. The scenarios highlight that the current momentum in the climate system means that the Earth is committed to a further warming of at least 0.4^{o}C regardless of human actions, so that there is confidence in the trends to 2030 or so. Beyond that, management and policy responses need to allow for the alternative possible futures. An example of how these scenarios might inform risk management against an uncertain future is provided for assessing management options for long-lived 'biological infrastructure' (Box 9).

Box 9 – Climate scenarios, risk spreading and conservation strategies

In many ecosystems such as forests and woodlands, long-lived tree species have critical roles as keystone ecological structures. The investments made today in the conservation management of these structures (and the large quantities of biodiversity associated with them) can have implications that span centuries, just as our investments in power stations and dams today create infrastructure legacies that last decades. Yet, we cannot know what climatic conditions will be in 100–200 years time, because they depend on how the management actions that humans use to respond to the challenge of climate change. Therefore, we need to consider management strategies that hedge our bets against these different futures. We can do this by identifying the responses we should take to a variety of future climate scenarios; if all scenarios require the same responses, then this is a 'no regrets' option and we should get on with it. But if each scenario requires different actions, then we need to consider implementing multiple actions in the same region.

A hypothetical example comes from the ash-type forests of the Central Highlands of Victoria, south-eastern Australia. Large species of trees in these forests like mountain ash *E. regnans* and shining gum *E. nitens* do not develop tree hollows suitable for occupancy for more than 40 species of vertebrates for at least 120–150 years. Exemplar species are the yellow-bellied glider and yellow-tailed cockatoo. A temperature rise of 2–3°C would not prevent the survival of such vertebrate species, as both have extensive distributions covering large parts of eastern Australia. However, we know they will decline rapidly if they do not have access to tree hollows for nesting and sheltering, as would happen if the mountain ash fails to recruit in the face of climate change. But our management needs to be different depending on how we think the future might play out.

Under the 'runaway' scenario in Figure 9, the dominant tree species will continue changing over coming centuries, first to messmate *Eucalyptus obliqua* then to yet other species characteristic of lower and warmer environments (e.g. red stringybark *E. macrorhyncha* and narrow-leaved peppermint *E. nicholii*). For this scenario, we might need to encourage the natural movement of species across the landscape to ensure a perpetual supply of large, long-lived trees species that can form hollows. This is promoting *self-organising transformation* of the vegetation community.

The key point is we do not know which of these scenarios is going to happen, yet we need to begin this type of planning now. We can plan for such uncertainty by applying all three strategies in different places in the Central Highlands of Victoria. For example, we might recommend that one park follows the recovery strategy, particularly in areas with many good refugia, another specifically encourages the recruitment of messmate, and yet another allows unrestrained recruitment of any long-lived tree species. In an active adaptive management approach, we can review this decision in 30–50 years, as it becomes clearer which scenario is playing out, and gradually refine the strategies.

In contrast, there will conservation issues where the same management strategy is needed, irrespective of which future scenario manifests. For example, this may be the case for short-lived vegetation types such as coastal heathlands where managing disturbance and other threats may be appropriate regardless of the future (Woinarski 1999). In this case, the management strategy is one of 'no regrets'. That is, we can afford to simply do the same things in all places.

This kind of risk management using scenario-based thinking needs to becomes a key part of conservation planning, particularly as we will not know what the future holds until we are living it, yet we cannot wait until then to make decisions about some of our 'biodiversity infrastructure'.

Under the 'recovery' scenario (Figure 9), we need to keep existing populations of tree species alive *in situ*. This is because by 2100 (well within the lifespan of some of the trees germinating today) the climate will return towards conditions that the mountain ash can tolerate. For this scenario, we could identify some key refugia, and work hard to keep them free from fire and other disturbances. This is preserving the *resilience* of the existing vegetation.

Under the 'stabilisation' scenario in Figure 8 we need to establish tree species more typical of lower and warmer elevations such as messmate *E. obliqua* in areas where mountain ash lives today. When this species matures in one to two centuries, it will provide suitable tree hollows in those areas where mountain ash can no longer establish. Under this scenario, we might actively establish messmate (e.g. through deliberate planting or on-site releases of seed) in areas burned naturally over the coming decades. This approach is facilitating *directed transformation*.

Source: Mark Stafford Smith (CSIRO Sustainable Ecosystems) and David LIndenmayer (Australian National University).

