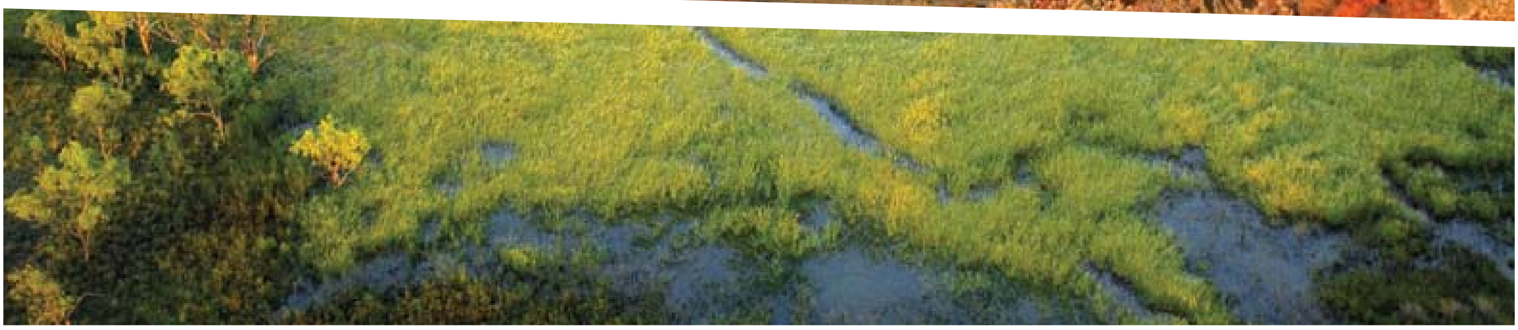
Australian Government
Department of Climate Change
Department of the Environment, Water, Heritage and the Arts

IMPLICATIONS OF CLIMATE CHANGE FOR AUSTRALIA'S NATIONAL RESERVE SYSTEM A PRELIMINARY ASSESSMENT



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Implications of climate change for Australia's National Reserve System: A preliminary assessment

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CSIRO Sustainable Ecosystems

Report to the Department of Climate Change, and the Department of the Environment, Water, Heritage and the Arts

March 2008

CSIRO

Published by the Department of Climate Change

ISBN: 978-1-921297-73-1

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Please cite this report as:

Dunlop, M., & Brown, P.R. 2008. Implications of climate change for Australia's National Reserve System: A preliminary assessment. Report to the Department of Climate Change, February 2008. Department of Climate Change, Canberra, Australia.

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4. Mornington Sanctuary, WA (Australian Wildlife Conservancy)

ACKNOWLEDGEMENTS

Many people contributed to this project and report through discussions, comments on early drafts and provision of written material. Sue McIntyre, Leanne Webb and Jim Rickets contributed substantially to the regional analyses in Part C. Other contributors included: Mike Austin, Steve Crimp, Saul Cunningham, Michael Doherty, Mark Howden, Darren Kriticos, Rohan Nelson, Sarah Pizzey, Lou Rodgerson, Andy Sheppard, Kate Stokes, Martin Taylor, Barry Traill, Kristen Williams, Graham Worboys, participants at the project workshop in February 2007 (see Part B, Appendix 4), members of the National Biodiversity Review Task Group and members of the National Reserve System Scientific Advisory Subgroup. Tim Bond provided the maps of the reserve system and agro-climatic zones. We are very appreciative of all your contributions.

We benefited greatly from discussions at three recent meetings focussing on the impacts of climate change on protected areas: Australian Alps National Parks Conference April 2007, Parks Forum May 2007, and the WWF/WCPA Symposium in June 2007.

We acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the World Climate Research Programme's Working Group on Coupled Modelling (WGCM) for their roles in making available the Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

We also thank Veronica Doer, David Hilbert, Michael Doherty and Roger Jones for their thoughtful comments on drafts of the report.

We thank the Department of Climate Change and the Department of the Environment, Water, Heritage and the Arts for the opportunity to undertake this project. In particular we acknowledge the cooperation, engagement, feedback and contributions made by Bruce Cummings, Tim Bond and Rachael Dempsey from Parks Australia, and Anna van Dugteren and Liz Dovey from the Department of Climate Change.

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PREFACE BY THE AUSTRALIAN GOVERNMENT

Climate change increasingly presents a major challenge for biodiversity conservation planning in Australia and for managers of key natural assets such as protected areas. It is not only adding directly to more familiar risks such as habitat loss and degradation, invasive species and changes to fire regimes, but to the consequences of these threats themselves being affected by climate change.

The more than 8,000 protected areas in Australia's National Reserve System (NRS) represent the premier terrestrial biodiversity conservation investment in Australia. This network has been developed through collective efforts of the Australian Government, State and Territory governments, local government, non-government organisations and the community. Protected areas across Australia contain key areas for the protection of Australia's biodiversity, including high conservation value native ecosystems which do not occur, or are limited in their occurrence outside of protected areas, plus core habitats for many native species of high conservation value. The strategic national approach to the establishment and management of a comprehensive, adequate and representative protected area system builds on the framework provided by the *Directions for the National Reserve System - A Partnership Approach*, endorsed by the Natural Resource Management Ministerial Council in 2005.

In 2006, the Australian Greenhouse Office (now the Department of Climate Change) and Parks Australia commissioned the CSIRO to undertake a preliminary assessment – *Implications of climate change for Australia's National Reserve System* – to provide an initial assessment of the implications of climate change for Australia's national network of terrestrial protected areas. This report provides an overview of the state of knowledge on climate change and the NRS, including the likely impacts, key risks and knowledge gaps relevant to reserve system planning and policy decisions.

A number of other Australian Government and intergovernmental initiatives are underway and will contribute to the understanding of risks to biodiversity and to natural areas as a result of climate change. These include a series of preliminary assessments on the implications of climate change for Australia's World Heritage values and areas, for Australian Government managed reserves, for ecological water requirements, and for fire in relation to areas managed for biodiversity and to Australian biodiversity more broadly.

In April 2007, the National Climate Change Adaptation Framework highlighting priority actions for a range of vulnerable sectors, including biodiversity, was endorsed by the Council of Australian Governments. The Australian Government is investing $126 million over five years in climate change adaptation policies, programs and research. A further $44 million is being invested in a CSIRO Climate Adaptation Flagship. These initiatives will position Australia to manage risks arising from the impacts of climate change and will rely on strong partnerships between governments and decision-makers in industries and communities in all sectors. The success of this work program will rely on collaboration with government, research and industry partners to develop tools, techniques, and resources to assist biodiversity managers manage the challenges posed by climate change.

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EXECUTIVE SUMMARY

Background

This report investigates the possible future impacts of climate change on Australia's system of formally protected conservation areas, the National Reserve System (NRS), and the consequences of these impacts for the development and management of the reserve system. It has been prepared by CSIRO Sustainable Ecosystems for Parks Australia (now in the Department of the Environment, Water, Heritage and the Arts) and the Australian Greenhouse Office (now the Department of Climate Change) to help them scope further analyses and appropriate responses. The report summarises information about the potential impacts of climate change on biodiversity, provides an estimate of which impacts might be more important in different regions, and discusses key implications for conservation policy, management of protected areas and the strategic framework used to develop the NRS. The implications for the reserve system were compiled through extensive consultations with experts, NGOs, conservation policy developers and reserve managers.

Increases in the atmospheric concentration of CO_2 and other greenhouse gases (GHG) will lead to changes in temperature and rainfall, and the occurrence and intensity of storms, wind, run-off, floods, droughts, fires, heat waves, El Niño and other climate cycles. These changes affect primary productivity and many biological processes; hence there is every reason to believe many if not virtually all species on Earth will be affected. Many different types of impact have been hypothesised.

Extensive modelling and monitoring studies over the last 20 years provide considerable evidence that global climate change is already affecting and will continue to affect many species and ecosystems, leading to declines and extinctions of many species. However, because of the interacting nature of biological and ecological systems, with their positive and negative feedbacks, and the multifaceted nature of the environmental changes in response to climate change and other pressures, it is not immediately obvious what the net impacts on biodiversity are likely to be.

Climate change will affect many aspects of Australia's biodiversity that are valued by society including the "look, sound and smell" of ecosystems, as well as tourism and recreational opportunities. Significant reductions of diversity would be likely to also result in interruptions to ecosystem function and loss of ecosystem services. These changes will also have a wide range of implications for biodiversity conservation and the NRS, including managing ever-changing biodiversity, new and changing threats, different information requirements, and a need to reassess the fundamental goals of conservation.

The National Reserve System is a network of almost 9000 protected areas including national parks, nature reserves, private conservation reserves, Indigenous Protected Areas and other reserve types covering 88 million hectares (11.5% of the continent). In recent times the NRS has been developed using a bioregional framework based on the Interim Biogeographic Regionalisation for Australia (IBRA) and the selection criteria of comprehensiveness, adequacy and representativeness. The NRS aims to strategically protect habitat so that the diversity of all native landscapes, flora and fauna across Australia is conserved.

Globally, and in Australia, concerns have been raised about the impact of climate change on the effectiveness of fixed protected areas.

Key findings of this project

Climate change will have a wide range of impacts on species and ecosystems, including changes in: species distributions and abundances, ecosystem processes, interactions between species, and various threats to biodiversity. Four threats that will be affected by climate change and will be particularly hard to manage due to strong biophysical and social dimensions are: the arrival of new (native and exotic) species in a region, altered fire regimes, land use change and altered hydrology. Differences between species and the complexities of natural ecosystems will lead to uncertainties about the exact nature of change in biodiversity. Key uncertainties concern the dynamics and processes of ecological changes and the role that habitat variability across the landscape plays in mediating changes.

Different changes will have different implications for conservation and the NRS. Therefore it is important that a broad range of changes is considered in planning adaptation actions, and that plans are updated as new information becomes available. Three different mental models, highlighting different impacts and change processes, are proposed to assist in this task.

The inevitability of significant change in species and ecosystems leads to a need to reassess the core challenge of conservation and embrace the task of “managing the change to minimise the loss”. This has considerable consequences for many conservation programs; it may require revision of management guidelines and policies, as well as scientific debate and community consultation (about how much change is acceptable). Both coordinated observation of actual changes and more research (with better methods) will be required to inform future policy and management decisions about effectively conserving biodiversity as the changes continue.

A critical component of conserving species is the availability of suitable habitat. Species and ecosystems will change in their requirements and distributions, therefore ensuring that widespread and diverse habitat is protected in the future will be essential for conserving species. The bioregional framework used to develop the NRS targets habitat diversity at multiple scales; this is an excellent process for strategically developing a system of protected areas that will remain effective under climate change. However, to be effective the bioregional framework must be implemented as widely as possible through the NRS and other habitat protection programs.

There is also a need to manage habitat for specific conservation outcomes (facilitating change or maintaining suitable habitat for vulnerable species) and to reduce threats. Habitat protection may also be required to maintain the connectivity required for various ecological processes that occur at landscape scales, including the movement of species in response to disturbance and climate change. However, in some situations habitat connectivity will facilitate processes with undesirable outcomes, including the spread of fire and the expansion of species that may exclude threatened species. Protection of isolated areas of habitat, as well as well-connected ones, would reduce those risks.

Part A - Impacts of climate change on biodiversity

Australian species have experienced considerable climatic changes in the past, including many cycles of warming and cooling over the last few million years. Considerable biotic changes have occurred globally during these cycles; changes in Australia appear to have been dominated by changes in the relative abundance of different types of species rather continental-scale changes in the distribution of species. For the last 11,000 years the Earth has been in a relatively stable warm phase of the cycle and is probably within a degree or two of being the warmest it has been for over 2 million years. Without significant reductions in GHG emissions, future climate change in Australia will be unlike any previous changes due the extensive fragmentation and modification of habitat by human activities, the presence of exotic species, decreasing (rather than increasing) water availability, and the rate, magnitude and direction of temperature change.

A schema is presented for considering the many different types of impact on biodiversity in terms of a “cascade of impacts” from changes to the climate, through impacts on individual organisms, species and ecosystems, to implications for human wellbeing (Figure A). This process was designed to illustrate the details of different types of changes, rather than to catalogue all the changes that have been documented across different ecosystems. Many analyses of the impacts of climate change on biodiversity conservation focus on changes in the distribution of species, typically pole-ward and uphill. The presentation of this cascade of impacts provides a greater level of understanding of the impact of climate change at different levels, highlights the interactive nature between individuals, species, populations and ecosystems and their responses, and introduces a new way of thinking about managing climate change impacts on biodiversity.

- **Environments impacts**: the changes arising from increased GHG concentrations that drive impacts on biodiversity; they include changes in CO_2, temperature and rainfall regimes, fire regimes, and sea temperature, chemistry and level. These impacts can combine with other (non-climate-related) environmental stresses on biodiversity, and are affected by feedbacks from population and ecosystem impacts (below).

- **Biological impacts**: the direct changes to organisms arising from environmental changes; they include changes in physiology and the timing of lifecycle events (phenology).

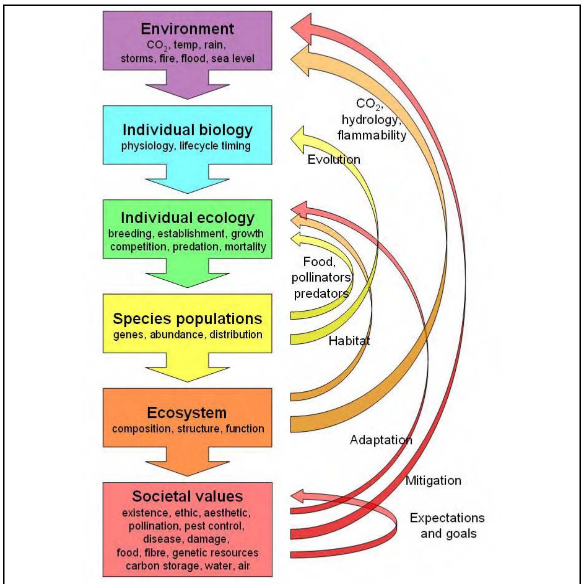


Figure A. Schematic representation of the cascading impacts of climate change on biodiversity. The direct flow of impacts is represented by large arrows. Important indirect impacts are shown as feedbacks.

- **Ecological impacts**: result from changed interactions between organisms and the environment; they include changes in breeding, establishment, growth, competition and mortality. These impacts flow directly from climate change related impacts (above), and indirectly via interactions with other species that are affected by climate change leading to changed competition, food, habitat and predation. These indirect impacts can be represented as feedbacks from population impacts and ecosystem impacts (below) to ecological impacts. Ecological impacts are also affected by how climate change impacts interact with other stresses.

- **Population impacts**: the ultimate impact on species in terms of changes in gene frequencies, abundance and distribution.

- **Ecosystem impacts**: changes in the identity, composition, structure and function of assemblages and ecosystems that result from cumulative impacts on populations of many species.

- **Value impacts**: represent impacts on human well-being – the reason society cares about climate change and biodiversity. These include economic and other material benefits derived from consumptive and non-consumptive uses of biodiversity (e.g. production of food and fibre and regulation of hydrological and carbon cycles), and many less tangible values (e.g. existence of species and ecosystems, stewardship of the planet, and aesthetics).

The direct flow of impacts of climate change on biodiversity (the downward arrows in Figure A) will include some rapid changes and others that take decades or centuries to materialise. The dominant impacts on some species will be because species with which they interact strongly are affected by climate change in some way: many feedbacks may lead to such indirect impacts. Examples include: changes in food species, predation and competition, evolution of species' responses to climate and other environmental parameters, altered habitat, changes in ecosystem function altering the environment (upward arrows in Figure A). Human responses can also be represented as feedbacks, including reductions in GHG emissions, ecological management to facilitate adaptation, and altered expectations about the state and dynamics of biodiversity.

Observational and modelling analyses consistently report that different species and different ecosystems are expected to respond to climate change in very different ways. Key aspects of changes to biodiversity with implications for conservation include: changes in species distributions and abundances, interactions between species, ecosystem processes, threats to biodiversity, the rates of ecological change, and the role of habitat and landscape diversity in mediating changes.

The patchy state of knowledge about the impacts on biodiversity limits the capacity of conservation planners and researchers to consider the full range of likely impacts when assessing conservation implications. There is a risk of developing adaptation responses on the basis of a narrow conceptualisation of the changes and their implications. We provide three alternative mental models of biodiversity change representing different ways to conceptualise the impacts on biodiversity.

1. **Relative abundance change model** – The abundance of most species is affected by the combination of many impacts, leading to *in situ* changes in relative abundance and ecosystem structure and function, but minimal changes in composition. Dramatic and rapid changes are possible with rapid increases in abundance and "in-filling" by species that are currently in low densities or scattered micro-sites. Declining species become confined to restricted microhabitats or locally extinct. In general, changes in species abundance and ecosystems services will probably be harder to predict than changes in functional types.
2. **Long-distance or rapid distribution change model** – Altered environmental conditions lead to improved establishment opportunity beyond existing ranges. A small proportion of species respond rapidly via rapid gradual expansion or long-distance dispersal followed by local population expansion. Most newly establishing species are likely to be relatively benign. However, a few may have a major impact on other species and potentially transform ecosystem structure and function. Increased species richness will be observed first; the potential sources and identity of new species and their impacts on other species and ecosystem function will be very hard to predict.
3. **Gradual distribution shift model** – Changing climate leads to shifts in the bioclimatic habitats in which populations currently exist; the direction of shifts is dominated by warming but rainfall is also important. Gradual species turnover (species arriving and leaving a region) drives shifts in structure and function. Species will respond differently, so communities and ecosystems will change as well as shift in distribution. This model is intuitively appealing: it is simple, directional predictions can be made and it has clear conservation implications. It is also widely supported by observations and species models. This model has dominated many impact assessments, possibly due more to its intuitive appeal and ease of implementation, rather than as a result of any assessment of its relative accuracy or likelihood.

Each of these models is supported by observations and theoretical predictions, however it is not clear which type of changes might dominate in any one situation or time period. They are presented as alternatives to highlight that there is no one best way to frame the likely impacts on biodiversity, and that each type of change should be considered when observing changes, anticipating future changes, assessing conservation implications and considering management options. However, the models are not strictly mutually exclusive; all impacts will happen, the important question is: which model will dominate at what scale? Key uncertainties include the process and dynamics of declines in abundance, the nature of expansions in distribution and abundance, the key drivers of change (direct or indirect impacts), and the timing of changes. Observation of actual changes combined with improved modelling will be needed to distinguish which changes will actually dominate in different settings. The purpose of outlining the three mental models is to provide some context for managers into which observations and new information can be placed, to help in the formulation of hypotheses about particular regions or ecosystems, and to ensure adaptation responses are designed to address the full range of possible changes.

The impacts of climate change are unlikely to lead to *marginal* changes in biodiversity. It is convenient in many analyses to consider the impact of a single factor with “all else being constant”. As the climate continues to change we can expect simultaneous changes in many factors that could affect outcomes. Furthermore, the ways species and ecosystems respond to individual factors are also likely to change. Benchmarks for species and ecosystem outcomes may need to be revised, and it will be increasingly less feasible to regard species as static and in equilibrium with other species and the environment, and to assume “all else is constant”. This change in the fundamentals of biodiversity will be an issue for research (including the suitability and parameterisation of many biodiversity models) and for conservation planning and management.

Part B - Regional impacts of climate change

A qualitative assessment of the impacts of climate change on biodiversity is presented for each of ten agro-climatic zones in Australia. The approach is essentially ecosystem-process based; it draws heavily on assessing how seasonal patterns of plant growth may change, but the impacts of other ecologically important changes are also considered. The assessment used the agro-climatic zones of Hobbs and McIntyre (2005) which were based on a spatial agro-climatic analysis of modelled plant growth responses using data from 1135 climate stations across Australia (Figure B). Future climate changes were drawn from CSIRO analyses of the most recent IPCC climate projections (Suppiah *et al.* 2007).

The analysis identified the ‘Temperate cool-season wet’ and the ‘Temperate subhumid’ zones as the zones likely to experience the most significant ecosystem-level changes, since they are likely to undergo the most significant changes in their patterns of season growth potentially leading to a wide range of ecological impacts. These are likely to include: marked changes in vegetation composition, structure and function, and increases in fire frequency and changes in land use that will affect biodiversity. In addition, the impacts of these changes are potentially amplified in these zones as they are already heavily cleared and fragmented.

This was a first attempt at using this approach and was largely based on broad-scale information about each zone; very little information about species-specific vulnerabilities to climate change was included. Before being used for detailed planning or prioritisation it should be reviewed and revised by experts who are familiar with climate change impacts and the ecosystems in each zone. Refinements to the process could include: using quantitative information about changes in ecological processes, conducting the analysis at finer scales (e.g. bioregions), using more local knowledge, and integrating potential ecosystem-level changes with species-specific information.

This analysis differs from “standard” assessments of the most vulnerable terrestrial regions which typically identify Queensland Wet Tropics, the Australian Alps, and southwest Western Australia (e.g. IPCC Fourth Assessment Report, Hennessy *et al*. 2007). This difference reflects the traditional use of species-level information as opposed to our use of ecosystem-level information. This highlights the importance of approaching issues of impact and priority from multiple ecological perspectives, and the need to develop new approaches to impact assessment.

A separate analysis was conducted of projected climate changes for each of the 85 IBRA regions based on high, medium and low greenhouse gas emissions scenarios using three different models. Parameters were calculated for annual and seasonal periods for 2030 and 2070 and include temperature, rainfall, temperature extremes and snow depth.

Part C - Implications for the National Reserve System

This report discusses key challenges for the development and management of the NRS arising from continued climate change; however the NRS is part of a broader physical, social and political landscape that must be considered if changes in conservation management are to be effective.

Much of the scientific literature on climate change and conservation focuses on the implication of changing species distributions combined with the fixed nature of protected areas. This is a concern especially where reserves are declared to protect specific threatened species, but it does not decrease the importance of protected areas in conservation. Furthermore, changes and threats other than distribution changes may be more significant for many species. Some studies suggest modification of standard reserve design guidelines may be warranted, placing more emphasis on a system of protected areas that covers a wide geographic distribution and includes a high diversity of habitat types; the bioregional framework of the NRS already does this.

We identify eight key implications arising from climate change for biodiversity conservation and the NRS. Comprehensive responses to most of the issues would require significant policy development and further analysis over 5-10 years, however for each issues there are tangible responses that could be commenced immediately (some are already under way) to begin to address the issue.

1. **The changing conservation challenge.** Understanding the challenges resulting from climate change is a complex task for planners, managers and conservation stakeholders. It will necessitate changing the very nature of Australia’s core conservation objective from essentially “preventing ecological change” to “managing the change to minimise the loss”. This change will have implications for the development and the management of the NRS, as well as for conservation programs more broadly.

   This objective can be broken down into two conservation goals that need to be balanced:

   i. to **facilitate natural changes** in species and ecosystems, including natural adaptation to climate change, and

   ii. to **preserve elements of biodiversity** that are both particularly valued and threatened.

   In some situations these goals would call for incompatible management responses requiring managers to actively choose one goal over the other. Wide community debate about the changing nature of conservation objectives would assist in forming guidelines and making trade-off decisions. Some legislative changes may also be required.

2. **Dealing with changing threats.** The nature and impact of threats to biodiversity are likely to change with strategic and practical implications for the NRS. Changing threats may alter priority regions and ecosystems for habitat protection, and new skills and resources may be required to address threats in different regions. It may be possible to anticipate some changing threats, but there will be a need for ongoing monitoring and flexible responses to address other changing threats.

3. **"Wicked" threats.** Four key threats that are likely to change include: altered fire regimes, the arrival of new (native and exotic) species, changing land use and altered hydrology. Each of these threats has strong biophysical and social dimensions greatly complicating management; in some cases the societal response to the threat may have a greater impact on biodiversity than the direct impact of the threat. Australia currently lacks a framework for assessing the implications and appropriate management responses to the arrival in regions of new native species that are likely to have negative impacts on local species.