7.4 Opportunities arising from socio-economic trends

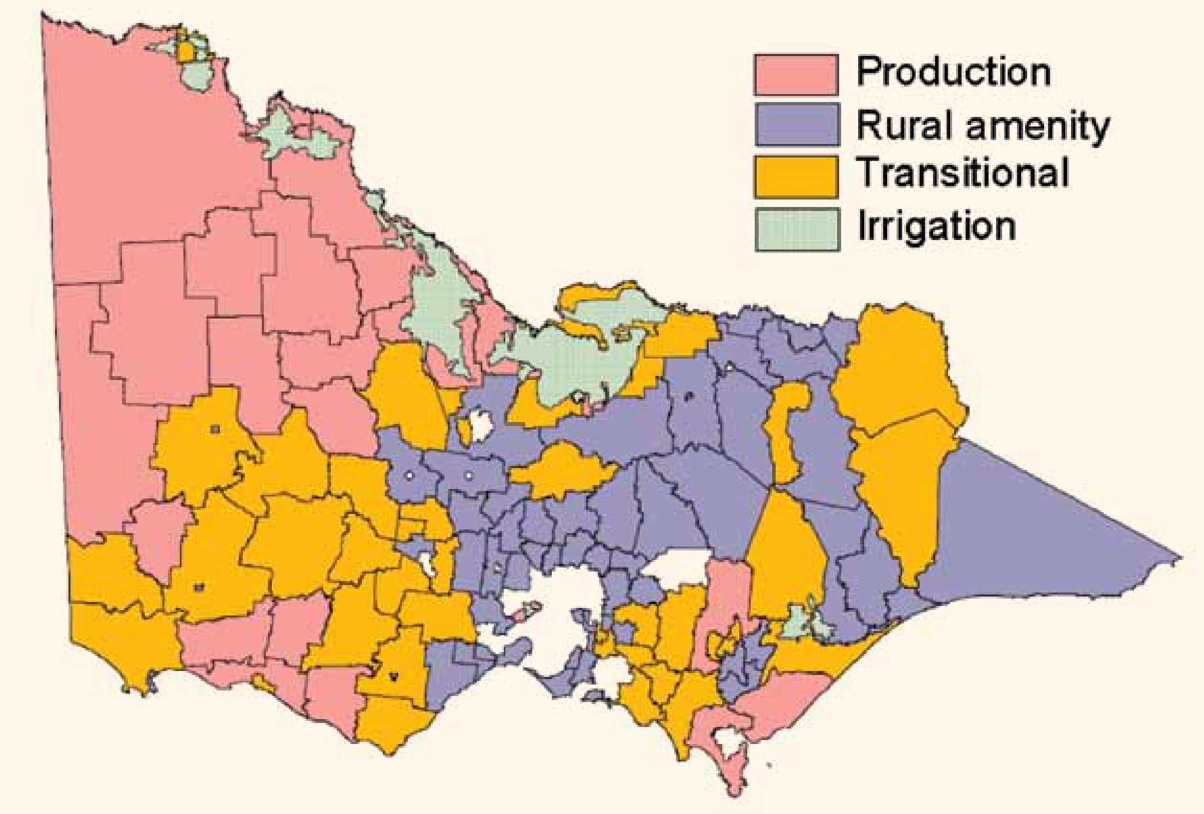
In addition to climatic trends presented in the previous section, significant socio-economic changes are sweeping across Australia, which provide further opportunities to develop robust adaptation responses. Given the consistency in the underlying drivers of increasing population and individual affluence, most existing trends will continue or even intensify over the coming century, in some cases creating additional challenges but often offering new opportunities for dealing with climate change in the regions where they are occurring. Key socio-economic changes include:

- ***decline of agriculture in marginal lands*** – Marginal agricultural and rangeland regions are already experiencing declining human populations and land use diversification. Possible large-scale abandonment of agriculture in further large regions (e.g. northern part of Western Australia wheat belt, western New South Wales) would create opportunities for new management regimes that emphasise land stewardship and promote carbon storage, biodiversity or tourism markets in large areas of Australia.
- ***private sector conservation*** – The continuing rise of private organisations like Bush Heritage Australia, The Nature Conservancy, Australian Wildlife Conservancy, Bush Tender and similar schemes for improving biodiversity outcomes on privately-held lands offers additional opportunities for entraining more private investment in biodiversity conservation. As in other parts of the world, these sectors have the ability to be more nimble and adaptive than government agencies; more effective communication and collaboration between government and non-governmental sectors would contribute strongly to the achievement of biodiversity conservation goals
- ***high-density urban living*** – There is considerable potential to manage inner-city suburban and peri-urban areas differently for better biodiversity outcomes. As the form of Australian cities changes towards higher-density housing, the associated changes in land use offer opportunities for creative redevelopment that builds in more biologically diverse parklands, river corridors and green belts
- ***'sea change' and 'tree change' movements*** – Retirees (or escapees) from the cities often have a strong interest in nature and its preservation, and relatively high capacity for private investment in biodiversity outcomes. It is possible that the considerable investment in revegetation by these people (sometimes focused on mallee oil or blue gum monocultures) could be better directed with respect to its potential value for biodiversity under climate change
- ***expanding Indigenous estate*** – With the advent of land rights since the 1970s and native title since the 1990s, an increasing proportion of land (particularly in more remote regions by area, now around 22% of the rangelands) has returned to Aboriginal and Torres Strait Islander ownership. The validity and value of Indigenous inputs to management have been recognised in other areas, particularly in joint management arrangements for parks, as well as weaker engagement around managing natural and cultural heritage on other tenures. In particular, the rapid expansion of Indigenous Protected Areas creates another new way of considering public/community partnerships for conservation

- ***new landscapes* –** Major new landscape uses, such as sequestration of carbon as offsets to fossil fuel emissions and the potential strong growth of a biofuels industry, are developing even in core agricultural regions. The associated financial markets and incentives currently take little heed of biodiversity but could readily redirect their priorities towards the joint supply of carbon and biodiversity services.

As an example of these major regional socio-economic trends and their implications for landscapes, a spatially explicit representation of major socio-economic trends occurring in rural Victoria is shown in Figure 15, distinguishing agricultural production, irrigation, amenity and transitional landscapes.

Figure 15 – Stylised social landscapes of rural Victoria



Source: Barr *et al.* (2005).

7.5 Towards a systematic regional approach for biodiversity conservation in the 21st century

On-the-ground application of general principles for biodiversity conservation under climate change requires consideration of the characteristics of particular areas or locales within their regional contexts – a 'place-based approach'. This could easily lead to a huge number of individual approaches, with a high risk of unnecessary duplication and loss of synergies, collaboration and learning. Such risks could be reduced by adopting a regional approach, with the regions defined by common socio-economic characteristics and trends, existing biomes, and climate change regimes. Importantly, there are opportunities for synergies between existing socio-economic trends, which have their own drivers and momentum, and different strategies for biodiversity conservation. In addition, the new type of governance system described previously is well-suited to a regional approach that integrates biodiversity values, socio-economic trends and levels of government.

Table 9 illustrates how one might think differently about regions that have varying current biodiversity value and that are on different socio-economic trajectories. Hobbs and McIntyre (2005) defined a series of agro-climatic zones which combine the underlying major biomes with broadscale land use patterns. Dunlop and Brown (2008) used these zones to analyse how different impacts of climate change across the continent would have differential implications for the National Reserve System in each zone. The table extends this analysis by beginning to disaggregate the zones in terms of Holmes' (2008) social trends towards production, amenity or protection-oriented landscape uses. The table then shows how such a regional understanding might be applied to develop an integrated package of responses for each of these regional types. *It must be emphasised that the table is meant only to demonstrate the approach, and is not meant to be complete, representative or thoroughly researched. It is a 'proof-of concept' exercise*. The table is a critical illustration of the level of sophisticated analysis that is needed to understand the challenges created for biodiversity in each region from the combination of underlying environments, current and future socio-economic trends, and impacts of climate change. Furthermore, it identifies the opportunities that exist in recognising that different management responses are required in regions with different combinations of drivers. Much more work is required to implement the concept in practice, capturing local and regional knowledge in collaboration with policy and scientific inputs.

Table 9 covers three regions with contrasting socio-economic characteristics and trajectories (additional regions are presented in the corresponding table in the full assessment). Each type of region has a specific area selected as an example, but other cases could have been given for most types. For each regional type, the analysis qualitatively indicates the state and trends over current and future decades in four important characteristics – population, agricultural and/or forestry production, economic performance and biodiversity. It also estimates the socio-economic trends that are at least partially responsible for changes in population, production, economic performance and biodiversity. The analysis also lists the present biome/vegetation type and climatic regime.

The subsequent columns work towards an integrated response package tailored to the characteristics and trends of the particular type of region. This is constructed from the perspective of enhancing biodiversity conservation under a changing climate in the context of regional socio-economic trends, whilst simultaneously hedging the response with respect to alternative potential future scenarios where these have different implications for actions. The climate change scenario column is particularly important – this briefly assesses whether different forms of action would be required in the different climate scenarios – recovery, stabilisation, runaway (Figure 9). If not, the actions are 'no regrets'; if so, then a mixed strategy may be needed to ensure preparation for all possible futures. This column is complemented with some comments on the education strategies and governance/institutional frameworks that will be required to support the integrated management package, which itself aims to build synergistically on the social trends of the region where possible. A significant strength of the approach is that the integrated response package (management, education, governance) is tailored to the characteristics of the particular region, where the region is considered as a linked social-ecological system. The table also includes comments on a 0–5 year action plan for each regional type to suggest what can be done now to begin implementing the package.

Table 9 – A systematic regional approach for biodiversity conservation in the 21st century. The table shows for various regional types: (i) the biomes and their climate trends; and (ii) the current state (low, medium, high) and trends of biodiversity (B), human population growth (H), economics ($) and agricultural production (P). The implications of the three climate scenarios (Figure 8) are also shown, with approaches in governance and investment sources (off-reserve), education, integrated response packages, and a 0–5 year action plan.