4. **Single species and strategic management.** The changing nature of biodiversity and biodiversity conservation will affect the balance between single species and strategic conservation programs, with logical arguments for the need to increase efforts in both. Rapid change will also reduce the usefulness of many current surrogates for biodiversity; however *habitat diversity* is likely to be a relatively robust surrogate for species diversity. There will also be a need to clearly define the role of species-level and ecosystem-level information and aspirations along the conservation planning "value chain": from ecological knowledge, through conservation aspirations, planning processes, and data and management goals, to national conservation outcomes.

5. **Bioregional and landscape conservation.** Climate change will lead to broad-scale changes in biodiversity and threats. The adequacy of Australian conservation efforts collectively would be enhanced by better coordination across programs to strategically address habitat protection, threat management and landscape-scale objectives (e.g. connectivity). Coordination would assist in setting conservation goals, prioritising investment, assessing biodiversity and threats, and evaluating investments. The bioregional framework that is used in the NRS would provide an effective basis for such coordination.

6. **Development of the NRS.** The process for assessing *comprehensiveness* and *representativeness* of the NRS focuses on protecting a diversity of habitat types (at multiple scales). It therefore provides an excellent basis for developing a protected area system that effectively and practically conserves as many species as possible in the face of climate change. The process will not guarantee all species are protected, but given the likely changes and uncertainties, it is probably the best available option for strategically targeting habitat protection. However, to be effective, progress must be made in completing habitat protection targets in line with the framework. Additional emphasis could be placed on maintaining landscape diversity (including protecting both well connected and isolated areas of habitat) and conserving areas with high habitat diversity and known fire and climate refuges.

   The question of *adequacy* is much more challenging. In general, larger areas and more populations of species would probably be required to ensure the same viability for species as could be expected without climate change. However, it is almost certain that some species will become extinct in the wild.

7. **Management of protected areas.** In the near term, climate change will probably be a greater issue for the management of individual reserves than for the development of the NRS. Managers will be directly confronted with changes in the distribution and abundance of species, altered ecosystem structure and function, and the challenge of implementing new conservation objectives (e.g. "managing the change to minimise the loss") in the face of considerable uncertainty. They will also need to manage changing and possible new threats to biodiversity, and will require new types of information – much of which will not be available, especially in the short term. Managers will increasingly be required to make difficult choices that are outside their experience, and for which current guidelines may offer little advice.

8. **Information needs.** Due to the changing nature of biodiversity, new threats and evolving conservation goals, new types of information will be needed by managers, planners, researchers and the general community for them to fulfil their respective roles. Acquiring much of this information will require carefully designed and concerted monitoring programs, experimentally planned "adaptive management" and good research. Opportunities for learning about impacts and their implications for management can be facilitated by clear mental models about possible changes and coordinated programs for recording, collating and analysing observations nationally. Increasingly, planning will need to consider future changes, the details of which will be quite uncertain.

Summary of priority actions

Actions to address many of these issues can be summarised in terms of four key priority areas.

1. **Understand how biodiversity will respond to climate change and the implications for conservation.** To effectively address climate change, the management, policy, research and general communities need a good and broad understanding of the possible changes to species and ecosystems, and the implications of those changes for conservation and the NRS. One immediate implication is the need to revise the core objective of conservation to accommodate ongoing changes in biodiversity – "manage the change to minimise the loss". Implementation of this objective will require community debate (to inform trade-offs) and better information about change. Coordinated observation and formal monitoring programs can identify what types of change are actually occurring; further research (including improved methods) is needed for assessing likely future changes on a bioregional basis. Key uncertainties include the importance of changes in distributions and abundances, interactions between species, changes in ecosystem processes, the dynamics of changes, changing threats (especially new species, altered fire regimes, land use change and altered hydrology) and the role of habitat and landscape diversity in mediating changes.

2. **Protect more habitat and more diverse habitat.** Protecting habitat is probably the best way to conserve species under climate change. While the species and ecosystems in any one area will change over time, the greater the total area of habitat available, and the more diverse that habitat, the greater the number of ecosystems and species that will be able to survive. The bioregional framework used in the NRS is therefore very well suited for building a robust reserve system, and it will be much more effective under climate change than systems that mainly target endangered species and communities. However, at present the effectiveness of the NRS is limited as habitat in many regions is very poorly represented. Further habitat protection through the NRS and other conservation programs is a priority in these regions and in regions that are identified as likely to experience the most significant

ecological changes. Protection of additional habitat may also be required for some species that are particularly vulnerable.

3. **Manage habitat to reduce threats.** Management of protected areas and other areas of native habitat will be required to reduce the impact of known and anticipated threats to biodiversity. In addition, active management will be required in some situations to facilitate natural adaptation processes, and in other situations to maintain habitat that is suitable for species that have been identified as particularly vulnerable to climate change. Policies and guidelines about managing protected areas may need to be revised to accommodate changing conservation objectives under climate change.

4. **Manage landscape-scale issues.** Many important ecological processes occur at scales larger than that of individual protected areas. Additional protection may be warranted for areas that act as fire or climate refuges for species within a broader region. Connectivity of habitat at various scales can be important for facilitating the movement of different species, which may increase their viability and ability to respond to climate variability and change. Connectivity may also facilitate the spread of fire and movement of species that might have negative impacts on other species; hence it may be beneficial to protect isolated as well as well connected habitat areas, and to assess the risks and benefits before increasing the connectivity of habitat. Some threats, including new species, land use change and altered landscape hydrology, may be best addressed at broad-scales via the coordinated efforts of a variety of conservation programs.

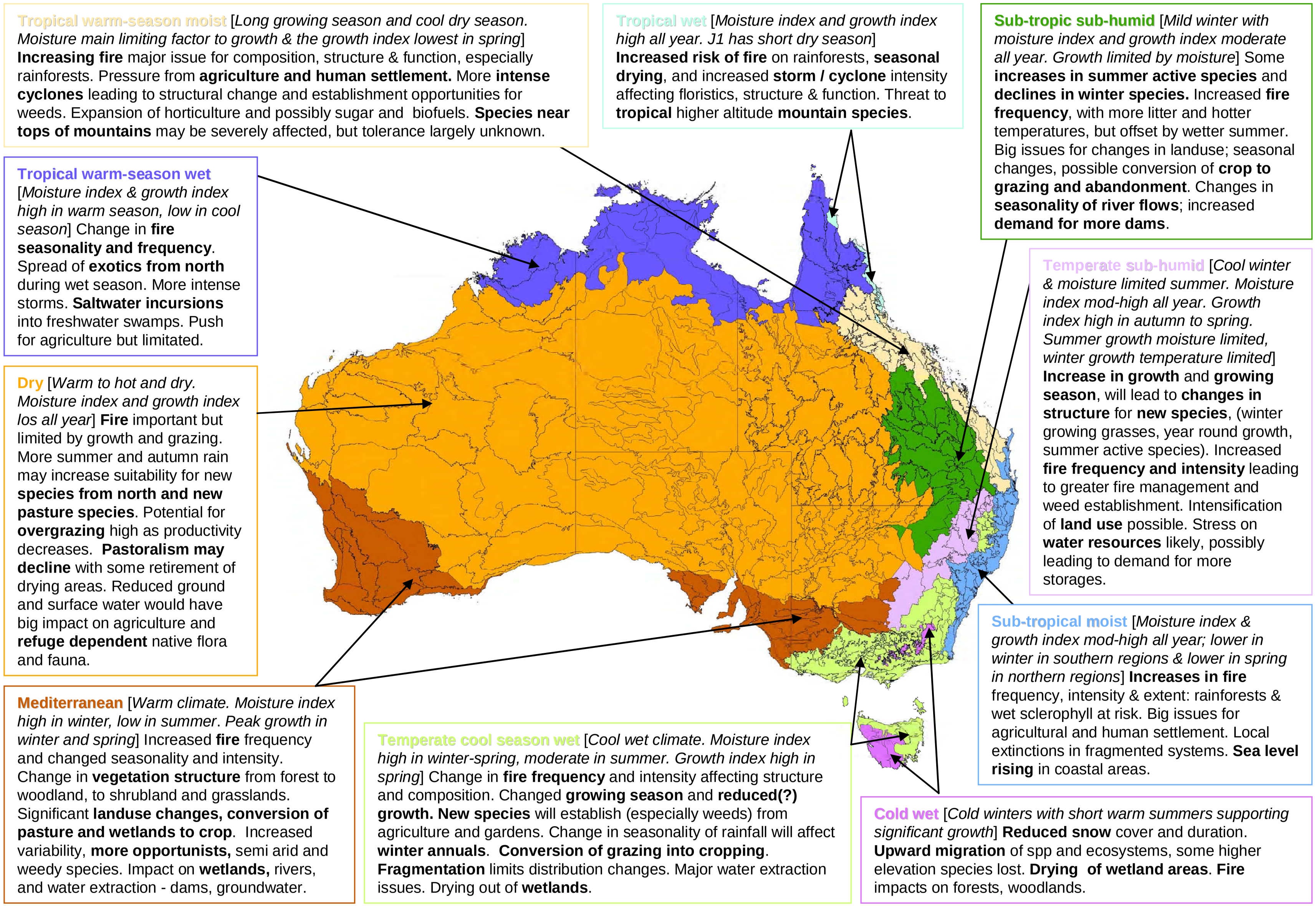


Figure B. Agro-climatic zones with summaries of the key issues for biodiversity resulting from changes seasonal growth and other ecosystem processes due to climate change.

1. INTRODUCTION

1.1 Background: climate change, biodiversity, conservation and the National Reserve System

Since the industrial revolution human-initiated emissions of carbon dioxide (CO_2), methane and nitrous oxide have increased markedly leading to increased concentrations of these gases in the atmosphere. These "greenhouse gases" (GHG) reflect radiation back towards the Earth enhancing the natural greenhouse effect. These increases, together with other human-induced changes to the atmosphere, have led to an increase in the average temperature of the Earth's surface of about 0.76 ± 0.19°C since the late 1800s (Solomon *et al.* 2007) and 0.33°C since 1990 (Rahmstorf *et al.* 2007). The IPCC Fourth Assessment Report estimates continued increases in atmospheric GHG concentrations would lead to temperature increases between 1.1 and 6.4°C over the 1990 baseline by the end of the century (Solomon *et al.* 2007); however recent observations of temperature increases since 1990 are most consistent with increases toward the top of the IPCC range (Rahmstorf *et al*. 2007). Along with further increases in average temperature, the Earth will experience changes in the variability of temperature over space and time; changes in rainfall patterns including average amounts and variation; increases in sea temperature, level and acidity; and changes in extreme events such as storms, droughts, fires, floods, and heatwaves.

Widespread concern about these impacts has resulted in calls to reduce the rate and magnitude of global climate change by reducing GHG emissions. However, even if emissions were reduced substantially to maintain GHG concentrations at year 2000 levels, temperatures would continue to increase for decades and the global Earth system would continue to change for thousands of years (Solomon *et al.* 2007).

These changes will have impacts on most if not all species and ecosystems on Earth. Many different types of impact have been observed and modelled for many thousands of species on all continents over the last 20 years. Impacts are likely to vary markedly among regions, ecosystems and species. Due to the multifaceted nature of the changes in the climate and the environment, other ongoing pressures, and the complex dynamics of biophysical and ecological systems, with their many interacting components and positive and negative feedbacks, the net impact of climate change for most species is very uncertain. The evidence suggests climate change will affect growth, competition and survival of species. In turn this will lead to a significant "re-sorting" of species with changes in the relative abundance of species in assemblages, changes in vegetation structure, shifts in the distributions of species, genetic loss and evolution, and the extinction of some species (Hughes 2000; Thomas *et al.* 2004; Lovejoy and Hannah 2005; Parmesan 2006). Changes to species richness and abundance will affect ecosystem function and ecosystem services (Chapin *et al*. 2000; Hooper *et al.* 2005). In short, climate change will alter many aspects of Australia's biodiversity that are valued by society, including the "look and feel" of ecosystems.

Changes in species interactions, population sizes and ranges are of great concern for biodiversity conservation (Lovejoy 2005). Reduced populations and range sizes will increase the chance of species extinctions, and some bioclimatic habitats to which some species are currently restricted will disappear altogether (e.g. Thomas *et al.* 2004). Many species will expand in range and abundance, possibly including some exotic weeds and pests, but other species, both native and exotic, that are currently not considered invasive may also expand and have transforming impacts on other species and ecosystems. As well as directly increasing the threat to many species, these climate change impacts may increase the vulnerability of species to other existing threats, and adaptation to climate change in other sectors (e.g. intensive agriculture shifting to new regions) may also increase existing threats and pressures.

World wide such concerns are leading to reassessments of biodiversity conservation plans and protected area strategies (e.g. Halpin 1997; Midgley *et al.* 2002; Scott *et al.* 2002; Gaston *et al.* 2006). This reassessment is also occurring in Australia: in 2004 the Australian and State governments released a *National Biodiversity and Climate Change Action Plan 2004-2007*; the impacts of climate change on biodiversity and conservation are a major consideration in the on-going review of the *National Strategy for the Conservation of Australia's Biological Diversity*; and most States have developed biodiversity and climate change strategies or incorporated climate change into recent biodiversity strategies.

In Australia managing habitat primarily for biodiversity is a critical component of national, state and private conservation investments. The establishment of formal protected areas is coordinated and largely funded in Australia through the National Reserve System (NRS) program (NRMMC 2004a). The aim of the program is to ensure that the full diversity of Australian ecosystems are preserved, and it uses a bioregional planning framework and a partnership approach to develop and fund acquisition priorities. The NRS currently comprises 88,436,811 ha, or 11.5% mainland Australian (including Tasmania) (*Personal communication,* Tim Bond, NRS Section, Department of the Environment, Water, Heritage and the Arts; Figure 1.1).

This report investigates the possible future impacts of climate change on the NRS and the consequences of these impacts for development and management of the reserve system. It is one of a series of scoping studies being undertaken by Parks Australia (in DEWHA) and the Department of Climate Change; these include, among others, assessments of climate change impacts on World Heritage Areas and Commonwealth Reserves.

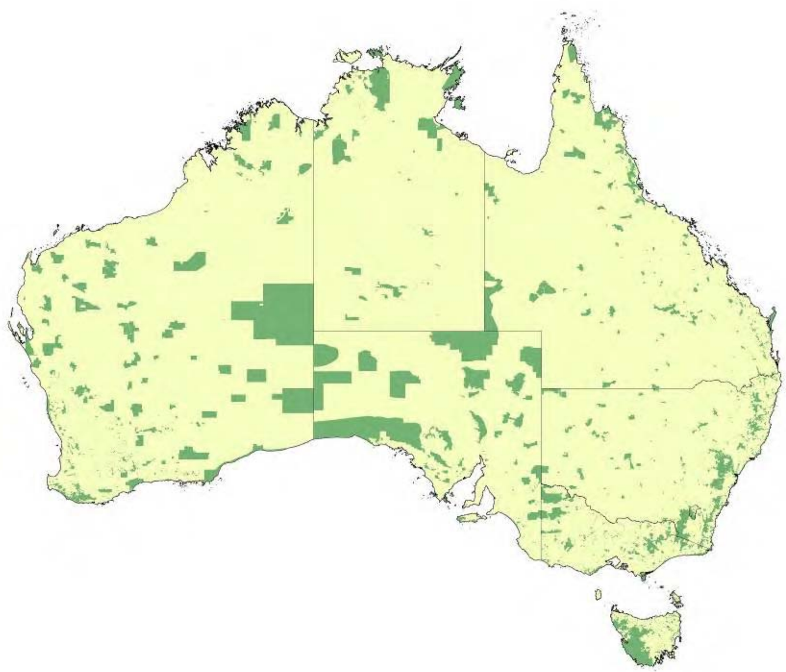


Figure 1.1. Australian National Reserve System accounts for 11.5% of Australia's land area (88,436,811 ha) and has 8667 protected areas.

1.2 Outline of this report

The report is broken into three parts. The different parts, and some sections, of the report can be read independently, as such there is some repetition between sections.

Part A provides an overview of the impacts of climate change on biodiversity. After this introduction, past climatic changes and their impacts on Australia's biota are briefly discussed (Section 2); then a framework is presented for conceptualising the cascade of impacts from GHG concentrations through to societal values for biodiversity, and the mechanisms by which climate change affects biodiversity is reviewed (Section 3); finally a synthesis is presented from the point of view of what needs to be understood in order to conserve biodiversity (Section 4). Due to the focus of the project on the NRS, the review and discussions concentrate on terrestrial biodiversity.

Part B presents two regional analyses of impacts: one provides an estimate of which biodiversity impacts might be more important in ten different agro-climatic zones (Section 5), and the other reporting a range of climate parameters, drawn from recent climate change projections, for each of the 85 regions of the Interim Bioregionalisation of Australia (IBRA) (Section 6).

Part C reviews some of the literature on the impacts of climate change on protected areas (Section 7), and then discusses the implications of climate change for biodiversity conservation and the NRS in particular (Section 8).

PART A:
REVIEW OF THE IMPACTS OF CLIMATE CHANGE ON BIODIVERSITY

PART A – REVIEW OF THE IMPACTS OF CLIMATE CHANGE ON BIODIVERSITY

2. PALAEO CONTEXT

The Earth has experienced constant change in its climate over the last 400 million years since life established on land. It has been warmer and cooler than at present, wetter and drier, and CO_2 concentrations have been higher and lower. In addition, global oceanic and climate circulation patterns have been very different and continents have separated, drifted apart and collided. The Earth has also been in markedly different regimes of climatic variation. Natural drivers of climate change have included the evolution of life itself, continental drift, changes in the Earth's rotation around the Sun, meteorite impacts, volcanic activity and discharge of methane from marine sediments. In the last 500 million years there have been four major hot-cold cycles. The Earth is currently in a short-term relatively warm phase (so far lasting 11,000 years) in a series of cycles (with periods of about 100,000 years), which has been the coldest million years of a glacial period that has lasted over thirty million years.

During the Jurassic period (~160 million years ago, Ma), the megacontinent Pangaea split into a northern supercontinent, Laurasia, and a southern supercontinent, Gondwana. Over time, Gondwana fragmented, with India and New Zealand separating and moving north from an Australia-Antarctica-South America group about 140 Ma. By about 100 Ma this southern group of continents had begun to separate. About 80 Ma the Earth was at a temperature maximum (possibly 20°C warmer present) and much wetter than the present, and CO_2 concentrations were possibly eight times current levels (Overpeck *et al.* 2005). At this time the Earth began to gradually cool.

By about 35 Ma Australia was fully separated from Antarctica. Northward drift from Antarctica of Australia and the other Gondwanan continents led to formation around this time of a strong persistent current around Antarctica, which resulted in further significant changes in climate including further cooling, glaciation of Antarctica, and increased aridity and strengthening of temperature gradients across Australia (Mummery & Hardy 1994; McLoughlin 2001; Markgraf & McGlone 2005). The steady global cooling was interrupted by two periods of about 15 Ma where the Earth warmed a few degrees. The first of these marked the K-T (Cretaceous-Tertiary) boundary and the most recent of the five mass extinction events (including extinction of the dinosaurs) at about 65 Ma. The second warming, at about 25 Ma, led to the thawing of Antarctica. Antarctica reglaciated after further cooling from about 15 Ma.

Prior to its break-up, Gondwana was covered in rainforest. As the climate in Australia cooled, dried and became more variable, the vegetation became more geographically variable. By around 20-15 Ma Australia had moved into the drier mid-latitudes and species from the Myrtaceae family (the family of *Eucalyptus* species) became more dominant suggesting that the rainforests were being replaced by more open, wet sclerophyll forests. This period of isolation and climatic change was a time of significant evolutionary radiation and development of the characteristic arid-adapted sclerophyll vegetation of Australia, which probably originated from species originally adapted to nutrient poor soils around 30-60 Ma (Kershaw *et al.* 2002). As well as being drier overall, the climate became more seasonally dry from about 15 Ma. Cooling and drying led to many plant extinctions, with most major changes complete by 5 Ma (Markgraf & McGlone 2005). By about 2 Ma, the once extensive rainforests were more or less restricted to their current distributions in isolated wetter and primarily higher and cooler "islands" among the warmer drier climates of the east coast, the so-called 'mesotherm archipelago' distribution (Moritz *et al.* 2005).

About 3 Ma the Earth began further cooling, and since about 1 Ma it has been in the current phases of glacial-interglacial cycles of cold dry periods (approximately 6°C cooler than today) lasting roughly 100,000 years punctuated by rapid (10,000 years) warmings to temperatures similar to the present, followed by gradual irregular cooling and drying. For at least the last 450,000 years the atmospheric CO_2 concentration has cycled synchronously with temperature between 180 ppm (cool min.) and 280 ppm (warm max.), and it may have been within these bounds for 25 million years (Overpeck *et al.* 2005). This period has also seen many global and regional temperature fluctuations on the scale of one to a few thousand years, some regional changes associated with changes in ocean currents have been extremely rapid (10°C in a decade) (Overpeck *et al.* 2005). For the last 11,000 years the Earth has been in an interglacial (warm and wet) period that has been uncharacteristically stable compared to the previous 450,000 years; and regional differences not withstanding, the Earth is probably currently within 1-2°C of being the warmest it has been for over 2 million years (Overpeck *et al.* 2005) which is about when the genus *Homo* evolved. Over the last several million years sea levels have lowered by up to 130 m during glacial periods and increased by no more than about 6 m above current levels during interglacial periods (Overpeck *et al.* 2005).

Globally, there have been significant fluctuations in biomes over the last million years, with forest communities dominating most areas in interglacial periods and herbaceous communities dominating in glacial periods (Huntley 2005). In the Northern Hemisphere these cycles were characterised by major changes in populations of many plant and animal species; during glacial periods the distribution of some species contracted towards the equator up to 2000 km (Huntley 2005). Recent evidence (including genetic analysis) suggests that many species may also have persisted in very restricted populations in micro-refuges (McGlone & Clarke 2005, Rowe *et al*. 2004; McLachlan *et al*. 2005; Svenning & Skov 2007; see also discussion of ‘Cryptic refuges’ in Section 3.3.4). All species examined in the fossil record showed marked rapid changes in distribution at the end of the last glacial period, with individual species responding in different ways leading to considerable changes in species assemblages; changes in the distributions of many species have continued to the present due to lagged responses to past climate change and in response to more recent millennial temperature fluctuations (Huntly 2005). These climatic fluctuations are believed to have led to relatively few plant species extinctions, although many vertebrate species, especially larger mammals, became extinct during the last glacial maximum possibly through a combination of extreme climate and human activities (Huntly 2005; Bush & Hooghiemstra 2005); between 40 and 10 ka (thousand years ago) at least 40 species of mammal became extinct in Australia, including all those over 60 kg (Markgraf & McGlone 2005).

During these cycles Australia was not exposed to the widespread glaciation that occurred in the Northern Hemisphere disturbing vegetation and creating soils. While there were changes in vegetation in Australia during glacial cycles, it appears that rather than widespread changes in distributions, vegetation changes were characterised by changes in abundance of wetter and drier adapted species (Martin 1994; Markgraf & McGlone 2005). Species persisted during cooler or warmer extremes of the glacial cycles in favourable habitat largely within their ranges or in nearby areas (Markgraf & McGlone 2005). Extensive local speciation among major tree species in Australia (e.g. *Acacia* and *Eucalyptus*) reflects *in situ* persistence rather than widespread distribution changes (Markgraf & McGlone 2005). Increasing climatic variability, in particular from the El Nino Southern Oscillation, appears to have been very important in shaping the evolution of Australia’s biota, with many plant and animal species having adaptations to survive variable climate (Markgraf & McGlone 2005). Over the last few million years most of Australia was dominated by sclerophyll vegetation (e.g. Myrtaceae, including *Eucalyptus*) and herbs and grasses (Kershaw *et al.* 2002). During the last glacial period much of southern Australia was probably treeless grassland and the inland deserts were more extensive than at present, with wetter forest species remaining more or less *in situ* but in lower abundance or in local climatic refuges (Markgraf & McGlone 2005).