Regional type (example)	Biome, climate, trend Agro-ecological zone	Trends in biodiversity (B), human population (H), economics ($), and agricultural production (P) [1], and current state – low (L), medium (M) and high (H)				Future climate/ biodiversity	Implication of climate change scenarios*	Governance and investment sources (off-reserve)	Education	Integrated response package	0 – 5 year action plan (to begin now)
		B	H	$	P						
Amenity rural landscape (e.g. in eastern Victoria)	Temperate/ Mediterranean Drying with more extremes	L ↗	M ↗	M ↗	H ↘		1>3 similar capacity to invest in assisting change in current vegetation, so some increase in severity/ rates of change, but actions similar in all	Voluntary action-based on extension and education Strong private investment from individual wealth with public guidance	Sophisticated, focused on solutions and actions, practical information on ecosystem management and appropriate species	Infusion of wealth Investment in environment Need information to avoid perverse incentives Possibility of big biodiversity gains	Vigorous education campaign Research on ecosystem replacement
South-west Western Australia (world megadiversity hotspot)	Mediterranean: abrupt drying change in mid-1970s with a trend of increasing fire and drought	H ↓	M ↑	M ↑	M ↘	Drying trend, biodiversity loss	1 Invest in enhancing resilience for survival, focus on refugia 2 Invest in enhancing resilience, *ex situ* conservation, translocations and development of novel ecosystems 3 will cause massive species loss, difficult choice between heavy 'engineering' investment or abandonment; main hope may be *ex situ* conservation	Public-private partnerships Potential for significant private mining and other production industry funding.	Engage private industries/ bodies about saving Gondwanan hotspot; information and action on minimising existing threats	Vegetation corridors and translocations Fire management Focus on refugia and south-west corner where rainfall should not decline as much, water demand and management	Urgent to engage mining leaders while mineral boom is strong Mitigate aggressively or 'Gondwana' is gone Manage to enhance resilience as much as possible

Regional type (example)	Biome, climate, trend Agro-ecological zone	Trends in biodiversity (B), human population (H), economics ($), and agricultural production (P) [1], and current state – low (L), medium (M) and high (H)				Future climate/ biodiversity	Implication of climate change scenarios*	Governance and investment sources (off-reserve)	Education	Integrated response package	0 – 5 year action plan (to begin now)
		B	H	$	P						
Developing tropical coastline (e.g. Great Barrier Reef and Wet Tropics, north Queensland)	Reef: Sea level rise, nutrient runoff, acidity, sea surface temperature, cyclones Tropical forest and woodland – more fires, harder to manage	H ↘	M ↗	M ↗	M ↘		1 Invest heavily in enhancing resilience and protecting refugia Under 2 or 3, GBR is gone; Wet Tropics will retreat to small patches where engineering options may preserve species	GBRMPA, as an example agency, cooperating with local governments for marine areas; tourism industry-public sector alliances on land Private investment through tourist fees; public investment in stewardship	GBRMPA already running extensive education campaigns; need to convey sense of urgency and need to pull all relevant parties together	Increase Reef resilience: particularly manage nutrient runoff, and tourism and fishing Rainforest: reduce existing stresses and manage fire on boundaries	Vigorous education in Australia and overseas – mitigate or lose the Reef Focus on reducing land use stresses

*Climate scenarios
1 = 'Recovery' (recovers within 200 years)
2 = 'Stabilisation' (stabilises about 2100 but at ~3°C higher)
3 = 'Runaway' (keeps on changing)

A more complete systematic analysis aimed at such an approach would involve:

- collating the various regional socio-economic typologies already available for different regions
- running a qualitative expert-knowledge driven process for intersecting these with an appropriately resolved classification of environments (biome or biogeographic regions, or perhaps something like agroecological regions)
- identifying what climate change scenarios may be useful for planning in each type of region.

The results could then be taken into a series of regional workshops that deal with several geographically adjoining regions in practice. At a minimum level the regions might be the agro-climatic zones of Hobbs and McIntyre (2005), intersected with trends towards maintaining core production (farming or forestry), taking land out of production in unsustainable marginal agricultural regions, or changing towards peri-urban intensification and amenity uses. It will also be useful to consider urban areas and marine regions separately. In the longer run, such regional differentiation should be taken up through regional natural resource management governance mechanisms with ongoing local flexibility, adaptability and sensitivity to regional conditions.

8. Key messages and policy directions

The impacts of climate change on Australia's biodiversity are now discernible at the genetic, species, community and ecosystem levels across the continent and in our coastal seas. The threat to our biodiversity is increasing sharply through the 21st century and beyond due to growing impacts of climate change, the range of existing stressors on our biodiversity, and the complex interactions between them.

A business-as-usual approach to biodiversity conservation under a changing climate will fall short of meeting the challenge. A transformation is required in the way Australians think about biodiversity, its importance in the contemporary world, the threat presented by climate change, the strategies and tools needed to implement biodiversity conservation, the institutional arrangements that support these efforts, and the level of investment required to secure the biotic heritage of the continent.

The key messages coming out of the assessment, presented below, comprise an integrated set of actions. The order is arbitrary; they are highly interdependent and of similar priority. Taken together, they define a powerful way forward towards effective policy and management responses to the threat to biodiversity from climate change.