As a result of long periods of isolation, evolutionary origins and climatic history, the composition and structure of Australian vegetation is quite different from that in many other parts of the world and Australia has a high proportion of endemic species. Since about 2 Ma fluctuations in sea level have led to periodic exposure of extensive land areas connecting Australia with Melanesia to the north facilitating exchange of species and the colonisation by humans (Dodson 1994). Aborigines had a significant influence on the flora of Australia through their use of fire. The removal of large herbivores also resulted in significant vegetation change.

There is strong association between fire, climate and vegetation in Australia. Fire activity increased significantly around 10 Ma associated with reduced precipitation, increased seasonality and the expansion to domination of sclerophyll forest and heath vegetation (Kershaw *et al*. 2002). It also appears to have peaked during glacial maxima over the last 250 ka when climates were drier and open sclerophyll vegetation more predominant. In both these cases fire activity appears to have followed vegetation changes in response to climate (Kershaw *et al*. 2002). Fire activity also increased markedly around 40,000 years ago due to Aboriginal burning, and there has been high fire activity over the last few thousand years with a peak coinciding with early European settlement followed by a reduction in fire activity (Kershaw *et al*. 2002). In contrast to past peaks in fire activity, these episodes appear to have driven or at least accelerated vegetation changes (Kershaw *et al*. 2002).

The long isolated evolution of the Australian biota, combined with relatively recent connections with Melanesia, has led to two distinct elements in Australia's flora (Barlow 1994):

1. The Gondwanan element comprises:
    a. largely rainforest species that have evolved very little since Gondwanan times and are largely confined to wetter areas, and
    b. a large number of species that have evolved during the period of isolation in response to poor soils, aridity and fire, giving rise to the high proportion of endemic species.
2. The intrusive element contains plants that have entered more recently including:
    a. tropical species from Melanesia,
    b. cosmopolitan (global) species with high dispersal ability, and
    c. temperate species derived from Northern Hemisphere taxa.

The fauna shows similar patterns. Some ancient Australian bird groups established in Asia and persist there to this day. Some subsequently spread to the rest of the world, radiated, and recolonised Australia as newer forms. Australia was also colonised by birds that originally radiated elsewhere. Thus there are three basic groups: the old endemics, newer versions of the old endemics, and newer species that originally evolved elsewhere. Monotremes, marsupials and placental mammals were present on Australia when it separated from Antarctica (~40 Ma), and apart from bats, the placentals subsequently died out. The marsupials radiated widely throughout Australia adapting to increasing aridity. As the Australian continent moved closer to the Asian landmasses, there were invasions and colonisations through the north and including corals, lizards, snakes, placental mammals, scorpions and insects.

Australian flora and fauna have survived considerable glacial and annual climatic fluctuations over the last few million years, often by persisting in refuges and probably surviving periods of small populations. However, future climate changes are markedly different from past ones. While some regions around the world have experienced short periods of warming in the past at similar rates to those expected over the coming century, the combination of the rate of warming and the magnitude of warming will soon be outside the range that has been experienced for most regions and the Earth as a whole (Overpeck *et al.* 2005). Past warming periods were also associated with increased humidity, whereas water availability is expected to decrease in Australia with climate change. In addition, species survived previous large climatic changes in Australia in the absence of the extensive habitat clearance and modification, widespread grazing by exotic species, exotic pests and weeds, alteration of river flows, and other pressures that have been experienced over the last 200 years.

3. THE IMPACT OF CLIMATE CHANGE ON BIODIVERSITY

With contributions from Steve Crimp, CSIRO Sustainable Ecosystems

3.1 Introduction

This section describes a conceptual framework for understanding the various ways in which climate change affects biodiversity, and then it reviews a wide range of the many impacts. The aim is to provide a clearer picture of the different ways genes, organisms, species and ecosystems are affected by climate change, based on observations, modelling and theoretical considerations. Section 4 provides a synthesis from the perspective of conserving biodiversity that focuses on outcomes for species rather than ecological mechanisms. Section 5 describes an analysis of impacts on biodiversity in different regions; it draws on the review in this section, and as part of the methods of the analysis the impacts are summarised around a series of key ecological processes and threats (Part B, Appendix 1). Literature on the impacts of climate change on protected areas is reviewed in Section 7.

This review draws heavily on recent reviews (Hughes 2000 & 2003, Walther 2002, Root *et al*. 2003, Parmesan & Yohe 2003, Lovejoy and Hannah 2005, Parmesan 2006) and information relevant to Australia.

3.2 Conceptual framework: cascade of impacts

The framework describes the "cascade of impacts" from changes in the environment (including climate) through levels of biodiversity to societal values (Figure 3.1). It describes the direct flows and indirect impacts via feedbacks, including adaptation and mitigation actions.

Environmental impacts: the changes arising from increased GHG concentrations that drive impacts on biodiversity. They include changes in CO_2, temperature and rainfall regimes, fire regimes, and sea temperature, chemistry and level. These impacts clearly combine with other (non-climate related) environmental stresses on biodiversity, and are affected by feedbacks from population and ecosystem impacts (e.g. affecting hydrology and flammability; below).

Biological impacts: the direct changes to biology of organisms arising from environmental changes. They include changes in physiology and the timing of lifecycle events (phenology).

Ecological impacts: result from changed interactions between organisms and their environment including other species. They include changes in breeding, establishment, growth, behaviour, competition and mortality. These impacts result directly from climate change related impacts (above), and indirectly via interactions with other species that are affected by climate change leading to changed competition, food, habitat and predation. These indirect impacts can be represented as a feedback from population impacts and ecosystem impacts (below) to ecological impacts. For some species these indirect impacts may be stronger than direct impacts. Ecological impacts are also affected by how climate change impacts interact with other stresses.

Population impacts: the ultimate impact on species in terms of changes in gene frequencies, abundance and distribution.

Ecosystem impacts: changes in the identity, composition, structure and function of assemblages and ecosystems.

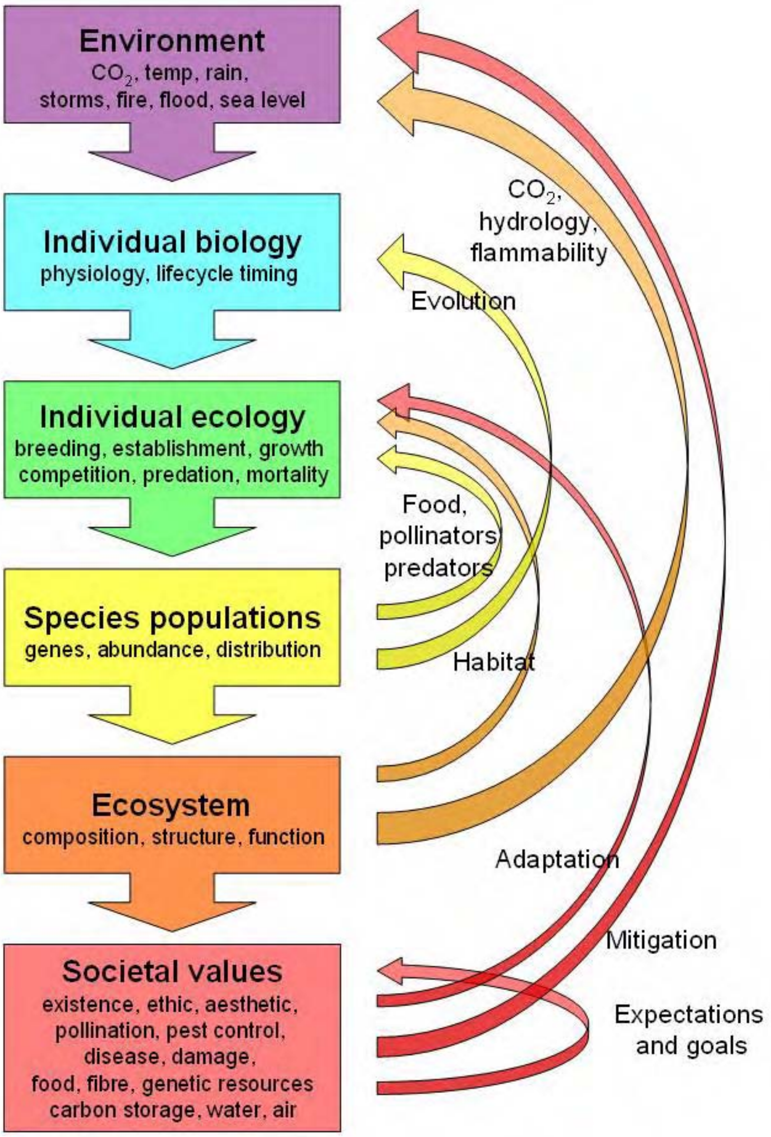


Figure 3.1. Schematic representation of cascading impacts resulting from environmental changes caused by climate change. The direct flow of impacts is represented by large arrows. Important indirect impacts are shown as feedbacks.

Value impacts: represent the impacts on human well-being, the reason society cares about climate change and biodiversity. These include "non use" values, for example:

- existence of species and ecosystems,
- land ethic, "caring for country", stewardship of the planet for future generations, and
- aesthetics.

The economic and other material benefits derived from consumptive and non-consumptive uses of biodiversity are considered, for example:

- production of food and fibre,

- pollination and pest control, as well as damage and diseases,
- regulation of water and air quality, and
- carbon storage and cycling.

The direct flow of impacts arising from climate change on biodiversity (downward arrows in Figure 3.1) will include some rapid changes (e.g. many disturbances would have almost instantaneous impacts on each level), and other changes that may take decades or centuries to materialise (e.g. changed composition and structure resulting from altered fire regimes would take several fire cycles; some population declines may lag behind interruptions to reproduction due to the longevity of adults).

There are many feedbacks that will lead to indirect impacts and may change the way impacts occur over time. Some of these are indicated by the upward arrows on the right of the diagram. A very important feedback will be via interacting species (competitors, predators, pathogens, prey, dispersers and other facilitators). For some species, indirect impacts due to strong interactions with other species affected by climate in some way may be more significant than direct impacts on their biology. Feedbacks will also lead to altered habitat, changed environmental parameters and evolution of the sensitivity of species to climate. Human responses can also be represented as feedbacks, including: reductions in GHG emissions, ecological management to facilitate adaptation, and altered expectations about the state and dynamics of biodiversity. All these feedbacks can be expected to occur at quite variable rates, possibly with significant delays.

Many other human pressures affect the environment, species and ecosystems. As the emphasis in the diagram is on climate change impacts, these other pressures are not shown on the diagram but they could be represented by additional arrows into each box. Importantly, the cascading climate impacts are likely to interact with these other pressures changing their actions, and in many cases magnifying their impacts on biodiversity.

3.3 What types of impacts on climate, the environment, species and ecosystems should we expect?

3.3.1 Impacts on the climate and environment

Observed changes

Carbon dioxide

The two best understood and globally-documented impacts on the physical environment of increased GHG emissions are increases in atmospheric concentrations of CO_2 and increases in temperatures (Collins 2000). Globally, CO_2 has increased from 280 parts per million (ppm) in 1750 to 379 ppm in 2005 with 70% of this increase occurring since 1970 (Solomon *et al.* 2007). Current concentrations of atmospheric CO_2 far exceed pre-industrial values, measured from polar ice core records of atmospheric composition, dating back 650,000 years and the rate at which the concentration of CO_2 has increased since pre-industrial times is unprecedented in more than 10,000 years (Solomon *et al.* 2007).

Temperature

Australian average temperatures have increased by approximately 0.9°C since 1910, with greater warming in minimum temperatures (1.2°C) than maximum temperatures (0.7°C) (Data sourced from http://www.bom.gov.au/cgi-bin/silo/reg/cli_chg/timeseries.cgi). More than twice as much warming has occurred since 1950 than over the entire historical record. The warmest annual mean temperature since 1910 occurred in 2005 with a national average temperature of 22.9°C, 1.06°C above the long-term mean.

In addition to changes in mean temperatures, Australia has experienced changes in the frequency of extreme hot and cold temperatures. Since 1957 Australia has experienced an increase in hot days (35°C or more) of 0.10 days/year, an increase in hot nights (20°C or more) of 0.18 nights/year, a decrease in cold days (15°C or less) of 0.14 days/year and a decrease in cold nights (5°C or less) of 0.15 nights/year (Nicholls and Collins 2006).

Most regions in Australia have warmed over the last 50 years; the greatest warming has been in southwestern Queensland in summer. There has been a slight cooling in the northwest of Australia most noticeably in summer.

Rainfall

In Australia, significant changes in regional rainfall patterns have occurred between the earlier part of the historical record, 1910 to 1950, and the more recent record. Since 1950, both large and spatially coherent rainfall changes have occurred across the continent. They include rainfall increases of up to 50 mm per decade in the northern third of Western Australia and the Northern Territory and rainfall declines in excess of 20 mm per decade across the much of the eastern seaboard (Smith 2004). There was also a notable step-increase in rainfall from the 1950s to the 1970s in south-eastern Australia (Vivès and Jones 2005); and a sustained decrease in rainfall in southwest Western Australia since the 1970s (Pittock 2003). Key contributors to recent changes in Australia’s rainfall include variability in ENSO (El Niño Southern Oscillation) activity, enhanced monsoonal activity in the 1970s and changes in other large-scale circulation features such as the Southern Annular Mode (SAM) that affects the passage of fronts across southern Australia. Modelling studies have estimated that approximately 40% of the rainfall reductions experienced in southwest Western Australia can be attributed to anthropogenic influences (Cai *et al.* 2003; Cai &Cowan 2006). Anthropogenic changes in SAM may also have contributed to recent declines in rainfall in south-eastern Australia.

In Australia, trends in extremes (i.e. both temperature and precipitation) are very highly correlated with mean trends (Alexander *et al.* 2007). Since 1950, the highest daily rainfall amounts have declined in keeping with declines in mean annual rainfall along the eastern seaboard (Alexander *et al.* 2007) and southwest Western Australia (Li *et al.* 2005).

Anthropogenic warming is increasing the severity of Australian droughts, by raising temperatures and hence increasing evaporation (Nicholls 2004). Anomalously warm conditions and associated increases in evaporation made effective rainfall far lower in the 2002, 1994 and 1982 droughts compared to those earlier in the record.

Natural rainfall variability over the twentieth century has demonstrated that the Australian climate is affected both by step changes in decadal rainfall regimes, and also by trends, although attribution of individual phenomena is difficult because of high variability between years. Recent findings indicate that both anthropogenic and natural changes are affecting Australian rainfall, and it is important to be able to attribute such changes in order to gauge whether phenomena will be short- or long-lived, and how they may combine.

Water resources

Rainfall in Australia varies considerably from year-to-year and over longer periods leading to considerable variability in runoff. The inter-annual variability of river flows in temperate Australia is roughly twice that of river flows in most other regions of the world. In their natural condition many

Australian rivers would experience flooding flows interspersed with periods of low (or no) flows more often than they would experience sustained steady water levels, and many of Australia's riparian and aquatic ecosystems are adapted to, even dependent on, such variability. The proportion of rainfall that ends up in streams and reservoirs is also affected by the type and condition of native vegetation, e.g. regrowth after fire or logging can significantly reduce catchment yields. However, over the last 100 years storage, release and use of surface water, altered stream courses, and extraction of groundwater have substantially altered flow regimes in many systems.

The recent drought has place considerable stress on water resources across much of Australia. A sustained decline in winter rainfall (10 to 20% reduction over 30 years) in southwest Western Australia has resulted in a 50% decrease in inflows into Perth dams (Pittock 2003). Degradation of wetlands has occurred in many parts of Australia due to altered flow regimes, increased sediment, nutrient and salt loads, suppression of high flows exacerbated by current dry conditions, and changes in groundwater regimes (Arthington & Pusey 2003; Gell *et al.* 2007).

Gedney *et al*. (2006) claim to have detected increases in runoff due to suppression of plant transpiration due to CO_2-induced stomatal closure in a number of river basins around the world through the twentieth century.

Oceans

Changes have been observed in sea surface temperatures, sea level, ocean current strength and seawater acidity around Australia. Warming has been observed in all three oceans surrounding Australia with the Indian Ocean warming more rapidly than both the Pacific and Southern Oceans. In response to this warming, sea levels have risen on average by 1.2 mm per year (1920 to 2000) (Church *et al.* 2006) with large regional variation. In addition to changes in sea level, oceanic warming has also served to alter ocean currents around Australia. In response to both ocean warming and stratospheric ozone depletion the East Australian Current has increased in strength by about 20% since 1978 (Cai 2006).

Cyclones and East Coast Lows

Globally, increases in the frequency of intense cyclones have already been observed in both the Atlantic and Pacific basins (Easterling *et al*. 2000; Emanuel 2005; Hoyos *et al*. 2006).

Along the eastern Australian coast the total number of tropical cyclones has declined since the 1970s, although there has been an increase in the number of very intense systems (i.e. minimum central pressures of 970 hPa or less) (Kuleshov 2003).

East Coast Lows often produce heavy rains and flooding in coastal and near-coastal areas of eastern Australia and are more common during La Niña events (Hopkins and Holland 1997). Records since 1973 suggest no trend in East Coast Lows (BOM 2007). A longer time series of lows affecting south-east Queensland suggest pronounced decadal variability that follows decadal mean rainfall (Harper & Granger 2000).

Snow

Mean snow cover has declined significantly over the period from 1960-1974 to 1975-1989 in the Australian Alps. Maximum winter snow depth at Spencers Creek in the Snowy Mountains has declined since 1962, with the spring snow depth exhibiting a strong decline trend (i.e. approximately 40% decline in depth since 1962) (Osborne *et al*. 1998; Green & Pickering 2002; Nicholls 2005).

Frost

There has been little research on frost risk. However, recent changes in frost occurrence have been implicated in increases in plant productivity (Stone *et al*. 1996; Nicholls & Alexander 2007; Hennessy *et al*. 2007). This appears to be stronger in the northern end of the wheat belt. However, the risk of late frost has actually increased in many southern areas apparently due to changes in synoptic circulation.

Fire

Since 1950, rainfall has decreased in south-eastern Australia, droughts have become more severe and the number of extremely hot days has risen, but the effect of these on fire frequency is currently not apparent, although hotter and drier years have a greater fire risk (Hennessy *et al*. 2005).

In the western U.S.A., large wildfires have increased in frequency and duration and changed in season since the mid 1980s; analysis suggests fire risk was strongly associated with increased spring and summer temperatures, reduced winter precipitation and earlier spring snowmelt, and land use changes had little effect (Westerling *et al*. 2006). Kitzberger *et al*. (2007) identified that the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation were the main drivers of fire variation at the year to decade scale, but their influence varied with the Atlantic Multi-decadal Oscillation. It is not known the extent to which these or similar cycles influence fire activity in Australia. Changes in fire frequency in the Sydney Basin since the mid Holocene have been linked to increased ENSO behaviour (Black 2006). However, there is insufficient evidence to be able to determine the extent to which recent patterns of fire occurrence are related to climate (affecting fuel production and fire weather), fire management and land use changes.

ENSO

The El Niño-Southern Oscillation has a significant impact on Australia's climate, with strong linkages established between rainfall, temperature and tropical cyclone activity. The Southern Oscillation Index (SOI), a measure of ENSO activity, has demonstrated significant seasonal, decadal and multi-decadal variability over time (Allan *et al.* 1996; Power *et al*. 2006). In recent years the frequency of El Nino events has increased although it is unclear whether this is a function of natural or anthropogenic factors. While the drivers of recent changes in ENSO behaviour remain unclear, other significant changes have been measured. A comparison of the SOI relationships with both temperatures and rainfall has shown that since 1973 temperature and rainfall have been higher for any given value of the SOI (Power *et al*. 2006), suggesting a change in impact of the SOI on these variables (Nicholls *et al*. 1996).

Predicted changes

The predictions below for changes in CO_2, temperature and rainfall are consistent with the those of the IPCC Fourth Assessment Report (Solomon *et al.* 2007; Hennessy *et al*. 2007; Suppiah *et al*. 2007); detailed breakdowns of the changes in temperature and rainfall for each of the 85 bioregions in Australia will be available electronically from the Department of the Environment, Water, Heritage and the Arts and are summarised in Section 6 of this report. Possible impacts of climate changes on plant growth and other aspects of ecosystem function are discussed for each of 10 agro-climatic zones in Section 5.

Carbon dioxide

It is predicted that atmospheric concentrations of CO_2 will increase by between 540 ppm to 970 ppm by 2100 depending on which emission trajectory the world follows (Solomon *et al.* 2007). About half of the uncertainty in the rate of future global warming is due to uncertainty concerning anthropogenic emissions of GHG.

Temperature

Australia will get hotter; in all regions maximum and minimum temperatures in all seasons are expected to increase (Suppiah *et al*. 2007). The annual average temperature is anticipated to increase between 0.2 and 2.2°C by 2030, and between 0.4 and 6.7°C by 2070, depending on the climate model, region and emissions scenario (Suppiah *et al*. 2007, based on 15 global climate models and the full range of SRES emissions scenarios, IPCC 2000). Spring and summer temperatures will increase more than autumn and winter, the warming will be up to 2°C greater inland than on the coast, and night-time temperatures will increase more than day-time temperatures (Suppiah *et al.* 2007). For temperate cities the average number of days above 35°C is expected to increase by 4 to 18 days by 2030, and by 9 to 56 days by 2070.

Rainfall

Changes in rainfall are expected, with averages, seasonality and inter-annual variability all likely to change in regionally specific ways. Changes in total precipitation are amplified at the extremes (Easterling *et al*. 2000). Rainfall is much harder to predict than temperature and the ranges on the predictions are much wider. In general, Australia will very likely be drier overall, but there will be regional and seasonal variations. Southwest Western Australia, southern South Australia and most of Victoria are very likely to be drier, while Tasmania, northern New South Wales, parts of southern Queensland and parts of the Northern Territory may be slightly wetter (mainly in summer and autumn) (Suppiah *et al.* 2007). Significant increases in rainfall in north-western Australia observed over the last 50 years are not indicative of expected trends associated with long-term climate change (Hennessy *et* al. 2007; Suppiah *et al.* 2007).

The seasonality of rainfall will also change, affecting the seasonality of moisture availability and moisture stress (which is also related to temperature). Reduced winter rainfall may be critical for annual growth in southern states. Increased summer and autumn rainfall in parts of northern Australia may strengthen the seasonality of water availability (Suppiah *et al.* 2007).

Water resources

As well as changes in rainfall regimes, there are likely to be increases in potential evaporation by up to 8% per degree of global warming across most of Australia (CSIRO 2001). Together these will affect the dynamics of soil moisture, runoff and stream flow, leading to significant reductions in flow and freshwater availability in many river systems (Arnell 1999; Chiew & McMahon 2002). Changes in rainfall have a disproportionately large impact on stream flows: proportional reductions in runoff are expected to be double any proportional decreases in rainfall in wet and temperate catchments and more than four times those in ephemeral catchments (Chiew & McMahon 2002).

Chiew and McMahon (2002) provide the following estimates for changes in annual runoffs in catchments located in different parts of Australia by 2030 (relative to 1990): northeast coast of Australia -5 to +15%; northeast Murray-Darling -25 to +25%; east coast of Australia -15 to +15%; southeast coast -20 to 0%; southeast Murray-Darling -15 to +5%; Tasmania -10 to +10%; South Australian Gulf -25 to 0%; and, southwest coast of Australia -25% to +10%. Stream flows in the Murray Darling Basin have been estimated to reduce by 5% (most likely; worst foreseeable 20%) over 20 years from 2000/01 and by 15% (most likely; worst foreseeable 50%) over 50 years (EarthTech 2003).

Oceans and coasts

Sea-surface temperatures are predicted to continue to increase, with estimates of warming in the Southern Tasman Sea of between 0.6 to 0.9ºC by 2030 and between 0.3 to 0.6ºC elsewhere along the Australian coast (Church *et al*. 2006).

Sea levels will increase by 18 to 59 cm by 2100 in response to both thermal expansion and melting of ice-sheets (Solomon *et al.* 2007). This will lead to some coastal inundation affecting mangroves, salt marshes and coastal freshwater wetlands. Freshwater aquifers may also be affected by saltwater intrusion, especially if recharge is reduced or extraction for human use is increased. It is also likely that there will be some shoreline erosion and realignment.

Storms

Climate change is expected to affect disturbance regimes, including increases in storm intensity (5 to 10%) and/or frequency (including cyclones/hurricanes, high wind events, flooding) (Pittock 2003; Walsh *et al*. 2004). An increasing proportion of rain is expected to fall in more intense events (20 to 30%), and large storms and cyclones are expected to be more severe, with higher winds, causing more damage, flooding and coastal inundation (Pittock 2003; Walsh *et al.* 2004). There is no clear evidence about regional changes in frequency and movement, but it is possible that cyclones may move further south (Leslie and Karoly 2007).

Snow and frost

There will be marked reductions in snow cover and extent (Hennessy *et al*. 2003). The total area of snow cover is expected to decrease by 14 to 54% by 2020 and 30 to 93% by 2050. Frost occurrence is expected to decrease overall; however temperature is not the only driver of frosts, changes in synoptic circulation and decreased cloud cover could lead to increased severity of frosts and changes in their timing in some conditions.

Fire

Many of the factors affecting fire risk and behaviour will be affected by climate change leading to significant increases in fire frequency (Beer & Williams 1995, Williams *et al*. 2001, Cary 2002). Hennessy *et al*. (2005) predict increases in the frequencies of days with very high and extreme fire ratings of 4 to 25% by 2020 and 15 to 70% by 2050 (Hennessy *et al*. 2005). Decreased relative humidity is likely to be the most significant factor affecting fire risk but changes in temperature, wind speed and rainfall will also contribute. Cary (2002) found an approximately doubling of fire frequencies in the Australian Capital Territory region with a climate change scenario equivalent to double CO_2; this result was mainly due to reductions in the likelihood of fire extinguishment rather than increases in intensity. Increases in lightening have also been predicted (doubling with "double CO_2" climate change scenario), but the impact on fire frequency has not been investigated (Cary 2002). In some regions increases in fuel loads are likely under increased CO_2 because of increased plant growth, particularly if there are reductions in wood and litter nitrogen concentrations and decomposition rates (Howden *et al*. 1999c).

These impacts are likely to lead to increases in the frequency and severity of fires and possible changes in the seasonality of fire (Cary 2002, Lindesay 2003, Hennessy *et al*. 2005). Thus there will be changes in the three defining characteristics of fire regimes each of which is important in determining species' responses to fire (Whelan 1995, Bradstock *et al*. 2002).

Feedbacks

As well as human-induced increases in GHG and associated changes in temperature and rainfall affecting the environment that species live in, some of the resulting changes in biodiversity will result in feedbacks that further affect the climate and the environment. For examples, changing biodiversity can affect many ecosystem processes including nutrient cycling, hydrology and fire regimes (Chapin *et al.* 2000; Hooper *et al.* 2005).

Carbon cycle feedbacks are a particularly important factor in global change and can arise from both changes on the land surface and in the oceans through physical and biological processes. Currently about 6.5 Gt of carbon is emitted per year through the burning of fossil fuels; terrestrial carbon sinks can absorb 2-3 Gt of carbon each year (Steffen 2006), but it is not known the extent to which this will continue in the future, as for example warming accelerates decomposition rates.

Enhanced loss of soil carbon with increases in temperature and the number and scale of ecological disturbances (e.g. large fires) are important positive feedbacks. Changes in temperature and soil moisture will affect carbon stored in terrestrial ecosystems, where two-thirds of carbon is stored in the soil. Soil respiration is likely to increase with increasing temperature (Rustad *et al*. 2000), but there is a counteracting effect as nitrogen is released as soil carbon is oxidised and becomes available for plants which would increase plant growth and enhance uptake of atmospheric CO_2 (Melillo *et al*. 2002). Melting of permafrost and drying of peat lands and wetlands are expected to result in significant releases of CO_2 and methane (which is 21 times more potent than CO_2 as a GHG) (Solomon *et al.* 2007). Furthermore, while the ocean can absorb large amounts of carbon, its capacity to continue to absorb CO_2 in the future will weaken through decreased solubility of CO_2 in warmer waters, increased stratification of the upper ocean and a possible decrease in the effectiveness of marine biota to absorb CO_2 from surface ocean waters (Steffen *et al*. 2004). The changing carbonate chemistry of the ocean may also slow the rate of CO_2 dissolution from the atmosphere (Steffen 2006).

Synergic changes

All these environmental changes, alone or in combination, will have significant impacts on almost all species, either directly or indirectly via feedbacks. Species and ecosystems are also affected by many other pressures which themselves may alter with climate change including: habitat degradation and loss, exotic and invasive species, grazing, fire management, harvesting of native species, recreation, pollution, altered hydrology, draining wetlands, water extraction, and modification of flow regimes. In many situations, not only will climate-induced environmental changes add to these pressures, they may combine to have impacts greater than the sum of the two independently; for example reductions in catchment inflows (due to climate change) combined with extractions of river water for human uses.

Almost all of the impacts on the environment discussed above will vary regionally (e.g. Suppiah *et al.* 2007). Therefore different species with differing distributions will not experience the same environmental changes, and individuals within species may experience different environmental changes at different times of their lifecycles or at different ends of their distributions.

3.3.2 Impacts on individual biology

Changes in the environment will have a range of impacts on the biology of organisms, most significantly on physiology and the timing of lifecycle events (phenology).

Changes in physiology

Carbon dioxide

Changes in atmospheric CO_2 concentration affect how plants photosynthesise: elevated CO_2 generally decreases leaf stomatal conductance, increases plant water use efficiency and enhances photosynthetic capacity and plant growth, the so call “CO_2 fertilisation” effect; these impacts are greatest when nutrients are available and water is limiting (DeLucia *et al*. 1999, Howden *et al*. 1999b; Conroy and

Ghannoum 2006; Karnosky 2003; Körner 2003; Steffen & Canadell 2005). However, below a certain level of water availability there is minimal growth and elevated CO_2 has little or no impact; thus there is a window of water availability in which elevated CO_2 significant increases water use efficiency (Steffen & Canadell 2005).

Productivity changes may be accompanied by changes in leaf morphology, tissue structure, and energy content, with effects varying among species and among plant tissues (e.g. seeds, leaves, stems, roots). Plant leaf size and anatomy are affected by elevated CO_2, but the magnitude of these responses decrease as the leaves mature, and they vary within and between species and with nutrient availability and temperature (Pritchard *et al*. 1999; Körner 2003). Increased carbon assimilation and more efficient water use combine to stimulate cell proliferation by promotion of cell division or cell expansion (Pritchard *et al*. 1999), and enhance the rate at which dry matter is accumulated (Roderick *et al*. 1999). It is likely that increases in CO_2 will lead to faster seasonal and successional canopy development and closure (Pritchard *et al*. 1999), but variation in species' physiological and structural attributes will affect their abilities to take advantage of the extra carbon. These responses to increased CO_2 concentrations will be non-linear (Körner 2003). Difference between species in their responses will lead to changes in ecosystem responses (Körner 2003).

Free-air carbon dioxide enrichment (FACE) experiments enable assessments of the impacts of elevated CO_2 in functioning ecosystems; above- and below-ground responses over whole growing seasons can be integrated to assess impacts on plant production, consumption and decay, nutrient cycling, soil carbon storage, tree-grass and plant-insect interactions and soil hydrology (Li *et al*. 2007; Stork *et al*. 2007). Such experiments have demonstrated impacts on almost all components of ecosystems, including trees, grasses and soil biota, but short-term effects showed an increase in CO_2 assimilation rates whereas long-term exposure resulted in decreased photosynthetic capacity (Li *et al*. 2007). Stokes *et al*. (2005) found large annual differences in the response of perennial C_4 grasses and C_3 tree seedlings to enhanced CO_2 concentrations in an ecosystem in which water and nutrient limitations are of differential importance during annual seasonal cycles. Elevated atmospheric CO_2 enhanced growth of snowgum (*Eucalyptus pauciflora*) seedlings when minimum temperatures increased above freezing, but had no effect over winter (Roden *et al*. 1999). While more natural than experiments in glasshouses, FACE experiments generally do not allow for full atmospheric and ecosystem feedbacks or interactions with herbivores or pollinators (Steffen & Canadell 2005).

The impact of elevated CO_2 on photosynthesis is expected to vary considerably between environments (greater in water stressed environments e.g. rangelands, grasslands, savannas and some alpine areas), between soils and between contrasting plant functional types (e.g. C_3 and C_4 species, deep and shallow rooted species, more and less woody species, and legumes and non-nitrogen fixing species) (Dukes & Mooney 1999; Howden *et al*. 1999a; Stokes *et al*. 2005; Sutherst *et al*. 2007). As most Australian soils are particularly nutrient limited, it is uncertain how strong the CO_2 effect will actually be in Australian native ecosystems (Hughes 2003); although there is some evidence that elevated CO_2 may also accelerate the nitrogen cycle partially reducing this constraint (Steffen & Canadell 2005). Modelling pasture growth, Howden *et al.* (1999a) found the relative impact of CO_2 on C_3 and C_4 pasture species varied depending on temperature, nutrients and water availability. The impacts of elevated CO_2 decrease as plants age, with young plants more likely to respond to elevated CO_2 and enhance net primary production than old growth or mature forests (Steffen & Canadell 2005).

Increased CO_2 has been observed to change leaf chemistry, typically increasing C:N ratios, in some plant species and can change the production of specific amino acids. Under elevated CO_2, Eucalyptus species leaves had reduced protein content and increased total phenolics and condensed tannins (Gleadow *et al*. 1998; Lawler *et al*. 1997); leaves of one species of Australian rainforest tree (but not another) had increased condensed tannins (Kanowski 2001); and *Lantana camara* had reduced N concentration and increased C:N ratios (Johns *et al*. 2003). Elevated CO_2 also increases the concentration of soluble carbohydrates which increases the digestibility of leaves.

Increased CO_2 also interacts with other aspects of physiology, for example with the freezing tolerance of seeds of the Joshua tree, *Yucca brevifolia* (Dole *et al*. 2003), and the frost sensitivity of snow gum seedlings (Roden *et al*. 1999). Increases in the growth rates of two Australian mangrove species under elevated CO_2 were greater when salinity was relatively low (Ball *et al*. 1997).

Temperature

Many studies have reported sensitivity to increased temperature in animals. The development rates of all ectotherms are affected by temperature. In many reptiles, gender is affected by the temperature of eggs during incubation; it has been suggested increased sand temperatures may lead to female bias in sex ratios of turtles (Glen & Mrosovsky 2004). Warmer temperatures will also affect moisture stress in many animals. Body size, morphology and physiology affect the regulation of body temperature and response to water balance in many birds, suggesting these may need to evolve for birds to adapt to increased temperature (Chambers *et al*. 2005).

Sensitivity to winter cold extremes determining range boundaries has been implicated in physiological and correlative studies for a range of species including North American songbirds, several well studied bird species in the U.K. and nondiapausing butterflies in North America; while in other species requirements for a specific warm period appear to determine cool boundary limits (Parmesan 2006). Sensitivity to temperatures only a few degrees above the maximums currently experienced in the wild have been demonstrated through observational and laboratory studies for a range of species including the symbiotic algae (zooxanthellae) in some corals, an Australian rainforest possum and North American scree-slope pika (Parmesan 2006).

Changes in phenology

The timing of lifecycle events in many species is often related to temperature, thus increases in temperature are expected to lead to changes in timing. The most likely changes are advances in spring events and delays in autumn events; shortening of various life-stages are also expected. Such changes have been observed in many species in the Northern Hemisphere, including herbs, shrubs, trees, insects, birds, amphibians and fish (reviewed in Hughes 2000; Fitter & Fitter 2002; Walther *et al*. 2002; Parmesan & Yohe 2003; Root *et al*. 2003; Parmesan 2006).

Parmesan and Yohe (2003) conducted a meta-analysis of changes in the timing of spring events in 172 species of birds and shrubs (mostly from United States), trees (mostly from Europe), butterflies (mostly from Great Britain), herbs and amphibians. They found an average advancement of 2.3 days per decade (95% CI 1.7-3.2 days per decade). A related analysis by Parmesan and Yohe (2003) categorised changes in the timing of spring events over 16-132 years (median 45 years) for 677 species: 62% showed trends toward spring advancement, 9% showed delayed spring events and 27% showed no trend. Another meta-analysis, by Root *et al*. (2003), of 61 studies covering 694 species (also taxonomically diverse and Northern Hemisphere dominated), found spring advancement of 5.1 days per decade (s.e.m. 0.1). In a categorical analysis that lumped timing changes, range shifts and abundance changes in over 1,473 species from 143 studies, Root *et al*. (2003) found 80% of observed changes were in the directions predicted from climate change. Several long-term multi-species studies reviewed in Parmesan (2006) report advances in spring phenology occurring in about one third of species. The timing of (often charismatic) spring events (e.g. shooting and flowering, emergence of butterflies, bird migration, egg laying and hatching, and frog choruses) is typically more consistently advanced than delays in the timing of autumn events (Walther *et al*. 2002; Parmesan 2006). While very similar changes have been observed in different taxa (e.g. specific birds and plants), a wide range of responses has been observed, including delays in spring events (Walther *et al*. 2002; Parmesan & Yohe 2003; Root *et al*. 2003; Parmesan 2006).

While changes in phenology are one of the best documented impacts of climate change, they may not be easy to predict and it is not clear how general the observed changes might be, especially in specific regions. Changes in some seasonal events may be related to climate changes in one but not other parts of species ranges. For example, spring arrival of some long-distance bird migrants is influenced by climate conditions in over-wintering areas, which affects food availability and build-up of reserves, which affects the onset of migration and its progress (Walther *et al*. 2002; Gordo *et al*. 2005).

Some lifecycle events are related to seasonal factors that will be unaffected by climate change (e.g. photoperiod), or to factors that may be affected less predictably than temperature (e.g. onset of summer storms) (Hughes 2000). However, in such cases changes in timing may still occur: Jonzen *et al*. (2006) suggest that rapid evolution of the endogenous response to photoperiod could also be responsible for advanced spring migration in northern European birds over-wintering in Africa; a similar evolution of photoperiod-threshold for winter diapause has been observed in a mosquito (Bradshaw and Holzapfel 2001).

Australian examples

In Australia, migratory birds have undergone changes in the first arrival date (3.5 days/decade), and last date of departure (5.1 days/decade) (Beaumont *et al*. 2006). Pairing of sleepy lizards has been observed to start earlier and last longer when the last months of winter are warmer (Bull & Burzacott 2002). Climate change may account for earlier arrival of bird species in the Australian Alps, but the change appears not to be a simple consequence of incremental annual warming resulting from earlier snow-melt (Norment and Green 2004; Green 2006). The development of Chrysomelid beetles was accelerated by 10-13 days when feeding on *Lantana* species at elevated temperatures (but adult body weight and feeding were not affected; Johns *et al*. 2003).

Species interactions

Variation among species in changes in phenology has the potential to lead to phenological miscuing or asynchrony (Hughes 2000; Parmesan & Yohe 2003; Parmesan 2006). A number of such changes have been observed involving phytoplankton and zooplankton, mammals and food plants, birds and food arthropods, and arthropods and food plants (Crick 2004; Visser and Both 2005).

However, there have also been observations of species successfully tracking the phenological changes in their resource species (Visser and Both 2005). For example, in Europe, the laying date of the great tit has advanced faster than the peak in abundance of food for chicks (Walther *et al*. 2002). However, the great tit has compensated for this by laying more eggs and delaying incubation thus reducing any impacts on the synchrony of hatching and emergence, and leading to increased clutch sizes and fledglings; there may also have been evolutionary changes with less selection for early laying (Cresswell and McCleery 2003). Concern has been raised that asynchronous changes in the flowering of eucalypt species may lead to long gaps in nectar availability.

Variation in change in phenology between species may also affect competition. For example, recent changes in flowering times of British plants have led to annual plants flowering earlier than perennials, and insect-pollinated plants flowering earlier than wind-pollinated plants (Fitter and Fitter 2002). These phenological changes, combined with potential changes in geographical range, may alter population-level interactions and community dynamics with ecosystem and evolutionary consequences (Fitter and Fitter 2002).

Growing and breeding season

Increases in temperature have also led to lengthening of growing and breeding seasons. Changes have been observed in many species and ecosystems in the Northern Hemisphere, with the increases being greater at higher latitudes where warming has been more pronounced (reviewed in Parmesan 2006). Many plants have a requirement to experience a period of cool temperatures prior to initiation of seed germination (cold stratification) or flowering (vernalisation); increased temperatures are thus expected to affect these reproductive processes. The sensitivity to this impact should be observable in variation in flowering and germination between warmer and cooler years, and possibly across species ranges. Increased temperatures have also been implicated in both the extension of the fruiting period and increases in fruiting from once to twice a year in some fungi (Gange *et al*. 2007).

Breeding season changes have also been observed in Australian bird species. Some southern high-latitude seabirds have extended their breeding seasons (Dunlop 2001). Forest Kingfishers are now breeding twice rather than once a year, and White-throated Nightjars and Little Bronze-cuckoos have started to over-winter in south-eastern Queensland (Roberts 2003). The length of the breeding season of some birds in the Australian Alps appears to be affected by temperature and snow cover (Norment and Green 2004; Green 2006).

The observed changes in phenology in a very wide range of species have been remarkable given the relatively mild changes in temperature (0.6ºC globally) (Parmesan 2006). Mismatches in phenology have been implicated in the local extinction of some butterfly populations leading to range shifts (Parmesan 2006). However, it is unclear what the impacts of climate-induced changes in phenology will be on species in general and on ecosystems.

3.3.3 Impacts on individual ecology

Climate change will alter how individuals interact with their environment and other species leading to changes in establishment, growth, competition, dispersal, breeding and mortality. Some of these changes will result directly from changes in phenology, physiology and behaviour; others will result from changes in other species.

Reproductive success

Increased germination and seedling survival has been observed in many species in cold environments including Antarctica and the Australian Alps (Hughes 2000); similarly expansions of trees into frost hollows has been observed in the Australian Alps. Warmer weather led to above average productivity for two-thirds of 32 bird species in France (Julliard *et al*. 2004). Increasing temperatures and declining snow cover could also affect the foraging ecology and breeding output of Richard’s pipits in the Australian Alps (Norment & Green 2004).

Growth

Increased CO_2 in combination with altered disturbance regimes has been implicated in increased tree and shrub establishment and growth, so called “vegetation thickening”, which affects the structure and function of vegetation communities (Berry & Roderick 2002; Gifford & Howden 2001). There is likely to be an increased growth rate of montane, temperate and tropical trees due to a combination of elevated CO_2 and increased temperature, although in experiments species vary in the nature of their responses (Delucia *et al*. 1999, Johns & Hughes 2002, Stork *et al*. 2007). Increases in the growth rates of two tropical mangroves due to elevated CO_2 were greatest at low salinity, and the growth impacts could affect competitive rankings along a salinity gradient (Ball *et al*. 1997).

Migration

Altered rainfall patterns and overall drying is expected to affect migratory birds that depend on inland wetlands; coastal migrants and staging migrants with very plastic migratory behaviour may be less affected (Bairlein & Huppop 2004). In Australia the timing of bird migrations has undergone similar changes in recent decades to that of Northern Hemisphere birds (Beaumont *et al*. 2006), but there is little evidence about how these changes could be affected by changes in water and food availability at staging points. Resources are required at stop-over points at the right time; if there are different changes in the timing of resource availability in different areas, migration success could be dramatically reduced, because animals are unable to alter the timing of each leg of a migration journey.

Australian Alps

A reduction in snow cover will have an impact on the unique flora and fauna of the Australian subalpine and alpine areas, where seasonal snow cover is a major determinant of the community composition. This will lead to changes in the diversity and abundance of plants and animals because of the minimal area of true alpine habitat and limited availability of high altitude refuges (Pickering *et al*. 2004). Altered hydrology is also likely to affect the relative growth rates and competition between grasses, herbs, shrubs and trees. Shrub species are particularly likely to expand in range along with some herbs and grasses of the tall alpine herbfields (Pickering *et al*. 2004). Decreased precipitation and increased temperatures will affect fens and bogs through replacement by grassland and heath communities.

Decreased snow is likely to reduce cover for the pygmy possum, leading to increased predation risk and increased exposure to lower temperatures due to reduced insulation (Green and Pickering 2002). These factors may have contributed to recent declines in some populations. The dusky antechinus and the broad-toothed rat, which are active under the snow throughout winter, have also experienced population declines in poor snow-depth years (Pickering *et al*. 2004).

Altered species interactions

Climate change has been observed to affect ecological interactions between species in a wide range of environments. Changes in the synchrony of lifecycle events in different species, can lead to changes in food availability, predation and other interactions; e.g., changes to the availability of new leaves for insect larvae; the availability of insect larvae for birds; and the temporal partitioning of spawning in amphibians leading to increased predation of larvae (Hughes 2000; Walther *et al*. 2002; Parmesan 2006). Changes in the structure and chemistry of leaves due to elevated CO_2 may affect growth, fecundity and population dynamics of herbivorous insects, and the carnivores feeding on them (Gleadow *et al*. 1998). Lawler *et al*. (1997) found that beetles feeding on eucalyptus leaves with increased C:N ratios had reduced digestive efficiencies and pupal body size, and increased mortality. Because of the poor quality foliage expected under increased atmospheric CO_2 and increased temperatures, leaf-miners did not have sufficient feeding time to compensate for their increased development rates due to warming (Johns & Hughes 2002).

Suttle *et al.* (2007) demonstrated that species interactions can dominate ecosystem responses to climate change. In an experiment in a Californian grassland, after two years of manipulating rainfall in accordance with climate change projections, there were significant increases in total plant productivity, productivity of nitrogen fixing forbs, plant and invertebrate richness, and abundance of invertebrate herbivores, predators and parasitoids which were in line with species-level predictions of change. After 5 years, feedbacks and interactions within and between trophic levels overturned the species-level changes and reversed each of the initial community trends listed above.

Changes in interactions between species and their parasites and diseases have also been observed. A faster lifecycle of the mountain pine beetle has led to an increased abundance and a greater spread of pine blister rust which they transmit (Logan *et al*. 2003). A shorter lifecycle of a parasitic nematode has had negative impacts on wild musk oxen host survival and fecundity (Kutz *et al*. 2005). In some areas dramatic frog population declines and species extinctions have been attributed to changed climatic conditions that have increased sensitivity to or the growth of chytrid fungus (Pounds *et al*. 2006; Parmesan 2006).

Other examples of ecological impacts arising from changes in species interactions in diverse environments include: changes in fire frequency affecting tree demographics and the formation and persistence of nesting hollows for arboreal mammals, birds and reptiles (Mackey *et al*. 2002); reduced chick provisioning, decreased growth rates and reproductive failure of wedge-tailed shearwater in southern Great Barrier Reef in 2002 because of reduced availability of forage fish (Smithers *et al*. 2003); reduced krill availability affecting production of Antarctic fur seal pups (Forcada *et al*. 2005); and increased exposure of folivores to plant toxins due to increased toxin concentration combined with increased leaf consumption in compensation for reductions in protein and increases in the thickness of leaves (e.g. Kanowski 2001). In contrast, increased leaf thickness and C:N resulting from elevated CO_2 did not affected leaf consumption rates or adult body weight of Chrysomelid beetles feeding on *Lantana camara* (Johns *et al*. 2003). Increased grazing by mammals (including native species) that extend their ranges higher into the Alps could have a very significant impact on the composition of alpine herb fields, which are historically mainly grazed by insects. Increased summer tourism and development of support facilities is expected to facilitate the introduction of weeds to the subalpine and alpine areas of Australia (Pickering *et al.* 2004).

Changes in soil biota affecting their regulation of nutrient cycling and interactions with plants are potentially very significant (Chapin *et al.* 2002). Gange *et al*. (2007) reported earlier fruiting and extension of fruiting period of fungi in a study covering 315 species monitored from 1400 sites for at least 20 years; the increase is very likely associated with increased decay rates. Changes in fungi diversity and activity can have very significant impacts on individual plant species and on net primary productivity (Chapin *et al.* 2002; Hooper *et al.* 2005).