Reform our management of biodiversity

We need to adapt the way we manage biodiversity to meet existing and new threats – some existing policy and management tools remain effective, others need a major rethink, and new approaches need to be developed in order to enhance the resilience of our ecosystems.

As we are rapidly moving into a no-analogue state for our biodiversity and ecosystems, there is a need to transform our policy and management approaches to deal with this enormous challenge. Climate change presents a 'double whammy', affecting species, ecosystems and ecosystem processes directly as well as exacerbating the impacts of other stressors. Many effective management approaches already exist; the challenge is to accelerate, reorient and refine them to deal with climate change as a new and interacting complex stressor. The National Reserve System, the pillar of current biodiversity conservation efforts, needs to be enhanced substantially and integrated with more effective off-reserve conservation. Acceleration of actions to control and reduce existing stressors on Australian ecosystems and species is essential to increase resilience. However, there is a limit to how far enhancing resilience will be effective. Novel ecosystems will emerge and a wide range of unforeseen and surprising phenomena and interactions will appear. A more robust, long-term approach is to facilitate the self-adaptation of ecosystems across multiple pathways of adaptation that spread risk across alternative possible climatic and socio-economic futures. Active adaptive management, backed by research, monitoring and evaluation, can be an effective tool to support self-adaptation of ecosystems. An especially promising approach is to develop integrated regional biodiversity response strategies, tailored for regional differences in environments, climate change impacts and socio-economic trends.

Strengthen the national commitment to conserve Australia's biodiversity

Climate change has radical implications for how we think about conservation. We need wide public discussion to agree on a new national vision for Australia's biodiversity, and on the resources and institutions needed to implement it.

If the high rate of species loss and ecosystem degradation in Australia is to be slowed and eventually reversed, a more innovative and significantly strengthened approach to biodiversity conservation is needed. To meet this challenge, particularly under a rapidly changing climate, perceptions of the importance of biodiversity conservation and its implementation, in both the public and private sectors, must change fundamentally. A national discourse is therefore required on the nature, goals and importance of biodiversity conservation, leading to a major rethink of conservation policy, governance frameworks, resources for conservation activities and implementation strategies. The discourse should build a much broader and deeper base of support across Australian society for biodiversity conservation, and for goals that are appropriate in a changing climate. In particular, biodiversity education, policy and management should be reoriented from maintaining historical species distributions and abundances towards: (i) maintaining well-functioning ecosystems of sometimes novel composition that continue to deliver ecosystem services; and (ii) maximising native species' and ecosystem diversity.

Invest in our life support system

We are pushing the limits of our natural life support system. Our environment has suffered low levels of capital reinvestment for decades. We must renew public and private investment in this capital.

There is as yet no widely accepted method – be it changes in natural capital, adjusted net savings or other indicators – to account for the impact of changes in Australia's biotic heritage due to human use. However, by any measure, Australia's natural capital has suffered from depletion and under-investment over the past two centuries. Climate change intensifies the need for an urgent and sustained increase in investment in the environment – in effect, in our own life support system. The challenge is to establish an enhanced, sustained and long-term resource base – from both public and private investment – for biodiversity conservation. In particular, significant new funding strongly focused towards on-ground biodiversity conservation work, carried out within an active adaptive management framework, is essential to enhance our adaptive capacity during a time of climate change. Monitoring the status of biodiversity is especially important as without reliable, timely and rigorous information on changes in species and ecosystems, it is not possible to respond effectively to growing threats. An effective monitoring network would best be achieved via a national collaborative program with a commitment to ongoing, adequate resourcing.

Build innovative and flexible governance systems

Our current governance arrangements for conserving biodiversity are not designed to deal with the challenges of climate change. We need to build agile and innovative structures and approaches.

While primary responsibility for biodiversity conservation resides with each state and territory, over the past two decades many biodiversity conservation policies and approaches have been developed nationally through Commonwealth–state processes. There has also been a recent trend towards devolution of the delivery of natural resource management programs to the level of regional catchment management authorities and local Landcare groups. Dealing with the climate change threat will place further demands on our governance system, with a need to move towards strengthening and reforming governance at the regional level and towards more flexibility and coherence nationally. Building on the strengths of current arrangements, a next step is to explore the potential for innovation based on the principles of: (i) strengthening national leadership to underpin the reform agenda required; (ii) devolving responsibilities and resources to the most local, competent level, and building capacity at that level; (iii) facilitating a mix of interacting regional governance arrangements sensitive to local conditions; and (iv) facilitating new partnerships with other groups and organisations, for example, with Indigenous and business entities. In addition, improved policy integration across climate change, environment protection and commercial natural resource use is required nationally, including across jurisdictional boundaries.

Meet the mitigation challenge

Australia's biodiversity has only so much capacity to adapt to climate change, and we are approaching that limit. Therefore, strong emissions mitigation action globally and in Australia is vital – but this must be carried out in ways that deliver both adaptation and mitigation benefits.

There is a limit above which biodiversity will become increasingly vulnerable to climate change even with the most effective adaptation measures possible. Global average temperature increases of 1.5 or 2.0 ºC above pre-industrial levels – and we are already committed to an increase of around 1.2 or 1.3ºC – will likely lead to a massive loss of biodiversity worldwide. Thus, the mitigation issue is central to biodiversity conservation under climate change. To avoid an inevitable wave of extinctions in the second half of the century, deep cuts in global greenhouse gas emissions are required by 2020 at the latest. The more effectively the rate of climate change can be slowed and the sooner climate can be stabilised, the better are the prospects that biodiversity loss will be lessened. Societal responses to the mitigation challenge, however, could have significant negative consequences for biodiversity, over and above the effects of climate change itself. Examples include planting monocultures of fast-growing trees rather than establishing more complex ecosystems that both support more biodiversity and store more carbon, and inappropriate development of Australia's north in response to deteriorating climatic conditions in the south. However, with flexible, integrated approaches to mitigation and adaptation, many opportunities will arise for solutions that both deliver positive mitigation/adaptation outcomes and enhance biodiversity values.

References

Alexander LV, Hope P, Collins D, Trewin B, Lynch A and Nicholls N (2007) Trends in Australia's climate means and extremes: a global context. *Australian Meterological Magazine* **56**: 1–18.

Barr NR (2005) *The changing social landscape of rural Victoria*. Department of Primary Industries, Melbourne.

Beeton RJS, Buckley KI, Jones GJ, Morgan D, Reichelt RE and Trewin D (2006) *Australia State of the Environment 2006*, Independent report to the Australian Government Minister for the Environment and Heritage, Department of the Environment and Heritage, Canberra. Retrieved 17 September 2008, <http://www.environment.gov.au/soe/2006/index.html>.

Cai W (2006) Antarctic ozone depletion causes an intensification of the Southern Ocean super-gyre circulation. *Geophysical Research Letters* **33**: L03712.

Canadell JG, Le Quéré C, Raupach MR, Field CB, Buitenhuis ET, Ciais P, Conway TJ, Gillett NP, Houghton RA and Marland G (2007) Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences of the United States of America* **104**: 18866–18870.

Chapman AD (2005) *Numbers of living species in Australia and the world*. Report for the Department of the Environment and Heritage, Canberra.

Church JA, Hunter JR, McInnes KL and White NJ (2006) Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events. *Australian Meterological Magazine* **55**: 253–260.

Commonwealth Scientific and Industrial Research Organisation and the Australian Bureau of Meteorology (CSIRO and BOM) (2007) *Climate change in Australia: observed changes and projections*. Technical Report. Retrieved 1 September 2008, <http://www.climatechangeinaustralia.gov.au>.

Connell D (2007) *Water politics in the Murray-Darling Basin*. Federation Press, Annandale, Australia.

Dunlop M and Brown PR (2008) *Implications of climate change for Australia's National Reserve System: a preliminary assessment*. Report to the Department of Climate Change. Department of Climate Change, and the Department of the Environment, Water, Heritage and the Arts, Canberra

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR and Mearns LO (2000) Climate extremes: observations, modeling, and impacts. *Science* **289**: 2068–2074.

Hennessy K, Fawcett R, Kirono D, Mpelasoka F, Jones D, Bathols J, Whetton P, Stafford Smith M, Howden M, Mitchell C and Plummer N (2008) *An assessment of the impact of climate change on the nature and frequency of exceptional climatic events*. CSIRO and Australian Bureau of Meteorology.

Hennessy KJ, Lucas C, Nicholls N, Bathols JM, Suppiah R and Ricketts JH (2005) *Climate change impacts on fire-weather in south-east Australia, Report C/1061*. CSIRO Marine and Atmospheric Research, Bushfire CRC and Australian Bureau of Meteorology. CSIRO, Aspendale, Victoria.

Hilbert DW, Ostendorf B and Hopkins M (2001) Sensitivity of tropical forests to climate change in the humid tropics of north Queensland. *Austral Ecology* **26**: 590–603.

Hilbert DW, Hughes L, Johnson J, Lough JM, Low T, Pearson RG, Sutherst RW and Whittaker S (Eds) (2007) *Biodiversity conservation research in a changing climate. Workshop report: research needs and information gaps for the implementation of key objectives of the National Biodiversity and Climate Change Action Plan*. A report produced by CSIRO for the Department of Environment and Heritage, Canberra.

Hobbs RJ and McIntyre S (2005) Categorizing Australian landscapes as an aid to assessing the generality of landscape management guidelines. *Global Ecology and Biogeography* **14**: 1–15.