The expulsion of zooxanthellae from some corals with elevated sea temperatures leads to bleaching. Bleached corals may recover (over many years) but they have reduced growth without the energy provided by the zooxanthellae (GBRMPA 2007). Excessive or regular bleaching will however kill corals (Hoegh-Guldberg 1999; Parmesan 2006). In 1998 a combination of elevated sea temperature and solar radiation exacerbated by lower salinity on inshore and some offshore reefs bleached corals in every ocean, including up to 95% of some corals in the Indian Ocean, and killed of 16% of the world's corals (Berkelmans & Oliver 1999; Parmesan 2006). Many corals appear to be already at their thermal tolerance limit and increased temperature will almost certainly result in more frequent and severe coral bleaching episodes, leading to increased coral mortality. In addition altered seawater chemistry due to increased CO_2 will reduce calcification rates. There is, however, evidence that in some places there has been evolution toward increased temperature tolerance in corals that were affected by the 1998 bleaching event, leading to greater survival in the 2000-2001 mass bleaching event (Parmesan 2006).

Interactions with other pressures

Biodiversity in Australia is affected by many other pressures, the most important being introduced species and habitat alteration; these are well documented in the National Land and Water Resources Audit (NLWRA 2001a) and *2006 Australia State of the Environment* (Beeton *et al.* 2006). Cats and foxes have had a dramatic impact on small to medium sized mammals in Australia especially in the rangelands (Morton 1990; Pickup 1998); rabbits have had a major impact on vegetation and landscapes across much of the continent. Other exotic animals, including cane toads and other amphibians, ants and other invertebrates, birds, mammalian herbivores, and other predators all have significant impacts on biodiversity in various regions. Introduced plants (over 2500 in Australia) are also a threat in many ecosystems, competing for resources, altering habitat for wildlife, and affecting fire regimes and other ecosystem processes. Terrestrial, aquatic and marine environments have been affected by exotic animals competing with native species, eating native species and modifying habitat.

Historically, various processes have led to habitat modification across the country (NLWRA 2001a,b; Beeton *et al.* 2006). In the intensive agricultural areas and urban areas, development of land, leading to loss and fragmentation of habitat has been widespread; in some regions 95% of native habitat has been removed. Across northern Australia, altered fire regimes continue to be a major driver of changing habitat. In most regions, but particularly the rangelands, grazing by native animals (promoted by water points), domestic stock and feral exotic species (e.g. rabbit, goat, camel, horse, deer) has a significant impact on individual plant species and on the structure and function of ecosystems, leading to impacts on other plant and animal species. Many native ecosystems and species are also affected by altered hydrological regimes: construction of dams and weirs, extraction of water from rivers and groundwater, altered flow variability and seasonality, draining of wetlands and increased recharge leading to dryland and irrigation salinity.

These pressures all have dramatic impacts on biodiversity in their own right, leading to over 100 extinctions and many species being threatened (almost 1600 are on the *Commonwealth Environment Protection and Biodiversity Conservation Act 1999* list of threatened species, as of June 2007). These pressures will also interact with climate change in a number of ways. Many are likely to change as a result of climate change and become more significant. For example, fire regimes will continue to change, and many exotic plants and animals will increase in abundance or extend their ranges.

These pressures will also decrease the natural ability of species to resist and adapt to pressures of climate change; the combination of climate change and these pressures may be much greater than the actions of either alone. For example, dispersal will be less successful in a fragmented landscape, and survival under less favourable climatic conditions will be harder for populations already reduced by interactions with exotics.

3.3.4 Impacts on populations

Impacts on the ecology of individual organisms, leading to changes in survival and reproduction over space and time, will lead ultimately to changes in populations: the distribution, abundance and genetics of populations area all likely to be affected. At a population level, four main outcomes might be expected:

- survival as is within the current distribution, possibly with abundance changes, due to minimal sensitivity, changed behaviour, phenotypic plasticity, or small-scale changes in habitat,
- evolution of traits to enable survival (what evolutionary biologists call adaptation),
- changing of distributions, or
- extinction.

The outcomes are not entirely mutually exclusive. The first three could occur together within a population, and species could lose some but not all populations. All four outcomes occurred during past climatic changes, although Botkin *et al.* (2007) note that surprisingly few plant species became extinct during recent ice ages.

Studies reviewed above have demonstrated some degree of sensitivity in vast numbers of species to the small level of climate change that has been observed since the industrial revolution. It is likely that many species will not be able to cope *in situ*, but the proportion is unknown. Observations of expansions of species ranges, along with changes in the timing of life-history events (discussed above), are among the best documented of recent impacts of climate change (Parmesan 2006). There is also a growing body of evidence for changes in abundance and genetics; many population losses have been observed and a few species have gone extinct. Similarly, models of the impacts of climate change on biodiversity predominantly focus on future changes in species distributions. We divide the discussion below into observations of impacts on species populations, modelled future impacts on species populations, and evolutionary change in populations. Methodological issues with observations and modelling are discussed in Box 1 and Box 3 respectively.

Box 1. Observing the impact of climate change on biodiversity

Observing the impact of climate change on species and ecosystems is made difficult due to the influences of short-term climate variation, non-climatic environmental changes (e.g. habitat loss), and natural fluctuations in range and abundance (Parmesan & Yohe 2003). This is particularly a problem for observations made on either a single species or in a single region. This can be addressed to some extent with meta-analyses comparing long-term observations across many species in different studies and regions.

Observational studies are also vulnerable to a bias towards more successful publication of observations of significant changes and changes conforming to climate change predictions. While such meta-analyses do not provide species or location-specific information, they do give very powerful information about the extent to which processes that have been predicted are actually occurring, and they can reduce positive-reporting bias by only including multi-species studies or studies with both positive and negative tends.

As discussed in the main text, Parmesan and Yohe (2003) and Root *et al*. (2003) conducted meta-analysis studies of over 1,700 and over 1,473 species respectively largely from the Northern Hemisphere. Both studies found variable responses among species in the literature (no change, predicted change and opposite change). However of those that showed some change over a decade or more, there were highly statistically significant trends in the directions predicted by climate change, i.e. pole-ward or upward distribution changes, earlier spring lifecycle events, abundance increases of warm-adapted species and abundance decreases of cool-adapted species. It should be noted however that while these studies confirm that *observed changes* are largely consistent with the predictions of climate change (about 80% of species changes in each study), they give no estimate at all of what proportion of all species (or even observed species) have responded significantly to climate change.

The power of observational studies of climate impacts can depend critically on the sampling effort, type of data used, and the historical baseline against which contemporary observations are compared (Shoo *et al*. 2006). In particular, studies using greater sampling effort at later times will be biased towards detecting range expansions. Shoo *et al*. (2006) used random sampling from extensive upland Wet Tropic birds survey data to demonstrate that comparing the *mean altitude* of occurrence records over time, as opposed to either *maximum or minimum altitudes*, gave more power (smaller range shifts could be detected and/or less sampling effort used) and was not biased by different sampling efforts at different times.

Observations

Global trends

Pole-ward and upward changes in species distributions have been observed for a wide range of taxa in many locations, especially in the Northern Hemisphere where a range of very good long-term data sets exists. These cover lichens, herbs, shrubs, trees, marine zooplankton, marine invertebrates, butterflies, moths, dragonflies, damselflies, other insects, birds, mammals, reptiles, amphibians and fish (reviewed in Hughes 2000; McCarty 2001; Parmesan & Yohe 2003; Root *et al*. 2003; Parmesan 2006). Rates of observed distribution shifts vary considerably among and within species (Thomas & Lennon 1999; Walther 2002; Parmesan 2006). Parmesan and Yohe (2003) conducted a meta-analysis of distribution changes in 99 species of United Kingdom birds, Swedish butterflies and Swiss alpine herbs and reported average changes of 6.1 km pole-ward or 6.1 m upward per decade (95% CI 1.3-10.9 km/ m per decade). A related analysis by Parmesan and Yohe (2003) categorised distribution changes over 17-1000 years (median 66 years) in 893 species or species groups. They found 40% showed distribution changes that were consistent with climate change predictions, and 10% showed changes that were in the opposite direction; half had distributions that appeared to be stable or showed changes that could not be compared to climate change predictions. The vast majority of observations of distribution changes that are consistent with the predictions of climate change are of expansions of the cool (pole-ward) boundaries; to date, the very few reports of contractions of warm boundaries are mostly in highly dynamic species, like butterflies, or polar species dependent on icesheets (Parmesan 2006). Distribution shifts are likely to be episodic rather than gradual, depending on occurrences of good and bad years (Parmesan *et al*. 2000; Walther *et al*. 2002) and respond to a complex relationship between interacting factors such as warming, rainfall and soil moisture conditions (Parmesan 2006) as well as species-specific dispersal abilities and habitat requirements.

Alpine environments around the world have experienced expansions of mammals, birds, insects (including vectors for human diseases) and plants to higher elevations (Hughes 2000; Walther *et al*. 2002; Parmesan 2006). In particular there has been increased establishment of tree species in alpine meadows leading to rising treelines (Hughes 2000; Parmesan 2006). However, global historic responses of treelines have varied between warm periods over the last 100 years; there is evidence that in some environments successful tree establishment may require increased rainfall as well as warming (Parmesan 2006). To date, mirroring observations of pole-ward range shifts, there have been many more observed expansions of upper boundaries than contractions of lower boundaries, leading to reports of increased species richness in alpine areas. Changes in lower boundaries have been poorly studied; however there have been some reports of disproportionate decreases in abundance at lower elevations and rising lower boundaries in a number of butterfly species and one mammal (Parmesan 2006). Several studies have shown, and others predicted, that species in mountain environments may be particularly vulnerable as they tend to be sensitive to climate and their core bioclimatic habitats (see Box 2) are liable to disappear off the tops of their mountains (Hughes 2000; Hilbert *et al*. 2004; Williams *et al*. 2003; Parmesan 2006). Indeed the first extinctions attributable to recent climate change are of amphibian species restricted to mountains (Parmesan 2006; Pounds *et al*. 2006). Mountain environments, however, may also be better buffered since much smaller distribution shifts would be required to remain within an existing bioclimatic envelope (Peterson 2003) due to the slope and topographic diversity.

Significant range and abundance changes have also been observed in species in arid environments, with extinctions and range increases (Walther *et al*. 2002).

High seawater temperatures have led to significant decreases in coral abundance, and in some places evolution of higher temperature tolerance by coral algal symbionts (Parmesan 2006). Some distribution expansions to cooler waters have also been observed (Parmesan 2006), however future decreases in calcification rates may reduce establishment in cooler waters as seawater acidity increases.

Box 2. Bioclimatic habitat

The distributions of many species are strongly influenced by different aspects of climate. “Bioclimatic habitat” or “envelope” is a *description* of a species’ (or ecosystem’s) distribution in terms of the ranges of a number of climatic variables that are thought to be ecologically important in determining its distribution on the ground. Bioclimatic habitat may be used conceptually to describe the (often unknown or presumed) range of climatic determinants of a species; or they may also be quantified and used in models of current distributions or future distributions under changed climates.

Where quantified, they are usually determined by *correlation* (either crude matching or statistically) between a species’ known geographic distribution and bioclimate (often calculated using surfaces of climate variables and elevation data). Quoted bioclimatic habitats may be defined by a single parameter (e.g. the range of average annual temperature across the species distribution), or by 30 or more climatic variables including seasonal rainfall and maximum and minimum temperatures, and they can include indices constructed from several variables (e.g. a moisture index that is a function of temperature and rainfall). Being correlational, there may be strong, weak or no actual causal influence of the selected climatic variables on the species distribution. “Core” bioclimatic habitat refers to a sub-set of the total bioclimatic habitat within which a species currently occurs which is presumed to be most favourable for a species.

Species may be threatened with decline or extinction if the area on the ground that experiences their core bioclimatic habitat decreases, moves to a disjunct area too distant for successful dispersal and colonisation (e.g. over a mountain, desert or agricultural region), moves faster than the species’ distribution can move, or it moves to areas that are otherwise unsuitable (e.g. wrong soils, out to sea).

Interesting details

Many observations of range changes have detected increased species richness and greater expansion at cool boundaries than contraction at warm boundaries (Walther *et al*. 2002; Parmesan 2006). It is currently unclear the extent to which this is due to colonisation events being faster than inevitable (but delayed) local extinction events (as assumed by many authors, e.g. Walther *et al*. 2002), or to the factors limiting cool boundaries actually changing faster than factors limiting warm boundaries; indeed in some regions minimum temperatures have increased more than maximum temperatures (Solomon *et al.* 2007).

Along with many observations of pole-ward and upward range expansions, there have been a number of range changes in the other direction that can also be attributed to climate change (Parmesan 2006). For example, on Mt Kilimanjaro the boundary between the open, dry alpine ecosystem and closed cloud forest has shifted downward by 400 m due to increased fire impacts (Hemp 2005). Such changes reinforce that species ranges are the result of complex interactions of climate and various other processes. These types of changes are likely to be hard to detect and attribute to climate change, and even harder to predict.

As well as marginal distribution changes, reported range shifts include a number of species in America and Europe/Africa that have become established in climatic zones from which they had previously been largely absent, e.g. tropical species in temperate regions. Similarly population elevation changes have included shifts into distinctly different habitat zones, e.g. into montane cloud-forests and above tree lines (Parmesan 2006). It is often anticipated that species moving into new areas made suitable by climate change will occupy similar habitats as in their historic ranges, indeed such a requirements are sometimes included in models. However, Davies *et al*. (2006) report significant relaxing of habitat restriction by a butterfly whose range in Britain is currently expanding, but was previous declining due to loss of its restricted habitat.

Australian examples

There have been far fewer observational studies in Australia than in the Northern Hemisphere, and while there are many Australian observations that are consistent with global patterns, there are insufficient local observations to conduct meta-analyses that might give some estimate to the generality of the global trends. Much of Australia has a climate that is far more variable (greater range) and less predictable (more between-year variation) than better studied parts of the world, suggesting that Australian biota are likely to be intrinsically better adapted to variation in climate and possibly less ecologically sensitive to climate extremes. For example, a high proportion of plant species in arid and semi-arid areas are dormant most of the time (as seed banks, below-ground parts or inactive standing plants) with flushes of growth and reproduction after particularly wet periods. And, 51% of Australian land and freshwater bird species are migratory or semi-migratory (Gilmore *et al.* 2007).

A wide range of changes in species ranges, migration and productivity of Australian birds have been observed. The distributions of the noisy pitta, Pacific bazza and several fruit-eating pigeons have expanded southward (Olsen *et al*. 2003). Changes in ocean temperatures and climatic conditions along the coast of Western Australia are thought to be the primary reason for observed southward distribution expansions of tropical seabirds (Dunlop 2001). The southward expansion of the distribution of beach stone-curlews has broadly corresponded with the southward contraction of the hooded plover (Garnett & Crowley 2000).

There are also likely to be significant impacts on water birds in the Macquarie Marshes and elsewhere in the Murray-Darling Basin through changes in occurrence of major flooding events combined with warmer temperatures, increased evaporation and decreased water flows (Kingsford & Norman 2002, Chambers *et al*. 2005). Reid (2003) provided data on shifts in distributions for many species, but these changes could be attributed to sources other than changes in climate alone, such as changes in land cover and land use. Other observed distribution changes are reviewed in Chambers *et al*. (2005), but the role of climate is not clear for many species.

In a study of lizards in temperate undulating landscapes, elevation (which was strongly related to temperature) was a significant factor in determining apparent abundance and species richness of lizards; and ecologically similar species replaced one another as elevation increased (Fischer & Lindenmayer 2005). In addition, lizards at higher elevations tended to have darker body colours and gave birth to live young, whereas lizards at lower elevations tended to have lighter colours and laid eggs.

In the New South Wales alpine area, there has been an increase in the altitudinal distribution of three species of feral mammals (horse, pig and rabbit) whose alpine distributions appear to be related to snow-related access to ground-based food, and the native swamp wallaby, which is a browser and less affected by snow covering food (Pickering *et al*. 2004). Therefore, the decline in snow cover will have a major impact on the faunal composition of the alpine and subalpine areas, with likely impacts on alpine vegetation due to increased burrowing, rooting, trampling and grazing. Native alpine fauna are likely to be affected by reduced competitive advantage and by increased predation by feral carnivores (especially foxes) due to reduced snow cover (Pickering *et al*. 2004). Higher levels of solar radiation, particularly ultraviolet light, have already had detrimental effects on corroboree frog populations in alpine areas (Green unpublished cited in Pickering *et al*. 2004).

In some locations in the Alps tree lines have shifted down hill into the edges of frost hollows. Tree lines are generally expected to shift up into the alpine zone through increased establishment of tree and shrub species in alpine meadows (Hughes 2000). Pickering *et al*. (2004) suggested that successful establishment may rely on an associated increase in rainfall, and that the rate of change will be very slow because of the extreme weather conditions. Changes in tree cover are expected to selectively affect fauna. Increases in elevation of sub-alpine and lower species may lead to an overall increase in biodiversity in the alpine areas; however there are likely to be significant reductions in the population sizes of many endemic alpine species and possibly some species extinctions.

Cryptic refuges

A number of studies, using genetic, pollen and macrofossil data, have suggested that the expansions of many plant species in North America and Europe occurred from very small populations in northern refuges, rather than solely via relatively rapid migration from “core” southern populations (Pitelka 1997, Rowe *et al*. 2004; Brubaker *et al.* 2005; McLachlan *et al*. 2005; Anderson *et al.* 2006; Svenning & Skov 2007). These findings have two important implications for responses to contemporary climate change. First, maximum plant migration rates may be considerably less than had been suggested from previous reconstructions of postglacial expansions. Second, species are capable of surviving for considerable periods (>10,000 years) in small populations and in regions well outside their imputed “core” bioclimatic habitat (Pearson 2006; see Box 2). These studies also suggest that, under contemporary climate change, increases in abundance and gradual range change, especially radiations from outlying “sleeper” populations, might be at least as important as changes in the ranges of core populations due to gradual or long-distance dispersal. Indeed, such spread from latent populations has been observed recently with the spread of exotic species from gardens and accidental introductions (e.g. on sub-Antarctic islands) into surrounding native vegetation as climate becomes more suitable (Walther *et al*. 2002; Sutherst *et al*. 2006).

Climate variability and extreme events

Extreme weather events can affect morphology, behaviour, reproduction, population and community dynamics, and ecosystem structure; changes to extreme events are likely to be important drivers of ecological responses to climate change (Parmesan *et al*. 2000). Responses of species and ecosystems to extreme events and climate variability (e.g. ENSO) can reveal information about the sensitivities of various species to climate (e.g. Ottersen *et al*. 2001); however climate responses in the presence of elevated CO_2, or to more frequent extreme events and persistent changes in climate may be not be so easily extrapolated from such observations. Easterling *et al*. (2000) reviewed observed impacts of climate extremes (storms, wet periods, droughts, frosts, and minimum and maximum temperatures) on natural systems and found evidence of impacts on plant and animal range boundaries, breeding behaviour, individual fitness and population dynamics (with climate related booms and busts reported), evolution of beak sizes, coral bleaching, and ecosystem structure. In addition, there are several studies on amphibian, bird and butterfly species with sufficient long-term and/or physiological data to demonstrate long-term changes in climate extremes have exerted long-term directional changes on ranges or abundances, as opposed to just contributing to natural variation.

Modelled impacts on species distributions

The impacts of climate change on species distributions have been modelled for thousands of species in different ecosystems around the world (reviewed in Peterson *et al*. 2005). Many modelling approaches have been used; however most rely largely on projecting future changes in the distribution of species' current bioclimatic envelopes. There are considerable conceptual and practical limitations with many of the approaches used and their results need to be interpreted with caution (Pearson & Dawson 2003; Araújo *et al*. 2005; Ibáñez *et al.* 2006; Box 3). However, model results, especially when combined with observational evidence, do serve to give an indication of how sensitive biodiversity might be to climate change, and models enable exploration of which factors might be critical in determining actual species abundance and distribution outcomes (e.g. Pearson & Dawson 2003, 2005; Brooker *et al*. 2007).

Many studies show considerable distribution shifts and contractions for many species, and both of these changes give rise to concerns about the persistence of species. In general, distributions tend to shift down temperature gradients (to cooler climes). However, the direction of shifts vary considerably among species depending on which bioclimatic variables are most important in the models for each species (e.g. changes in moisture availability may differ from changes in temperature, and the direction of temperature gradients may alter seasonally), and some species show little or no change. As well as the direction of change, there is variation among species in the rate of modelled distribution shifts. There is also variation among species in the size of their modelled future distributions: some expand, some don't change, some contract and the distributions of some species are projected to disappear completely under some scenarios. The most consistent result is that there is likely to be considerable variation among species in the responses of their distributions.

One notable global analysis, Thomas *et al*. (2004), used species-area relationships and extrapolations from five regional studies modelling bioclimatic envelopes of 1,103 plant and animal species to estimate that about 18 to 35% of species would be "committed to extinction" by 2050 depending on the climate change scenario. (No estimates were made of *when* those extinctions might occur). The estimates varied depending on assumptions about dispersal (about 21 to 32% committed to extinction with dispersal and about 38 to 52% without dispersal) and species-area relationships (1.4 fold variation). They estimate that climate change would have an impact greater than habitat loss, but of a similar magnitude. This ground breaking study attracted considerable attention in the media, scientific literature and tea rooms, with significant methodological and theoretical criticisms which serve to highlight current lack of consensus about knowledge of likely impacts on distributions and diversity and how to analyse them (e.g. Lewis 2006; Ibáñez *et al.* 2006). Different commentators suggested the analyses may greatly overestimate and underestimate the likely impact on future extinctions, and that projections of extinction *per se* are very difficult and not particularly useful (Ibáñez *et al.* 2006). This, and many other studies, do however highlight that significant impacts on many species are very possible.

Many studies have predicted that actual species migration rates may be less than is required for species to remain within their shifting bioclimatic envelopes (e.g. Malcolm *et al.* 2002), and that habitat fragmentation may limit migration (Higgins *et al*. 2003). Others have shown that species interactions and rates of long distance dispersal may be very important in determining distribution shifts, and that long distance dispersal can greatly reduce the importance of habitat connectivity (Pearson & Dawson 2005; Brooker *et al*. 2007).

Modelled distribution changes for Australian species are reviewed in the following sections, and implications for conservation are discussed in Section 7.

Box 3. Modelling the impact of climate change on biodiversity

A wide variety of methods have been used to model changes in the distribution of biodiversity as a result of climate change. The main differences are between: modelling individual species and modelling groups of species (functional types, communities, ecosystems or biomes); and between: modelling species' observed environmental niche and modelling ecological or physiological processes. Some models use a mixture of approaches. Also important are the aspect of the distribution that is modelled (presence/absence, abundance, probability of presence, or species richness), the type of observation data used (presence only or presence/absence data, and with or without planned sampling), and the process used estimate environmental niches (e.g. bioclimatic range, statistical fit, artificial neural networks, genetic algorithms). There are also variations in the implementation of each approach; and analyses vary in the extent to which the models they use have been validated.

The most commonly used approach has been to project future distributions of individual species' environmental niche (typically just a bioclimatic envelope) which is modelled from the observed association between a species and the environment (Box 2). Most modelling of changes in the distributions of native species in Australia has used this approach with the BIOCLIM program which uses a very simplistic bioclimatic envelope estimating procedure. Process-based models have been used widely for Australian agricultural and forestry species; but their applicability for native species has been limited due to lack of ecological knowledge that is required to parameterise them. However, they may be useful for exploring changes in interactions and some ecosystem processes. Ecosystem-level bioclimatic modelling (e.g. Hilbert *et al.* 2001) has similarly been used infrequently in Australia.