Hobbs RJ, Arico S, Aronson J, Baron JS, Bridgewater P, Cramer VA, Epstein PR, Ewel JJ, Klink CA, Lugo AE, Norton D, Ojima D, Richardson DM, Sanderson EW, Valladares F, VilÃ M, Zamora R and Zobel M (2006) Novel ecosystems: theoretical and management aspects of the new ecological world order. *Global Ecology and Biogeography* **15**: 1–7.

Hobday AJ, Poloczanska ES and Matear RJ (Eds) (2007) *Implications of climate change for Australian fisheries and aquaculture: a preliminary assessment*. Report to the Department of Climate Change, Canberra.

Hoegh-Guldberg O, Hughes L, McIntyre S, Lindenmayer DB, Parmesan C, Possingham HP and Thomas CD (2008) Assisted colonization and rapid climate change. *Science* **321**: 345–346.

Holmes J (2008) The multifunctional transition in Australia's tropical savannas: regional complexity and diversity in rural occupance modes. *Journal of Rural Studies* (submitted).

Hughes L (2000) Biological consequences of global warming: is the signal already apparent? *Trends in Ecology and Evolution* **15**: 56–61.

Hughes L, Westoby M and Cawsey M (1996) Climatic range sizes of Eucalyptus species in relation to future climate change. *Global Ecology and Biogeography Letters* **5**: 23–29.

Intergovernmental Panel on Climate (IPCC) (2007a) *Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (Eds S Solomon, D Quin, M Manning, M Marquis, K Averyt, MMB Tignor, HL Miller and Z Chen). Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate (IPCC) (2007b) *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (Eds M Parry, O Canziani, J Palutikof, P van der Linden and C Hanson). Cambridge University Press, Cambridge, UK.

Johnson JE and Marshall PA (Eds) (2007) *Climate change and the Great Barrier Reef: a vulnerability assessment*. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia.

Kanowski JJ (2001) Effects of elevated CO_2 on the foliar chemistry of seedlings of two rainforest trees from north-east Australia: implications for folivorous marsupials. *Austral Ecology* **26**: 165–172.

King RW, Pate JS and Johnston J (1995) Ecotypic differences in the flowering of Pimelea ferruginea (Thymelaeaceae) in response to cool temperatures. *Australian Journal of Botany* **44**: 47–55.

Kuleshov YA (2003) *Tropical cyclone climatology for the southern hemisphere. Part I: spatial and temporal profiles of tropical cyclones in the southern hemisphere*. National Climate Centre, Australian Bureau of Meteorology.

Landsberg J and Stafford Smith DM (1992) A functional scheme for predicting the outbreak potential of herbivorous insects under global atmospheric change. *Australian Journal of Botany* **40**: 565–577.

Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S and Schnellnhuber HJ (2008) Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America* **105**: 1786–1793.

Lindenmayer DB (2007) *On borrowed time: Australia's environmental crisis and what we must do about it*. CSIRO Publishing and Penguin, Melbourne, <http://www.publish.csiro.au/pid/5691.htm>.

Lindenmayer DB and Franklin JF (2002) *Conserving forest biodiversity: a comprehensive multiscaled approach*. Island Press, Washington, DC.

Lindenmayer DB, Fischer J, Felton A, Crane M, Michael D, Macgregor C, Montague-Drake R, Manning A and Hobbs RJ (2008) Novel ecosystems resulting from landscape transformation create dilemmas for modern conservation practice. *Conservation Letters* **1**: 129–135.

Lindgren E (2000) *The new environmental context for disease transmission, with case studies on climate* *change and tick-borne encephalitis*. Natural Resources Management, Department of Systems Ecology. Sweden, Stockholm University, Sweden.

Lorius C, Jouzel J, Raynaud D, Hansen J and Le Treut H (1990) The ice-core record: climate sensitivity and future greenhouse warming. *Nature* **347**: 139–145.

MA (Millennium Ecosystem Assessment) (2005) *Ecosystems and human well-being: synthesis*. Island Press, Washington, DC.

Mann ME, Bradley RS and Hughes MK (1999) Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Manning AD, Fischer J, Felton A, Newell B, Steffen W and Lindenmayer DB (2009) Landscape fluidity – a unifying perspective for understanding and adapting to global change. *Journal of Biogeography* **36**: 193–199.

Mansergh I and Cheal D (2007) Protected area planning and management for eastern Australian temperate forests and woodland ecosystems under climate change – a landscape approach. In *Protected areas: buffering nature against climate change*. (Eds M Taylor and P Figgis) pp. 58–72. Proceedings of a WWF and IUCN World Commission on Protected Areas Symposium, 18–19 June, Canberra. WWF-Australia, Sydney.

Marshall GR (2005) *Economics for collaborative environmental management: renegotiating the commons*. Earthscan, London.

Marshall GR (2008) Nesting, subsidiarity, and community-based environmental governance beyond the local level. *International Journal of the Commons* **2**: 75–97.

Musgrave W and Kingma O (2003) *Economic policy and sustainable use of natural resources. In Managing Australia's environment*. (Eds S Dovers and S Wild River) chap. 21. The Federation Press, Annandale, Sydney.