Recently a number of studies have assessed various bioclimatic modelling methods (e.g. Thuiller 2004; Araújo *et al.* 2005; Araújo & Rahbek 2006; Elith *et al.* 2006; Pearson *et al.* 2006). Comparisons consistently show considerable variation among models in the projections of future species distributions. They also show considerable variation among models in their ability to predict current distributions; and more recently developed methods appear to have better performance (e.g. Elith *et al.* 2006). The BIOCLIM model has repeatedly been shown to perform poorly compared to other models (e.g. Elith *et al.* 2006; Pearson *et al.* 2006); as such, its results should be used with great caution. There appears to be a trade-off among some models between precision of fit (in a region) and generality (between regions) (Araújo *et al.* 2005; Araújo & Rahbek 2006). Models of species with small distributions tend to be less accurate (Schwartz *et al*. 2006), and bioclimatic models generally appear to be more accurate at coarser scales (Pearson & Dawson 2003). Araújo *et al.* (2005) compared predicted distribution changes with observed distribution changes over about 20 years. They found "good to fair predictive performance" in a statistical sense but not necessarily in "decision-planning context"; a poor correlation between the ability of models to fit present and future distributions; and validation on random sub-sample data overestimates model performance. Uncertainty in the digital elevation models that underpin many bioclimatic models (Van Niel & Austin 2007) and in the climate models used (Beaumont *et al*. 2007) can significantly affect model results.

Current bioclimatic models typically do not address a number of ecological processes that are likely to be critically important in determining future changes in biodiversity, including: interactions between species, dispersal rates and distances, altered reproduction, CO_2 impacts on plant growth and chemical composition, population dynamics, evolution and the role of fine scale habitat diversity (e.g. Davis *et al.* 1998; Pearson & Dawson 2003; Araújo *et al*. 2005; Botkin *et al*. 2007). It may also be more useful and robust to focus on diagnostic variables rather than extinction (Ibáñez *et al.* 2006).

A very different approach has been to model the dynamics of virtual landscapes and ecosystems to explore the importance of particular processes such as interactions, rates of change, dispersal and the spatial structuring of habitat (Pearson & Dawson 2005; Brooker *et al*. 2007).

Australian rainforests

Bioclimatic modelling of rainforest species in the Australian Wet Tropics Bioregion predicted increases in temperature would lead to significant reduction or complete loss of the core bioclimatic envelope of all regionally endemic vertebrate species (Williams *et al*. 2003). By interpolating, they estimate increases in temperature between 1.4 and 5.8ºC would lead respectively to 6 and 96% of species losing their core bioclimatic habitat and possibly going extinct (including 65 regionally endemic vertebrates). In particular, the study suggested losses in bioclimatic habitat would be nonlinear, increasing rapidly beyond 2°C, and species would also be affected by other climate-related impacts. For example, the impact of elevated CO_2 on rainforest leaves would add significant additional pressure on folivores (Kanowski 2001).

Hilbert *et al*. (2004) estimated that suitable breeding habitat for the golden bowerbird in the Wet Tropics of North Queensland would halve with a 1°C increase in temperature. This is likely to affect population size and structure through more fragmented sub-populations. Similarly, Meynecke (2004) modelled the distributions of 12 endemic Wet Tropic rainforest vertebrates under four climate change scenarios and found that even species with current wide climate ranges may be vulnerable, with current bioclimatic envelopes becoming fragmented and decreasing in area on average by more than 50%. Shoo *et al*. (2005) estimated that 74% of rainforest birds of north-eastern Australia will be threatened as a result of warming; reduction of current bioclimatic envelope varied according to the altitude at which a species is currently most abundant, with upland bird species most affected, and some populations of lowland species possibly increasing.

Modelling ecosystems rather than species, Hilbert *et al*. (2001) predicted large changes in the distribution of forest environments even with minor climate change. Increased precipitation would favour some rainforest types, whereas a decrease in precipitation would increase the area suitable for sclerophyllous trees. Some rainforest types would increase, while others would decrease. Overall, it was predicted that highland forest environments would decrease by 50% (potentially affecting many endemic vertebrates), with potential impacts on 566 terrestrial vertebrates (12% regional endemics) (Hilbert *et al*. 2001).

Temperate Australian animals

Brereton *et al*. (1995) found that current bioclimatic habitats of 41 out of 42 fauna species from southeast Australia were likely to be affected by climate change, with moisture index the most important factor in the models. In particular, a decline or extinction of the alpine tree frog is expected through a reduction in its current bioclimatic habitat (Brereton *et al*. 1995). Pouliquen-Young and Newman (1999) found that with 0.5°C warming, current bioclimatic envelopes would disappear for three endangered frogs and 15 endangered or threatened mammals inhabiting important conservation areas. Like with most bioclimatic envelope analyses, the findings from Pouliquen-Young & Newman (1999) are conditional on a range of restrictive assumptions and sensitive to the availability of distribution data, which greatly qualify any extrapolations from the model findings (McKellar *et al*. 2007).

In Australia, it is anticipated that nearly 20% of migratory bird species are potentially affected through the loss of coastal habitat due to sea-level rise, and marine and coastal birds will also be affected in combination with the coastal development (Mallon 2007).

Beaumont & Hughes (2002) examined potential changes in the current bioclimatic envelopes of butterflies. Most had fairly wide climatic ranges in comparison to other taxa, but they may still be vulnerable to climate change: using a conservative climate change scenario, the bioclimatic envelopes of 88% of species decreased, with 54% decreasing by 20%. Under an extreme scenario, the bioclimatic envelopes of 92% of species decreased. The species identified as most vulnerable typically had narrow geographic and climatic ranges, in ability to migrate and other restricting life history characteristics. Poor dispersal ability and close mutualistic relationships with other species may greatly reduce the ability of some species to migrate with shifting climatic habitat or mutualists (Beaumont & Hughes 2002).

Australian plants

Plants are affected by temperature, rainfall and CO_2, as well as competition, herbivory, fire and other disturbance regimes, all of which are likely to alter under climate change. Many Australian plant species have narrow distributions or particular environmental affinities which may limit their ability to track shifts in bioclimatic habitat. Eucalyptus species have a highly skewed distribution of geographic range sizes. Hughes *et al*. (1996) found that, of 819 species, 68% have ranges that cover less than 1% of the continent and 3% have ranges covering more than 10%. Many of their distributions are closely associated with local environmental conditions (soil, temperature, rainfall and drainage); for 53% of species mean annual temperature varies by less than 3ºC across their range, for 25% it varies less than 1ºC and for 23% mean annual rainfall varies less than 20% across their distributions (Hughes *et al*. 1996). Consequently, although the genus is very widely distributed, many species may be entirely outside their current bioclimatic envelopes with relatively small changes in climate. Many *Dryandra* species of southwest Western Australia are also narrowly distributed; Pouliquen-Young & Newman (1999) found that with 2°C warming the current bioclimatic envelopes of 91% of *Dryandra* species would decline to less than half their current area and 66% would disappear completely. Similarly, they found the current bioclimatic envelopes of 27 *Acacia* species endemic to Western Australian would be lost with 2°C warming. These species may not readily track the movements of their current moving bioclimatic envelopes across the landscape because of differences in soil types, and they may be confined to smaller ranges within current distributions (Pouliquen-Young & Newman 1999). (Note the previous caveat about this study.)

As well as native plants changing their distributions and competing with resident species, many weeds are likely to expand or change their distributions. Indeed weeds may spread into previously inhospitable habitats more effectively than most native species because they have highly effective dispersal mechanisms and often do not have specific pollination requirements (Sutherst *et al*. 2007). Increased water use efficiency (due to elevated CO_2) may facilitate expansion of woody weeds in lower rainfall areas (Sutherst *et al*. 2007). The prickly acacia, *Acacia nilotica*, was introduced into Queensland for shade, fodder and ornamental value, but has subsequently been declared a noxious weed. Using CLIMEX, which models climatic habitat and some ecological processes, Kriticos *et al*. (2003) modelled its potential distribution under various climate change scenarios and predicted it would expand significantly into drier areas (due to increased water use efficiency) and to the south (due to increased temperatures facilitating reproduction).

Rates of distribution change

Many commentators have raised concerns that species might not be able to migrate fast enough to track shift in their core bioclimatic habitat (Malcolm *et al.* 2002; Lovejoy and Hannah 2005; Ibáñez *et al.* 2006). This raises questions about how fast species distributions can change. Many species can clearly disperse long distances rapidly (e.g. many weeds and flying animals), but how fast can tree distributions shift?

Historical (postglacial) rates of expansion of some Northern Hemisphere tree species distributions have been estimated to be up to 2 km per year and some seem to have been unaffected by dispersal barriers (Pitelka 1997; Huntley 2005). Inverson and Prasad (1998) cite the historic rate of migration as about 0.1 to 0.5 km per year for some species; Huntley (2005) suggests the boundaries of “most” tree species distributions shifted by at least 0.2 km per year. Using new evidence, McLachlan *et al*. (2005) revise downward (by greater than a factor of two) previous estimates of the rates of postglacial migration of red beech and maple to 0.08 to 0.09 km per year. However, it is questionable the extent which these estimates might provide insights about the rate of future distribution shifts of Australian species: many contemporary landscapes are heavily fragmented or degraded (NLWRA 2001b), and many Australian plants do not have adaptations for long-distance seed dispersal (Hughes *et al.* 1994) although long distance dispersal may occur via non-standard dispersal mechanisms (Higgins *et al*. (2003). There is also no evidence for distribution shifts being a widespread among Australian species to in response to warming after the last glacial maximum (Markgraf & McGlone 2005).

How fast might bioclimatic habitats shift in the future? Over the last 50 years global average temperatures have increased at 0.13°C per decade (Solomon *et al.* 2007). In Australia there are generally north-south and inland-coastal temperature gradients, with the strengths of each varying seasonally; maximum gradients (at 1000 km scale) vary from about 4.5°C to per 1000 km in autumn to 7.5 °C per 1000 km in spring. Thus the locations experiencing a given *average temperature* might be expected to shift at a rate about 3 to 17 km per year across the continent; rates of shift in regions with mountains will be considerably less. Shifts of actual core species-specific bioclimatic habitat may be greater or lesser depending on which particular climatic parameters (or combinations of them) are important, the impacts of changed variability in climate, and the extent to which increasing CO_2 changes core bioclimatic habitats for species. Further, it is unknown how much fine-scale habitat variability, especially due to topography, mitigates macro trends; and the consequences of not tracking shifts in core bioclimatic habitat are also not known for the vast majority of species.

Long-distance dispersal is likely to be very important in the expansion of some plant distributions (Pitelka 1997; Higgins *et al*. 2003). There are three long-distance dispersal mechanisms: water, wind and animals (birds and large mammals). The distance that a propagule falls from the source depends on wind velocity, drag or resistance to fall. There can be two distinct phases to invasion: a quiescent phase, with slight range shifts, and an active phase with an explosive expansion. In terms of establishment, newly founded populations may fail repeatedly and may take a while for founding plants/populations to send out enough seed. After dispersal, plants must also germinate, grow and reproduce to produce new propagules, which depend on existing conditions (e.g. existing vegetation, soil conditions, climate and disturbance). A similar process of long-distance dispersal and establishment of outlying founding populations occurs with many animal species. However, there are many examples of gradual changes in ecosystem boundaries with changing environmental conditions, e.g. rainforest colonising sclerophyll forest in the absence of fire.

Evolution

There are few studies that have examined the potential for species or populations to evolve traits enabling them to cope with the impacts of climate change, because such analysis requires genetic data sampled over time (Parmesan 2006). Hoffmann *et al*. (2003) looked at genetic responses to moisture stress in laboratory populations of *Drosophila* after 30 generations; they found low selection response for traits linked to climatic stress, but high levels of genetic variation for morphology. Umina *et al.* (2005) observed changes in genetic polymorphisms in wild *Drosophila* populations over 20 years that were equivalent to a 4^{o} latitude change. In a study of wild populations of another *Drosophila* species on three continents, Balanyá *et al*. (2006) found genetic shifts in 21 out of 22 populations (over 24 years on average) towards patterns more similar to those expected in populations about 1° of latitude closer to the equator. Confirmed or probable genetic changes have also been identified for corals, birds, squirrels and mosquitos (Bradshaw & Holzapfel 2006; Jonzen *et al*. 2006; Parmesan 2006).

It is likely that evolution will complement rather than replace projected ecological changes. There are few studies to suggest that climate change would allow species to evolve sufficiently rapidly to maintain current geographic distributions in the face of climate change which may become unsuitable in the future (Parmesan 2006 and references therein). New mutations or new genetic architectures are required for species-level evolution to occur. Species with short lifecycles and large population sizes (e.g. invertebrates) may be more likely to be able to adapt and persist whereas species with long lifecycles and small population sizes may be more likely to decline (Bradshaw & Holzapfel 2006).

3.3.5 Impacts on ecosystems

Evidence to date clearly shows that species respond in very different ways to climate change. Variation among species in changes in phenology, abundance and distribution will lead to steady changes in the relative abundance of different species, their co-occurrence and interactions, and ecosystem composition. Such changes will flow on to affect the structure and function of ecosystems (Hughes 2000; Walther *et al*. 2002). Species diversity (composition, richness and relative abundance) has a role in regulating ecosystem processes and affects how ecosystems respond to environmental change (Chapin *et al*. 2000; Hooper *et al*. 2005). These species-to-ecosystem changes can happen through the combination of direct impacts on many species, or through change in a potentially small number of species that have important ecological impacts on other species (e.g. influencing hydrological or nutrient cycling, direct population regulation, or providing or restricting food and habitat) (Chapin *et al*. 2000). Over time, species-level-changes will lead to evolution of ecosystem types and probably the formation of novel ecosystem types.

Due to the strong feedback mechanisms in ecosystems, changes to some ecosystem-level processes will affect many resident species. Many changes in ecosystem-level patterns and processes have been observed globally, including shifting ecosystem boundaries (Gates 1990), increases in forest productivity (DeLucia *et al*. 1999; Kirschbaum 1999; Boisvenue & Running 2006), and increases in continental river runoff due to CO_2 impacts (Gedney *et al.* 2006). Thus, climate change can be viewed as having both bottom-up and top-down ecosystem impacts.

Past human alteration of the environment has caused widespread changes to the abundance and distribution of many species, including extinctions and spread of exotic species, leading to impacts on ecosystems which may affect their resilience to climate change (Chapin *et al*. 2000; see Section 8.5.3 for discussion of resilience in the context of climate change). Hooper *et al*. (2005) identify both functional response traits (how a species responds to a disturbance or a change in environment) and functional effect traits (how a species affects ecosystem properties) as having important roles in determining dynamics of ecosystems experiencing environmental change.

Australian examples

Bottom-up: Species affecting ecosystems

In Australia, various studies have suggested that there will be large changes in the structure and dynamics of ecosystems resulting from changes in the relative growth rates both within and among different structural components (e.g. herbs, shrubs and trees). For example, increased CO_2 may increase pasture growth and ground cover in southeast Queensland cattle grazing systems (Howden *et al*. 1999a), with such changes affecting grassland ecosystem function, water use, carbon storage and nutrient cycling (Campbell *et al.* 1997). Changes in CO_2, temperature and rainfall are likely to affect the relative abundance of C_3 and C_4 plants leading to impacts on ecosystem production (Howden *et al*. 1999a; Conroy & Ghannoum 2006).

Changes in structure and ecosystem type are expected across the climate spectrum in Australia. In the rangelands, increased CO_2 is expected to improve pasture productivity, however it also favours trees and shrubs more than grasses, leading to more and thicker woody plants ("vegetation thickening"), leading to conversion of grassland to woodland or shrubland, and decreases in pastoral productivity (Pickup 1998; Gifford & Howden 2001). Expansions of rainforest into eucalypt forest and grassland have been observed in Queensland and New South Wales; many possible causes including changed land use, fire regimes, recent CO_2 and climate change, and even continuing response warming after the last glacial maximum (Hughes 2003). Large changes in rainforest-woodland ecotones have been predicted with small changes in climate (e.g. 1°C warming) in north Queensland (Hilbert *et al*. 2001).

It is possible that many coral reefs, particularly shallow reefs, will switch from coral to algal domination because of the inability of corals to regenerate after bleaching episodes (Hoegh-Guldberg 1999).

Alpine areas in Australia are likely to see significant ecosystem impacts from cumulative species-level changes. For example: changes in herb, shrub and tree competition will lead to structural and functional changes (e.g. changed tree lines, microclimate, hydrology); and changes in the composition and ecology of grazers (e.g. expansion of mammalian grazers to areas previously dominated by insect grazers) may have very significant impacts on the composition and structure of vegetation (Hughes 2003; Pickering *et al*. 2004).

Top-down: Ecosystems affecting species

The Australian Alps will also experience changes in ecosystem-level driving processes. For example: changes in snow cover and duration will affect snow-bank ecosystems; changes in hydrology will affect the distribution and persistence of fens and bogs and the species that depend on them; and changes in fire frequency will affect vegetation composition and structure and soil processes (Hughes 2003; Pickering *et al*. 2004).

Many ephemeral wetland ecosystems in arid and northern tropical areas of Australia are strongly influenced by tropical rainfall events, thus climate change could affect the distribution and functioning of such systems. Decreases in rainfall could have significant impacts on waterbirds and other species, including reducing breeding opportunities (Roshier *et al*. 2001; Kingsford & Norman 2002). On the other hand, a 10% increase in annual rainfall in the catchment of Lake Eyre could transform it from an ephemeral to a permanent wetland ecosystem, leading to increases in survival and abundance of some species, and dramatically altering migration patterns (Roshier *et al*. 2001). In northern Australia, sea-level rise could transform freshwater wetlands to saline mudflat ecosystems with major impacts on waterbird communities (Kingsford & Norman 2002). In semi-arid rangeland areas of Australia spatial and temporal patterns of runoff are determinants of ecosystem function and vegetation patterns. In these systems, the combination of land use change and shifts in rainfall distributions could lead to increased flooding and erosion due to changes in runoff regimes, which could affect runoff redistribution and erosion cell mosaics, resulting in changes in vegetation composition, patterning and structure (Pickup 1998).

Kirschbaum (1999) modelled forest responses to warming and elevated CO_2 and predicted increases in growth of 25 to 50% in southern Australia and decreases of up to 50% in northern and some inland regions. The magnitudes of the responses were dependent on temperature, and the directions of the responses were very sensitive to changes in rainfall. The same model predicted that net primary productivity of Australian forests would decline by ~6% for a scenario of doubled CO_2, +3°C and -20% rainfall. Net primary productivity was predicted to increase ~21% under the same scenario if rainfall increased by 20% (Lucas & Kirschbaum 1999).

Historical and contemporary richness of bird species across Australia is related to actual evapotranspiration (a measure of water-energy balance) through plant production and vegetation structure (Hawkins *et al*. 2005). Dry areas support fewer species and species from more highly derived families, whereas wet areas support more species of both basal and derived families (Hawkins *et al.* 2005). Therefore, it is likely that bird community composition and structure will be strongly affected by changes in vegetation production.

Many historical changes in Australia's vegetation can be attributed to changes in fire regimes (Mummery & Hardy 1994; Kershaw *et al.* 2002; Hughes 2003). A significant driver of future ecosystem change will be changes fire regime (season, frequency and intensity) resulting from increased temperatures, altered precipitation, lower humidity and changes in fuel loads (Howden *et al*. 1999c, Hughes 2003, Lindesay 2003). Westerling *et al.* (2006) found a strong association between variation in climate and wildfire activity in western USA. Whether fuel loads increase or decrease will be affected by seasonal change in growth, and the balance between understorey and canopy growth, which will be affected by many interacting factors including CO_2, temperature, rainfall (seasonality, amount and variation), and grazers. Changes to fire regimes can dramatically shape ecosystems, affecting composition, structure and function of the vegetation, and these changes also affect faunal assemblages. One interaction of note is the impact that increased fire frequency and intensity might have on the age structure of stands of forest trees (younger even-aged stands replacing many mixed stands) and the formation of tree hollows usually associated with very old trees (Mackey *et al.* 2002). Increases in fire frequency and intensity in many regions are likely to drive changes in ecosystem types from rainforest to forest to woodland to grassland systems.

Feedbacks on the Earth System and interacting drivers

Global impacts

Ecosystems are a fundamental part of the Earth System that includes the dynamics and chemistry of the atmosphere, soils and the oceans (Betts & Shugart 2005). During the last 450,000 years at least this system appears to have oscillated within relatively tight bounds of temperature and CO_2 with associated biotic changes. The oscillations were driven by changes in the Earth's movement around the Sun (Solomon *et al.* 2007), but the response and bounds were determined by the dynamics and feedbacks of the Earth System. Human-induced global changes, including emissions of GHG are now pushing the Earth System outside this tight envelope.

Many positive and negative feedbacks in the Earth System have been observed and hypothesised; for example, enhanced uptake of CO_2 by terrestrial plants, emission of methane from drying peat lands, changed fire regimes, altered aerosol initiation, altered albedo from changed land cover (including melting of icecaps) (Steffen *et al*. 2004; Betts & Shugart 2005). Impacts on the global economy and human population could also provide feedbacks: climate-induced interruptions to global trade could lead to increased use of "dirty" energy technologies enhancing GHG emissions, and disruptions to economies and populations could reduce energy consumption and emissions. It is largely unknown how the system will respond, and many authors have cautioned about the possibility of abrupt changes in the Earth System (e.g. Steffen *et al*. 2004; Betts & Shugart 2005).

Local impacts

Changes in different ecosystem processes might drive ecosystems in different directions. For example, elevated CO_2 driving vegetation thickening, increased fire favouring more open vegetation, and establishment of agricultural "seasonally green … annual and ephemeral herbaceous plants" (Berry & Roderick 2002; Hughes 2003). Thus, final ecosystem- and species-level outcomes will be the result of many and complex interactions.

In Australia, climate variability often interacts with other pressures on species leading to ecosystem-level impacts. In the arid and semi-arid rangelands, rainfall events can have long-lasting impacts on vegetation composition and structure, especially when combined with grazing and fire (e.g. Westoby *et al.* 1989). Periods of low rainfall combined with grazing can lead to degradation of soil and vegetation that may persist for many decades. Periods of unseasonably high rainfall can lead to some recovery of degraded lands and increases in herb growth, but generally growth is increased to a greater extent in non-degraded areas (Pickup 1998). Wet periods in combination with grazing will favour woody trees and shrubs leading to long-term reductions of herbage cover and pastoral productivity.

The dynamic between climate variability, grazing and the relative abundance of herbaceous and woody species also has impacts on the productivity of those systems for native wildlife. Historically, many native birds and mammals probably survived during dry periods in climate refuges, however over the last 200 years they would have been particularly vulnerable to feral predators occupying these areas (Morton 1990). But decreased productivity due to degradation would also make these refuges more critical for survival. The rangelands have a disproportionately high proportion of Australian threatened and extinct wildlife: 61% of mammal extinctions, 83% of threatened mammals and 59% of threatened birds (Pickup 1998). Thus climate, ecosystem processes (grazing and productivity) and population-regulating effects of feral predators interact to have a transformative impact on native wildlife.

It is also not clear the extent to which changes in ecosystem structure and function (e.g. in accord with modelled ecosystem distributions) due to changes in growth and abundance of current species might occur ahead of changes in composition due to shifting species distributions. For example, while there are current strong associations between species and ecosystem types, are such associations always fixed? Can increased aridity drive a transition from forest to woodland through changes in relative abundance or does the transition *require* colonisation by “typical woodland plant species”? Would a woodland without such species provide suitable habitat for “woodland fauna”?

3.3.6 Impacts on ecosystem services and biodiversity values

Ecosystems and biodiversity have significant cultural, intellectual, aesthetic and spiritual values that are important to the human society as well as providing more tangible ecosystem services critical to the productivity of economies and the maintenance of human societies (Daily 1997; Chapin *et al*. 2000; Abel *et al.* 2003; MEA 2003). These values can also include the belief that biodiversity has a right to exist “for its own sake”, and that damage to or loss of biodiversity as a result of human activities has an intrinsic dis-benefit or cost. All of these benefits and values contribute to human wellbeing in the short- and long-term; they underpin the sustainability of human existence.

Changes to species and ecosystems due to climate change will affect many of these benefits. In addition, the benefits received by society will to some extent be affected by changing societal values and expectations. These benefits to society give rise to the reason we care about conserving biodiversity and the impact that climate change may have on biodiversity.

These benefits are often described as ecosystem services and classified into four categories, each of which will be affected by climate change.