National Tidal Centre (2006) *The Australian Baseline Sea level Monitoring Project Monthly Data Report August 2006*. Bureau of Meteorology, Kent Town, South Australia, <http://www.environment.gov.au/soe/2006/publications/drs/pubs/366/co/co_03_aust_mean_sea_level_survey_2003.pdf>.

Nicholls N (2004) The changing nature of Australian droughts. *Climatic Change* **63**: 323–336.

Nicholls N (2005) Climate variability, climate change and the Australian snow season. *Australian Meteorological Magazine* **54**: 177–185.

Nicholls N (2006) Detecting and attributing Australian climate change: a review. *Australian Meteorological Magazine* **55**: 199–211.

Nicholls N (2008) *Australian climate and weather extremes: past, present and future*. Department of Climate Change, Canberra.

Noble IR and Slatyer RO (1980) The use of vital attributes to predict successional changes in plant-communities subject to recurrent disturbances. *Vegetatio* **43**: 5–21.

O'Connor MI, Bruno JF, Gaines SD, Halpern BS, Lester SE, Kinlan BP and Weiss JM (2007) Temperature control of larval dispersal and the implications for marine ecology, evolution, and conservation. *Proceedings of the National Academy of Sciences of the United States of America* **104**: 1266–1271.

Olsen P (2007) The state of Australia's birds 2007: birds in a changing climate. Supplement to *Wingspan* **14**: 1–32.

Orians GH and Milewski AV (2007) Ecology of Australia: the effects of nutrient-poor soils and intense fires. *Biological Reviews* **82**: 393–423.

Ostrom E (2005) *Understanding institutional diversity*. Princeton University Press, Princeton.

Parmesan C, Root TL and Willig MR (2000) Impacts of extreme weather and climate on terrestrial biota. *Bulletin of the American Meteorological Society* **81**: 443–450.

Pittock AB (2003) *Climate change: an Australian guide to the science and potential impacts*. Australian Greenhouse Office, Canberra.

Pounds JA, Bustamante MR, Coloma LA, Consuegra JA, Fogden MPL, Foster PN, La Marca E, Masters KL, Merino-Viteri A, Puschendorf R, Ron SR, Sánchez-Azofeifa GA, Still CJ and Young BE (2006) Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature* **439**: 161–167.

Productivity Commission (2004) *Impacts of native vegetation and biodiversity regulations*. Report No. 29. Productivity Commission, Melbourne.

Rahmstorf S, Cazenave A, Church JA, Hansen JE, Keeling RF, Parker DE and Somerville RCJ (2007) Recent climate observations compared to projections. *Science* **316**: 709.

Raupach MR, Marland G, Ciais P, Le Quéré C, Canadell JG and Field CB (2007) Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences of the United States of America* **104**: 10288–10293.

Ridgway KR (2007) Long-term trend and decadal variability of the southward penetration of the East Australian Current. *Geophysical Research Letters* **34**: L13613.1–L13613.5.

Ritchie EG, Martin JK, Krockenberger AK, Garnett S and Johnson CN (2008) Large-herbivore distribution and abundance: intra- and interspecific niche variation in the tropics. *Ecological Monographs* **78**: 105–122.

Shanks AL, Grantham BA and Carr MH (2003) Propagule dispersal distance and the size and spacing of marine reserves. *Ecological Applications* **13**: S159–S169.

Stafford Smith M and McAllister RRJ (2008) Managing arid zone natural resources in Australia for spatial and temporal variability – an approach from first principles. *The Rangeland Journal* **30**: 15–27.

Steffen W, Sanderson A, Tyson PD, Jäger J, Matson P, Moore III B, Oldfield F, Richardson K, Schellnhuber HJ, Turner II BL and Wasson RJ (2004) *Global change and the Earth system: a planet under pressure*. IGBP Book Series, Springer-Verlag, Berlin.

Walker B, Steffen W and Langridge J (1999) Interactive and integrated effects of global change on terrestrial ecosystems. In *The terrestrial biosphere and global change: implications for natural and managed ecosystems*. (Eds B Walker, W Steffen, J Canadell and JS Ingram) pp. 329–375. Cambridge University Press, Cambridge, UK.

Wallace KJ (2007) Classification of ecosystem services: problems and solutions. *Biological Conservation* **139**: 235–246.

Williams SE, Bolitho EE and Fox S (2003) Climate change in Australian tropical rainforests: an impending environmental catastrophe. *Proceedings of the Royal Society of London. Biological Sciences* **270**: 1887–1892.

Williams JW and Jackson ST (2007) Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment* **5**: 475–482.

Woinarski JCZ (Ed.) (1999) Fire and Australian birds: a review. In *Australia's biodiversity: responses to fire. Plants, birds and invertebrates*. (Eds AM Gill, JCZ Woinarski and A York) pp. 55–112. Department of the Environment and Heritage, Canberra.