- *Provisioning services* are the products obtained from ecosystems, including genetic resources, food and fibre, and fresh water.
- *Regulating services* are the benefits obtained from the regulation of ecosystem processes, including regulation of climate, water purification, pollination and pest control of crops and pastures, and regulation of human diseases.

- *Cultural services* are the non-material benefits people obtain from ecosystems through cultural practices, spiritual enrichment, beliefs, recreation, aesthetic experience and knowledge. These benefits have cultural, moral and aesthetic dimensions, and they underpin the ethics of "caring for country" or providing "stewardship of the planet for future generations".
- *Supporting services* that maintain natural ecosystems and provide the conditions to sustain life on Earth. They include: biomass production, production of atmospheric oxygen, cycling and storage or carbon; soil formation and retention, nutrient cycling, water cycling, provisioning of habitat, and species interactions (pollination, population regulation).

There are few studies considering the effects of climate change on ecosystem services. Schröter *et al.* (2005) reported large changes in ecosystem service in Europe from various land use and climate change scenarios; some of the changes were positive (e.g. increased forest area and productivity) and others negative (declining soil fertility and water availability). Many individual impacts are possible including impacts on human health through periods of thermal stress, air pollution impacts, impacts of storms and floods and infectious diseases (IPCC 2001). Positive and negative impacts on productivity of cropping, grazing and forestry are expected (Kirschbaum 1999; Reyenga *et al.* 2001; Howden *et al.* 2003; Pittock 2003; Steffen and Canadell 2005); these activities will also be affected by changes in plant diseases (Chakraborty *et al*. 2000). Recent impacts of drought and cyclone damage in Australia demonstrate the sensitivity of agriculture and the economy to climate. Bleaching threatens the survival of corals on the Great Barrier Reef which is a major Australian natural icon and an important asset to the tourism industry and regional economies.

In following sections (especially Sections 4 and 8) we discuss the implication of changing biodiversity for conservation. Extinction of some, maybe many, species is very likely; this presents a direct challenge to the aspirations of preserving biodiversity for its own sake, for the enjoyment of ourselves and future generations, and for economic benefits. Many other changes to species and ecosystems will also occur with various degrees of impact on society.

3.3.7 Key points

There are many different types of impacts on biodiversity and there is considerable variation in those impacts among species and ecosystems. Species interactions will be critical in determining net outcomes from climate change. Over time the susceptibilities and competitive abilities of species will change and species will encounter new species, thus interactions between species will change considerably from those that have been experienced and observed during the recent past, making accurate predicting of changes very difficult.

The impacts on species and ecosystems will be non-linear. There will be some delayed impacts, many positive and negative feedbacks and new interactions, all of which will alter the nature of changes over time. The changes that occur in several decades may be quite different from those beginning to be observed now.

There are some clear general trends (e.g. in distribution shifts and phenological changes), but there is considerable variation in these changes and they do not adequately characterise many of the impacts that have been observed and predicted.

Many impacts and changes will affect abundance of species and the composition, structure and function of ecosystems. These ecological changes will be complicated and very hard to predict, but they will happen.

The details of changes are important in trying to understand complicated change processes and in making predictions, and they are critical at local scales. As examples, they also reveal that biodiversity is very sensitive to climate change: significant changes are already beginning to happen.

However, the details are very variable (between situations), partial (a huge amount is not known) and biased (a lot more is known about a few impacts). As a result, the details are potentially a distraction from the task of developing strategic responses to climate change. For that reason we present below (Section 4) a synthesis focussing on types of biodiversity impacts and unknowns that might be important from the perspective of designing and managing conservation programs.

In Part C we focus more on conservation responses, outlining why the changes to biodiversity are a concern and discussing a series of specific issues for conservation management and the National Reserve System.

4. SYNTHESIS OF IMPACTS: SO WHAT'S GOING TO HAPPEN? WHAT DO WE NEED TO KNOW FOR CONSERVATION?

In this section we provide a description of possible changes that we believe are most relevant for biodiversity conservation, and we highlight some important unknowns that can be investigated at regional and continental scales, through a combination of observation and modelling, to better inform conservation management. Central to this synthesis we describe three different models of biodiversity change, each potentially leading to different consequences for conservation management. We present the three models to reinforce the point that planners and managers (and researchers) need to consider different types of change, as opposed to having a singular mental model of the impending changes that may lead to constrained and possibly suboptimal management responses.

4.1 Change is certain …

There is abundant observational, experimental and modelling evidence that climate change is already affecting the environment, species and ecosystems in many ways, and that the impacts are going to get more severe as climate change continues. Some impacts are better known and more easily conceptualised than others, and some have obvious implications for biodiversity conservation while others do not. Environmental changes will lead *directly* to a cascade of impacts on individuals, populations and ecosystems. Many species will also be affected *indirectly* via their interactions with affected species and ecosystems, and via other feedbacks to the environment. Summarising the cascade of impacts (Figure 3.1):

- **Impacts on the environment** There will be increases in CO_2 concentrations, minimum and maximum temperatures, sea levels and storm intensities; and decreases in snow-cover depths and durations. There will probably be an overall decrease in rainfall but some regions in some seasons will get wetter, and rainfall events are expected to be more intense and more variable. Similarly, frost occurrence is likely to generally decrease but in some situations the impact of frosts may increase due to changes in their timing. In many regions fires will become more frequent and more intense, and will probably change in season and extent; although changes in fire regime will also depend on litter production, which may reduce in some areas where water stress increases and primary production decreases.
- **Impacts on individual biology** The physiology and phenology of individuals of many species will change. Faster seasonal growth is expected for many plants and animals, and the timing of some spring lifecycle events in many species is expected to be earlier, and some autumn events delayed. Many plants will use water more efficiently. The chemical composition and growth structure of many, if not all, plants will change, with increased C:N ratios (and changes in many amino acids, toxic compounds and soluble carbohydrates) and changes in allocation to roots, stems and leaves. Some individuals will die earlier (or live longer) due to changes in temperature, water availability, fire and other disturbances. However, the changes will vary considerably between regions (depending on combinations of nutrient availability, seasonal temperature and moisture and CO_2), between species, and over time as the climate and environment continue to change.
- **Impacts on individual ecology** These changes will affect the way species interact with their environment and with other species, altering many competitive, facilitative and trophic relationships. Altered disturbance regimes may prevent or enable species to establish and develop effective persistence mechanisms (e.g. seed banks) between disturbances. These impacts will affect the survival, growth and reproduction of individuals of many species.

Again, the nature of the changes will vary enormously across taxonomic and functional groups and individual species, and between regions.

- **Impacts on populations** Changes in reproduction and survival will directly affect the abundance of species; and differential impacts may lead to genetic changes in populations (e.g. increased tolerance to temperature, changed host specificity, increased dispersal ability). Changes at the edges of a species' distribution may lead to expansions, contractions or shifts in its distribution; successful long-distance dispersal and establishment may lead to rapid changes in a species' distribution; and similarly, rapid increases in small, outlying populations of a species may also result in rapid distribution expansions. Conversely, some distributions will expand slowly or not at all due to dispersal and soil constraints even if climatic conditions become favourable for them beyond their current distributions. Species' abundances will change, possibly increasing in some regions and decreasing in others. Changes in disturbance regimes may also lead to changes in the age structure of populations, for example toward more even age stands if fire intensity increases.
- **Impacts on ecosystems** Changes in the distributions of different species will lead to changes in assemblages and the composition of ecosystems. Composition changes combined with changes in relative abundance and age structure will lead to changes in both the physical and functional structure of ecosystems. This in turn will lead to changes in ecosystem processes and functioning, including changes in carbon, nutrient and water cycling.
- **Impacts on society** All of these changes will have many impacts on society. There are likely to be changes in many ecosystem services (e.g. water cycling, pollination, pest control, food and forage provision). But there will also be aesthetic, cultural and other less tangible impacts. Indeed these impacts will alter the *feel* of ecosystems: the look, sound and smell of places we are familiar with will change as the composition and abundance of plants, animal, fungi and other micro-organisms change. For many people such characteristics of specific ecosystems contribute to a sense of place and directly "feed the soul"—this life-enriching process will be affected.

Many feedbacks are to be expected; indeed these may be more significant than the direct flow of impacts. For example, herbivory, predation, and parasitism have major impacts on many if not most species and directly constrain the abundance and distribution of many species; similarly, competitive and facilitative interactions are often important. Changes in these processes could affect many species. Similarly, changes at the ecosystem level will in turn feed back to affect individuals of many species through altered habitat and by affecting flammability, water availability, nutrient availability, CO_2 concentrations, and other environmental parameters. Some species have very strong ecological impacts on many other species through their provision of habitat, regulation of populations or control of critical ecosystem processes; changes to such species, including the arrival of new species with these characteristics, could have a rapid transforming impact on many ecosystems.

Finally, current and imminent changes in species populations and ecosystems could induce changes in society that feed back to biodiversity, for example, enhanced conservation management and reduced emission of greenhouse gasses. Increased understanding of the impacts of climate change on biodiversity may also feedback on societal expectations about biodiversity and its conservation.

4.2 …but there are many unknowns about the details

While there is plenty of evidence that enables us to catalogue the types of biodiversity impacts that might occur, there is significant uncertainty about which impacts might dominate, for which species and ecosystems, at what rate, and so on. Evidence suggests many of the impacts are highly species specific and contingent on other environmental or biotic factors. Furthermore, our knowledge is very patchy, and we tend to know less about impacts further down the cascade which are more important for society. Even within a level of the cascade we know much more about some types of impacts than others.

CO_2 impacts

An increase in atmospheric CO_2 concentration is the most certain environmental change; and impacts on plant physiology due to increased CO_2 concentration is the most certain class of the biological impacts and probably the one whose biological mechanisms are best understood. Significant impacts on herbivores and detritivores have been documented, however in general such impacts are less well understood, but probably just as certain to occur. These impacts of CO_2 changes are often overlooked in impact assessments, possibly because there is no simple, unidirectional generalised prediction with a clear conservation implication, nor a single obvious management response.

Phenology changes

The most widely observed class of impacts on biodiversity is probably changes in the timing of lifecycle events, and in particular the advancement in spring events due to increased warming. The environmental triggers for changes in some species are reasonably well understood and general predictions can be made about the changes: spring events will be earlier, lifecycles will be faster, autumn events later. However, in some species the proximal trigger for lifecycle events is day length; responses in these species would require evolution of the trigger mechanism, which has been observed in a few species but is far less well understood. Similarly, timing of events in some species is related to water availability (e.g. rainfall, storm activity or humidity).

Changes in timing of events that result in the miscuing of species interactions (e.g. arrival of a migrant before emergence of a seasonal food source) could lead to significant negative (and positive) impacts, although it will be hard to predict when such miscuing will arise, especially given the largely unknown potential for evolution or phenotypic plasticity of timing mechanisms.

Again, these impacts are frequently mentioned but not considered in assessments of the conservation implications of climate change.

Distribution shifts

The simplest class of impact to conceptualise is the shifting of species distributions along decreasing temperature gradients. Changes in species distributions have been very widely observed, and are the class of impact that has had the most attention from modellers and in assessments of the implications for conservation.

The majority of observed distribution changes are of expansions of “cool” boundaries towards the poles or uphill, and one manifestation of these changes is observations of increased diversity in some ecosystems. There have been far fewer observations of contractions of “warm” boundaries, but this is not surprising as absences (implying distribution contractions) are harder to detect with confidence than presences. It is also likely that in many species distribution contractions may lag behind any adverse climatic or biotic changes as the process of population decline and local extinction could take several generations, amounting to many centuries in some species. Indeed, some plant species may still be responding to climatic changes at the end of the last glacial period. Conversely, distribution contractions could occur much faster than expansions, especially in short-lived eruptive species (like butterflies) or when environmental changes are lethal to adults (e.g. severe coral bleaching, frequent high-intensity fires).

In most cases the ecological reasons for observed distribution changes are not known; as indeed the ecological processes limiting the distributions of most species are unknown. Most models of distribution changes are based on extrapolations from observed correlations of species' distributions and climatic parameters. By necessity (due to lack of knowledge) the relevant ecological processes are largely or totally absent in such models, modelled boundary changes are typically not limited by population processes, and spatial scales are too coarse to reveal the presence of suitable microhabitats and scattered refuges that may allow populations to persist in low densities.

Such models often predict significant shifts and reductions in distributions, and even extinctions, with climate changes of a few degrees. Distribution changes and their conservation implications are very easy to conceptualise, and straightforward conservation implications can be drawn, especially when apparently inevitable distribution changes are confronted with barriers (e.g. tops of mountains, deserts, coasts, different soils, agricultural zones and urban areas). However, as appealing as the concept may be, predictions from these models are based on many contested assumptions and it is unclear to what extent they actually reveal how likely potentially important distribution changes might be. There is also considerable uncertainty about the rates at which distributions might change and the consequence of them changing or not changing.

Abundance changes

Changes in abundance of species, in particular the relative abundance of different species in ecosystems, are among the least observed and least modelled of impacts. Abundance changes are more difficult to detect than distribution changes; and the processes behind abundance changes are less easy to conceptualise and model than simple climatic and environmental restrictions on distributions. In addition, simple conservation and management implications are not immediately apparent. However, it is extremely likely that changes in abundance will occur for most species either directly flowing from climate changes or indirectly via interaction with other species. In many ecosystems, abundance changes are likely to happen before significant distribution changes occur and are likely to be at least as important.

Predicting and diagnosing changes

One of the future challenges for research is to determine at what scales, and across which dimensions (e.g. spatial, temporal, taxonomic, functional), impacts might be more predictable. The most comprehensive analyses of observed changes (in timing and distributions) confirm that when changes occur they are most likely to be in the predicted directions (roughly 80% of the time; Parmesan & Yohe 2003; Root *et al*. 2003), but they give no indication of what proportion of all species have experienced change.

There are a number of factors that are known to be very important in affecting species abundance and distribution, especially those of species entering new environments, about which little is currently known in the context of climate change. They include: the ability of species to disperse including the importance of long-distance dispersal rather than creeping distributions; impacts on fecundity especially of new arrivals; rates of adaptation to new environmental conditions; the impact of changing and new species interactions; and the role of habitat heterogeneity in species persistence.

While ecosystem responses are clearly the result of the combination of responses of many species that are essentially responding in individual ways, it may be that some ecosystem changes can be more reliably predicted than changes in the constituent species. For example, changes in ecosystem primary productivity as opposed to individual species growth responses, and vegetation structure as opposed to species abundance. Likewise, predictions about the responses of functional groups might be more reliable. However, in most cases and especially at the local and shorter-time scales, the question would remain as to whether or not individual species are actually present to fulfil the predicted functional roles.

4.3 Three alternative mental models

The patchy state of knowledge about the impacts of climate change on biodiversity makes it difficult for conservation planners and researchers to consider the full range of likely impacts when assessing conservation implications. People run the risk developing one simple mental model of what changes will occur based on a single type of impact, and using that implicitly to drive expectations and proposed management actions. Below we explicitly describe three alternative mental models of change representing different key ways to conceptualise the impacts on biodiversity for assessing the implications for conservation. The models respectively emphasise:

I. *in situ* changes in relative abundance by most species,

II. rapid or long-distance distribution expansion by a few species, and

III. gradual distribution changes by many species.

The different mental models can be used to help design monitoring and research: "Which of these change processes is occurring?" And the models can be used to help in planning over a time horizon where change is uncertain: "If each of these changes occurred what actions would be most successful?", or "How would our conservation program fare under each of these changes?" This approach is similar to the scenario planning process that underpins the IPCC emissions scenarios and that has become an important part of strategic planning globally (e.g. Schwartz 1996; Almaco 2001).

One way to think of the models is as descriptions of the main changes that you would notice if you were to jump forward in time 50 or 100 years: "What happened and why?"

The models are described primarily in terms of changes in abundance and distribution, as these are the primary biological parameters that managers are likely to respond to. Mechanisms by which climate change could lead to these changes are given, but the changes could actually result from many other pressures or combinations of them. Many environmental changes will result in one (or a combination) of these types of changes. Therefore, these models could form a robust basis for biodiversity conservation planning in the face of changing and uncertain pressures, quite independently of climate change.

I. Relative abundance change model

- The abundance of most if not all species is affected by the combination of many impacts, including responses to elevated CO_2, altered fire, flood, drought and storm regimes, and altered species interactions.
- These lead to widespread changes in abundance, in particular relative abundance of different species within ecosystems and regions. **The main consequence is *in situ* changes in ecosystem structure and function, with minimal changes in composition at regional scales.** There are many flow-on impacts to other species, ecosystem structure and function changes, making ecosystems "feel" different despite minimal change in composition, and there are changes in ecosystem services.
- Dramatic and rapid changes are possible, e.g. replacement of corals with algae as dominant species on reefs, expansion of vines in rainforests experiencing more frequent storm damage, and restriction of fire-sensitive species to fire refuges.

- One important feature may be rapid increases in abundance and “in-filling” of species that are hitherto in low density or scattered micro-sites; these could include native species and many exotic species in “sleeper populations” in gardens, parks and roadsides.
- Declining species become sparser, are confined to restricted microhabitats or become locally extinct. Habitat heterogeneity and local fire and drought refuges may be particularly important in maintaining declining species.
- In general, abundance changes and losses of species and ecosystems services will be hard to predict. Some predictive models do address changes in relative growth or abundance, but outcomes will be the result of many interacting factors and will be hard to predict accurately.
- This model has some similarities to the dynamics that might be seen in environments dominated by regular disturbances where, from disturbance-to-disturbance and site-to-site, relative abundances may vary markedly but most species persist somewhere. The main difference being that in this model the changes are more likely to be directional and continuous than periodic.

II. Long-distance or rapid distribution change model

- Altered environmental conditions lead to improved establishment opportunity for some species beyond their current distributions. Possible mechanisms include response to fire (fire pioneers); CO_2 (increased competitive ability); reduced frost and snow (released constraints); warmer, wetter or drier conditions affecting growth and competition; increased dispersal in storms and floods.
- Rapid distribution expansions occur, but only for relatively few species. Change results from rapid creeping expansion or by long-distance dispersal followed by local population expansion.
- Most colonising species are likely to be relatively benign ecologically (i.e. they have minimal impact on other species or the ecosystem as a whole, as is the case with most introduced exotic species; Williamson 1996; Levine *et al.* 2003). However, a few colonising species will have a major impact on other species and potentially transform ecosystem structure and function. **The main consequence of the model is increased species richness with little ecosystem change; but in some situations a few new species will lead to significant impacts on ecological processes leading to impacts on composition, structure and function.**
- It will be very hard to predict which species will experience rapid distribution expansions, and which of those might have large impacts on other species and ecosystem function. Similarly it will be hard to predict the nature and extent of loss of species and ecosystems services.
- This model has similarities with the dynamics of establishment and spread of introduced and invasive species. The main difference is that many of the new species will be native. This may affect their ability to hybridise with resident species, to adapt to local conditions and to resist (or not) local pests and diseases, factors that are important determinants of exotic species establishment.

III. Gradual distribution shift model:

- Changing climate leads to gradual shifts in the bioclimatic habitats of most species. Warming patterns dominate the direction of shifts, but changes in rainfall, seasonal variation and responses to CO_2 are also important. The ecological determinants of distributions vary among species, as do dispersal abilities, species interactions and responses to disturbance and landscape heterogeneity.

- **The main consequence is that the distributions of most species gradually expand, generally down thermal gradients, with ecosystem distributions following those of dominant species.**
- Species responses vary: the direction and rate of species expansions vary, as does the rate and extent of contraction of the “trailing” edge of their distributions. Some species distributions get bigger, others contract, some disappear, some don’t change. The rates of change also vary over time. Therefore, ecosystem composition, structure and function also gradually change as they shift, with novel ecosystems types forming and some current ones disappearing.
- This type of change has been the most frequently analysed and has been represented in many predictive (computer) models. They generally lead directly to clear predictions of many distribution changes with frequent range reductions and extinctions. Changes conforming to this type of change have also been observed in many ecosystems in many regions around the world.
- Such distribution shifts will be a component of changes that occur. However, most of the expected impacts on species do not lead to simple directional predictions about distribution shifts, and it is not clear how general and dominant gradual distributions shifts will be.
- This is also the most prevalent mental model among those interested in the impacts of climate change on biodiversity. It is intuitively appealing; and simple, directional predictions can easily be made. It has dominated many assessments of the impacts of climate change on biodiversity and protected areas; although this is possibly due more to its intuitive appeal, ease of numerical implementation and simple predictions, rather than a result of any assessment of its likely relative importance and the accuracy of the predictions.

4.4 What can we predict about these changes?

Which changes are more likely?

Changes to species and ecosystems represented by each of the three mental models have been observed in palaeo-records and contemporary situations. The three models may not be equally likely, however we suggest the strong bias in the literature and consciousness of interested parties toward the third model does not reflect relative likelihood or importance. *We suggest that all three mental models should be regarded as equally important for the purposes designing monitoring programs, interpreting observed changes, anticipating future changes, assessing conservation implications and considering management options.*

The mental models are presented as alternatives to highlight that there is no one best way to frame the likely impacts on biodiversity, and that each type of change should be given equal consideration. However, the models are not mutually exclusive; all impacts will happen, the question is: Which will dominate and at what scale? In many situations the changes might be expected to occur roughly in the order they are presented above.

Modelling may be able to suggest situations where one or other of the types of changes may dominate, however careful observation will be needed to distinguish what is actually occurring. Indeed part of the purpose of presenting the three models is to provide some context for managers to assess new observations and information and to help them formulate hypotheses about changes in particular regions or ecosystems.

How will distributions and abundances change?

Many climate impacts could lead to abundance and distribution changes: e.g. removal or imposition of a constraint (high or low temperature, moisture availability), disturbance regimes, competition and other interactions among species, etc. Any of these impacts could lead to different models of change in abundance and/or distribution.

How will populations decline? Will a steady decline in favourability of climate lead to a gradual decline in abundance and eventual local extinction (a linear relationship); a rapid decline in abundance beyond some point (a threshold); or a continuing restriction to fewer micro-sites but with minimal actual extinction (a logistic or power law relationship)? It is natural to fear that a decline in a population indicates impending extinction (it is a necessary condition for extinction), however there are numerous examples of populations "crashing" but surviving in low density or in refuges (sometimes undetected for many years, and recovering with removal of a key threat), and in Australia the vast majority of species do survive in very low abundances or with widely scattered populations.

How will distributions expand? Will distributions of species expand gradually from the edge of current distributions; via rare long-distance dispersal events to a few sites combined with local expansion and in-filling; or from expansion of existing outlying populations that might be unknown or overlooked?

From a site or ecosystem perspective this same question can be expressed as: Where are the species currently that will dominate ecosystems in the future? Are they present in the current ecosystem (possibly in the tail of the species distribution); in separate, distant ecosystems (in currently warmer regions or elsewhere); or in isolated micro-sites or refuges in or near the current ecosystem (e.g. in gardens, paddocks or roadsides)?

Will changes in abundance and distribution occur slowly, resulting from gradual changes in establishment, growth and reproduction leading to small, incremental changes in composition and abundance following establishment events (i.e. a strong inertia in composition)? Or will they be dominated by infrequent, extreme events that are beyond thresholds for key species or that provide atypical establishment conditions (Parmesan *et al.* 2000)? Widespread but rare drought and flood events have been implicated in significant step-changes in the distributions of many species including exotic plants and native birds; and many species that survive fires through seedbanks are very susceptible to fires that are too frequent.

Will abundance and distribution changes occur in synchrony with changes in climate? Or, will population dynamic processes lead to delays in expansions and contractions? If favourable conditions for species do shift, then the relative rates of distribution expansion and contraction will be absolutely critical for determining the eventual fate of the species: if contraction is faster than expansion then the species will eventually become extinct, if expansion is faster than contraction it will expand in range. Due to practical issues, distribution expansions will always be more readily observed than contractions. But, are distributions and population expansions, in general, actually more likely to be faster than population declines and distribution contractions? The rates of change will be affected by both the functional relationships with climate at each end of a distribution and the population dynamics of expansion and decline. The limiting climatic parameters (if indeed there are any) are likely to differ between boundaries (e.g. frost in the south and winter rainfall in the north), and many climate parameters will not change or shift in synchrony; hence predictions for some species of range expansions and others of range contractions. Similarly, population processes of decline and expansion may be very different. For many annual species the dynamics may be similar, e.g. largely dependent on establishment conditions. But for longer-lived species, an "extinction debt" may arise if declines take at least as long as adult lifespans and possibly take several generations if there is some successful recruitment but not full replacement. Some changes could lead to rapid declines; e.g. those that result in increased mortality of adults, or a succession of fires that prevent build up of seedbanks. Distribution expansions will be limited by dispersal ability, which varies considerably among species. Many factors other than climate will also influence whether or not populations and distributions decline or expand, including local adaptation, the dynamics of other species and landscape factors (diversity of habitats, habitat barriers, mountain tops, availability or more suitable habitat, etc). Hence rates of change will be crucial factors in determining population outcomes but they are likely to remain very uncertain. The different ecological process leading to expansion and contraction (possibly at different ends of species distributions) are worth considering in impact assessments.

Analyses of the impact of climate change on biodiversity frequently project outcomes at a fixed time in the future, or for a fixed climate change (e.g. double CO_2). It is important to realise that changes will be ongoing probably for many decades. Hence, the rate at which changes occur, not just the magnitude of the change, is critical. The ability of species to evolve and respond behaviourally will also depend critically on the rates of change of the environment, species and ecosystems they are interacting with. From a societal perspective, environmental changes that occur slowly relative to a human lifespan (or career) may not be regarded as undesirable, while impacts that change what we are familiar with could be judged undesirable.

Indirect vs. direct impacts?

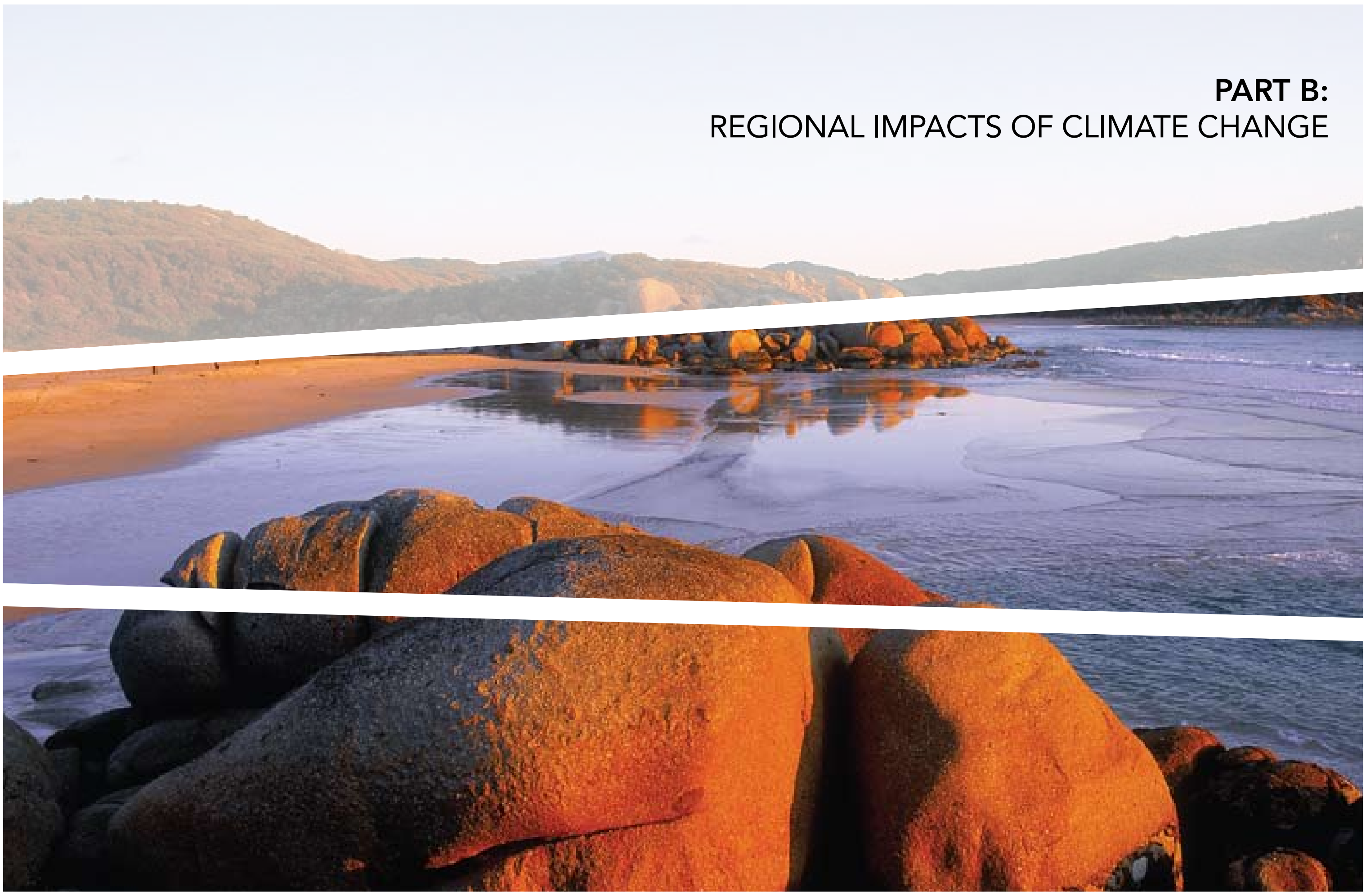
All species are likely to be affected by direct impacts (flowing directly from environmental changes affecting their biology and ecology) and by indirect impacts due to interactions with other species; and both types of impact can contribute to each of the three mental models of change. Direct impacts are likely to be much easier to conceptualise and predict, however indirect impacts may be just as important in determining outcomes. Indirect impacts can lead to correlations between a species distribution and climate if the species distribution is influenced by interactions with (e.g. competitive exclusion) a second species whose distribution is directly determined by climate. It is not clear whether direct or indirect impacts will dominate the eventual outcomes for most species. However, it is likely that some very significant changes will occur as a result of indirect impacts, if for example a newly established species has a dominant impact on an ecological process (e.g. new herbivore, highly flammable grass, new predator, or new disease vector). Understanding the role of indirect impacts will be important for predicting outcomes and interpreting observations of species and ecosystem change.

A particular special case of indirect impact will arise via societal adaptation to climate change. Agricultural and forestry land use changes, attempts to reduce the risk from increased fire frequencies and sea level rise, responses to more frequent floods and intense storms risk, securing water supplies, and translocations and other actions to protect particularly vulnerable species may all have impacts on biodiversity that may be greater than the direct impacts of climate change.

4.5 Change in some fundamentals

While the details of the many possible impacts on biodiversity due to climate change are quite uncertain, it is clear that the changes are unlikely to be *marginal* changes. It is convenient in many analyses to consider the impact of a single factor with "all else being constant". As the climate continues to change we can expect many things that will affect outcomes to change at the same time. For example, CO_2 increases may increase water use efficiency but decreased rainfall and increased temperature would limit water availability; and growth of individual species will be affected but so will those with which they compete. The ways species and ecosystems respond to individual factors are likely to change; for example, responses to fire, the likelihood of weed establishment, and impacts of pest animals. Climate change may alter the response functions we may be familiar with. Current knowledge about the priority of different threats and how to manage particular issues, whether scientifically based or implicit (learnt), will progressively become less applicable. Similarly benchmarks for species and ecosystem outcomes may need to be revised: the concept of "pre-European condition" may become unsuitable. In addition, biodiversity will be constantly changing; it will be increasingly less feasible to regard species as static and in equilibrium with other species and the environment, and to assume "all else is constant".

These changes in the fundamentals of biodiversity will also be an issue for research (including the suitability and parameterisation of many biodiversity models) and for conservation planning and management. Research and management will increasingly need to rely on both a good understanding of the types of impacts that *might* occur and observational data from many sites and ecosystems to understand what is *actually* happening.



PART B:
REGIONAL IMPACTS OF CLIMATE CHANGE

PART B – REGIONAL IMPACTS OF CLIMATE CHANGE

In this part of the report we present regional information about the impacts of climate change in two different forms. In Section 5 a subjective assessment of the impacts of climate change on biodiversity is presented for each of ten agro-climatic zones in Australia (Hobbs & McIntyre 2005). In Section 6 we summarise results from an analysis of various projected climate parameters for each of the 85 regions of the Interim Biogeographic Regionalisation of Australia (IBRA) based on several climate change scenarios and climate models.

The information in each of these analyses has relevance for planning at the national, regional and local scales. It can be use to assist setting goals, priority setting for development, designing monitoring programs, identifying future threats and management issues, and structuring further research and impact assessments. In addition, a logical next step for this work would be to use the two analyses together along with detailed bioregional-scale information about species and species functional types to do bioregional assessments of possible future changes and vulnerabilities. The broad agro-climatic information could provide indications of general drivers of change and possible responses, with the details being provided from bioregional-scale knowledge and information.

5. A PRELIMINARY ASSESSMENT OF IMPACTS ON BIODIVERSITY IN AGRO-CLIMATIC ZONES

With contributions from Sue McIntyre, CSIRO Sustainable Ecosystems

This assessment of the impacts of climate change on biodiversity uses a top-down approach, as opposed to the more usual bottom-up approach derived from species-level information. The aim was to trial an approach to regional assessment that could be conducted quickly and easily with a reasonable level of ecological knowledge. In the short term, this provides a more feasible alternative to impact analyses that are dependent on good data on species distributions and ecological knowledge about each species. It also addresses impacts that are not captured in typical bioclimatic envelope analyses.

The approach is ecosystem-process based. It essentially assesses how seasonal patterns of plant growth may change in different ways around Australia as the climate changes, and how these changes in growth (and some other factors) may drive or contribute to a range of other ecological changes to affect species and ecosystems. In particular the possible impacts on four key threats (Section 8.3) are considered. Regions experiencing a greater number or magnitude of ecological changes could be considered to be more vulnerable. Where species knowledge is known it could be combined with this approach, and we have included some region-specific species-level knowledge in part of the assessment.

5.1 Method

5.1.1 Data used

The assessment used the ten agro-climatic zones of Hobbs & McIntyre (2005) which were based on a spatial agro-climatic analysis of Australia by Hutchinson *et al.* (2005). Hutchinson *et al.* (2005) modelled plant growth responses using data from 822 weather stations across Australia, then classified them based on seasonal growth and moisture indices into 18 agro-climatic classes that were identified using and objective multivariate analysis. These were then used to classify each IBRA region (or subregion) into an agro-climatic class. Hobbs & McIntyre (2005) lumped these into ten agro-climatic zones (Figure 5.1) and describe key characteristics of seasonal plant growth in each zone, including whether it is temperature or moisture limited. Each zone has reasonably homogeneous patterns of seasonal growth and climatic determinants of that growth.

Information from the literature review (Section 3), expert input, likely changes in seasonal growth, and information on a number of other ecologically relevant attributes were then qualitatively assessed for each climatic zone. The other information used included coarse-scale mapped information about:

- current and projected seasonal temperature and rainfall (using CSIRO's 2007 projections, Suppiah *et al.* 2007),
- Australia's native vegetation (NLWRA 2001b),
- net primary productivity (Roxburgh *et al*. 2004),
- fire frequency and season (Graetz *et al.* 1995), and
- elevation (Australian Natural Resource Atlas, online).

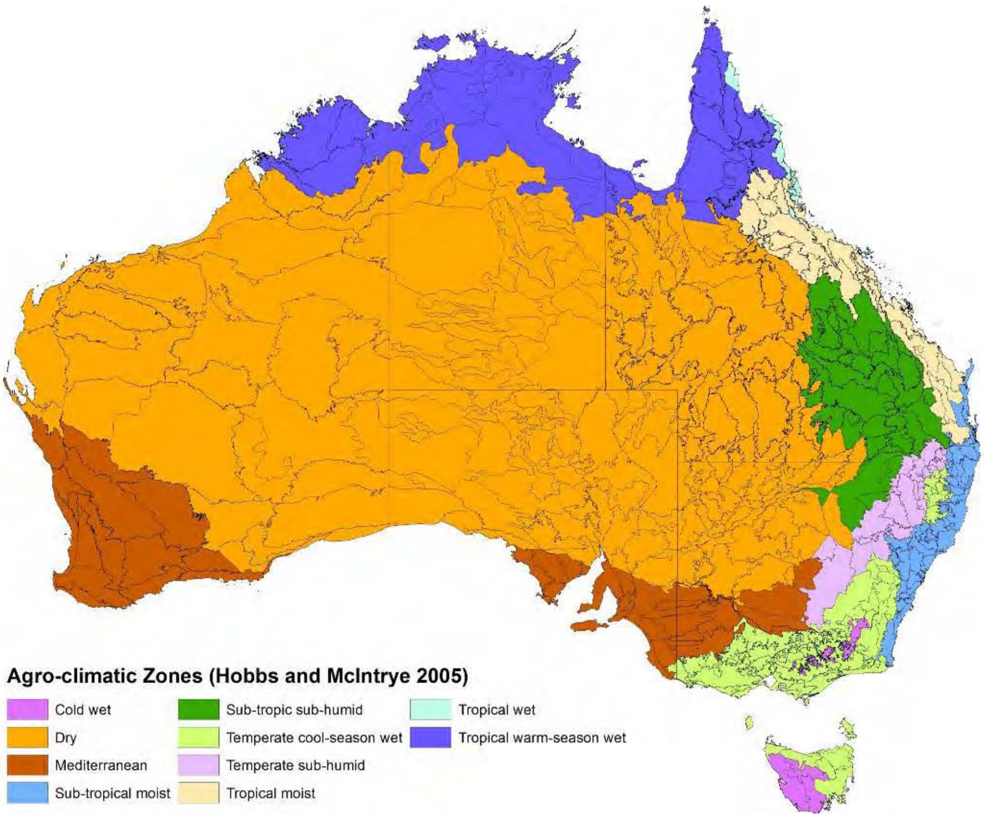


Figure 5.1. Ten agro-climatic zones described by Hobbs and McIntyre (2005).

5.1.2 Assessment procedure

There were three stages to the assessment: I – a description of potential environmental changes and how they generally affect biodiversity, II – a description of each agro-climatic zone, and III – an assessment of impacts in each zone.

I. **Descriptions of potential environmental changes and possible biodiversity responses** at a national scale, including the mechanisms by which changes might affect biodiversity. Information was summarised from the review in Section 3 and from expert input. This information is essentially the method of justification for the assessments made in stage III. It is included in Appendix 1, and is presented in terms of:
    - climate (temperature, rainfall, CO2, storms, sea level),
    - four threats to biodiversity (altered fire regimes, new species, land-use change, altered water resources; see Section 8 for discussion of these threats), and
    - possible responses of seasonal growth, vegetation structure and composition.

II. **Description of each zone** in terms of:
    - broad vegetation type, patterns of seasonal growth and the climatic influences on seasonal growth, where it is located, and
    - various landscape characteristics.

    This information is summaries in the first block of rows, labelled "current", in each of the ten tables in Appendix 2.

III. **An assessment for each zone of climate change impacts on biodiversity** in two parts. This information is included the second block of rows, labelled "future", in each of the ten tables in Appendix 2.
    1. *Descriptions of likely changes* in temperature, rainfall, storms and sea-level for each zone, including general ecological implications.

    2. *A subjective assessment of impacts* for each zone, focussing on:
        - four key threats that are likely to be compounded by climate change,
        - seasonal growth and implications for various functional types,
        - vegetation structure,
        - species composition,
        - other impacts, and
        - key priorities and issues synthesising the different impacts and considering interaction with other pressures on biodiversity.

    A *subjective assessment of vulnerability of biodiversity* in each zone can be made based on the key impacts in each zone. Zones potentially facing a greater number of severe impacts could be rated as more vulnerable.

    This assessment was based on ecosystem-level information with little consideration of species-specific vulnerabilities. Several zones have widely-reported broad species-specific vulnerabilities (e.g. due to narrow habitat or climatic sensitivities). Such information could be combined with the information presented here about potential ecosystem level changes. However, lack of such knowledge for other zones does not imply that particularly vulnerable species are not present.

An assessment of adaptive capacity could also be made based on the potential for management intervention to be able to reduce the impacts on biodiversity due to climate change and other pressures.

5.1.3 Constraints on the assessment

This assessment represents a first attempt at a rapid top-down, national-scale, regionally-disaggregated, ecosystem-process based approach to assessing the vulnerability of biodiversity to climate change in Australia. **It is a first cut and has had limited review. Before being used it should be reviewed and revised by experts familiar with climate change impacts and the functioning of the ecosystems in each zone.** Use of more and better knowledge of the landscapes and ecosystems in each zone would improve the assessment.

By necessity, any assessments of vulnerability made with the information presented here will be rough, partial and open to misinterpretation. As noted, the information summarised does not include species-specific vulnerabilities in each zone. The extensive literature on species impacts is unanimous that impacts vary considerably among species, hence actual changes and vulnerabilities will depend critically on species-specific factors. However, we are confident that vulnerability assessments that could be made with the information provided would be indicative of the more detailed assessments that could be made for broad zones, or individual bioregions.

Some feedbacks were considered in conducting the analysis, but in general many feedbacks that were not considered have the potential to drive considerable change or indeed to dampen change.

No attempt was made in this assessment to provide ranges of impacts or vulnerability. There are also considerable uncertainties about both future changes to the climate (due to uncertainties about GHG emissions and the climate system response) and the likely ecological responses to climate changes. Where two or more parameters affect the same ecological process in different ways outcomes could vary in direction as well as magnitude. For example, increased CO_2 and decreasing rainfall may have opposite impacts on growth; and increasing dryness may increase fire weather but decrease fuel availability.

The assessment was subjective; some of the processes considered would be amenable to quantification.

Many of these climatic changes are likely to continue for many centuries. The relevant question is then how fast the changes will occur, rather than what the eventual size of the changes will be. A key determinant of the actual impacts on biodiversity and vulnerabilities will be how quickly species can evolve and adapt, rather than whether or not they can cope with a given level of change.

5.2 Results and discussion

5.2.1 General

Significant differences between the zones were present in their seasonal growth and their likely growth responses to climate change. In some zones the main growing season will stay the same but there will be change in the amount of growth (more or less). In other zones there will probably be marked changes in the length or seasonality of the dominant period of growth; many ecological impacts were assessed as flowing from such changes. It is likely that the greater the number of such changes in a zone the greater the impact on biodiversity. The results of the analysis are summarised in Table 5.1 and Figure B in the Executive Summary.

The ‘Temperate cool-season wet’ and the ‘Temperate subhumid’ zones were identified as the zones most likely to experience significant ecosystem-level changes in biodiversity (see Fig. 5.1 for locations of the zones). Both zones currently have relatively limited growth in winter due to cool temperatures despite available moisture; hence warming could see significantly increased winter growth. Changes in growing season in these two zones were assessed as being likely to lead to marked changes in composition, vegetation structure and function. In addition, these two zones are likely to be affected by increases in fire frequency and changes in land use, which will be particularly threatening to grassland species. Furthermore, species in these zones are already stressed by extensive habitat clearing and fragmentation. This combination of climate-induced changes and existing pressure suggests that biodiversity in these zones may be particularly vulnerable to climate change.

Identification of these two zones is quite different from results of other integrated assessments, which typically identify the mountains of the wet tropics, the alpine zone and southwest Western Australia as the most vulnerable. (e.g. Hennessy *et al*. 2007; Hughes 2003). Such other assessments were based largely on observed species-level changes and implicitly give considerable weight to the impacts of species distribution shifts. The three regions typically listed as vulnerable have many endemic species in small distributions that have extremely limited options to migrate in synchrony with the bioclimatic habitats in which they are currently found, and they have also been well studied over many years.

This difference highlights the complementary nature of the two approaches. It is unknown the extent to which changes in ecosystem process or key sensitivities in individual species will lead to greatest threats to biodiversity, or how they will interact. Predictions could be made on the basis of each type of information, which could provide the foci for monitoring programs.

5.2.2 Possible next steps

This was a first attempt at using this type of approach to assess biodiversity impacts in Australia. The assessment could be improved by:

- incorporating more, more diverse, and region-specific expert knowledge,
- using more quantitative information about possible ecosystem-level impacts; e.g. changes in productivity (including CO_2 impacts), fire risk (including seasonal litter production), water availability,
- incorporating more knowledge about landscape diversity in each zone and factors underpinning it (topography, soils) and information about specific refuges,
- qualitative and quantitative modelling of responses of different functional types to regional climate changes,
- incorporating knowledge about species or species groups that are special to each zone,
- incorporating quantitative information about possible individual species-level impacts, and
- doing the assessments at a finer (e.g. bioregional) scale.

It may also be useful to stratify the assessment according to different species types (e.g. habitat specialists, refuge-dependent species, different functional types) and different types of habitat (e.g. seasonal wetlands, mountain tops). In addition vulnerability assessments could be done separately for species, landscapes and social-ecological systems in each zone (see Section 8.5.3 on resilience at these three scales).

Table 5.1. Summary of a preliminary assessment of the impacts of climate change on biodiversity in each Hobbs and McIntyre zone based on changes to ecosystem-level processes.

	Climate Zone	Climate	Where	Priority/Key issues
	Cold wet	Cold winters with short summers warm enough to support significant growth.	Tasmanian highlands and Victorian and NSW alpine areas	Reduced snow cover and duration. Upward migration of species and ecosystems: low altitude species moving to higher elevations, some higher elevation species lost. Drying of wetland areas. Change in tourism and recreation demands. Fire impacts on forests, woodlands.
	Temperate cool-season wet	Cool wet climate; Moisture Index high in winter-spring, moderate in summer; Growth Index high in spring.	Tasmanian lowlands, southern, central and eastern Victoria; southern and northern NSW tablelands.	Changed growing season and possible reduced total growth. Change in fire frequency and intensity affecting structure and composition. New species will establish (especially weeds) from agriculture and gardens. Change in seasonality of rainfall will affect winter annuals, but disconnected from most sources of summer growing semi-arid species. Conversion of grazing into cropping, but some abandonment of cropping because too dry. Fragmentation limits distribution changes. Major water extraction issues. Drying out of wetlands.
	Mediterranean	Warm climate; Moisture Index high in winter, low in summer; Growth Index moderate in winter. Peak growth winter and spring.	Southwest WA, southern SA, north-west Victoria, southern NSW.	Increased fire frequency and changed seasonality and intensity. Change in vegetation structure from forest to woodland, from woodland to shrubland and grasslands. Significant land use changes, some agriculture retirement/abandonment, conversion of pasture and wetlands to crop in wetter areas. Increased variability, more opportunists, semi-arid and weedy species. Impact on wetlands and rivers, and water extraction - dams, groundwater.
	Temperate, subhumid	Cool winter and moisture limiting summer. Moisture Index moderate to high year-round; Growth Index high in spring to autumn. Most plant growth in summer, although moisture limited; temperature limits growth in winter.	NSW western slopes	Increase in growth and growing season, at least initially, will lead to changes in structure and provides opportunity for many new species, (winter growing grasses, year round growth, summer active species). Increases in fire frequency and intensity will be significant, leading to greater fire management and weed establishment. Intensification of land use possible, constraints on changes unknown; changes in crops and seasonality likely. Potentially some crop-pasture abandonment. Stress on water resources likely, possibly leading to demand for more storages.
	Subtropical subhumid	Mild winter with Moisture Index and Growth Index moderate year-round. Growth limited by moisture.	North-west plains of NSW and QLD Brigalow Belt.	Some increases in summer active species and declines in winter species. Increased fire frequency may become an issue, with more litter and hotter temperatures, but offset by wetter summer. Big issues for agricultural and human settlement, changes in land use; seasonal changes, possible conversion of crop to grazing and abandonment. Changes in seasonality of river flows; important catchment with increased demand for more dams.
	Subtropical moist	Moisture Index and Growth Index moderate to high year-round. Both indices are lower in winter in southern regions and lower in spring in northern regions.	Coastal southern-QLD and NSW (climate is more temperate in southern NSW)	Many fire-adapted ecosystems, but increases in fire frequency, intensity and extent possible: rainforests and wet sclerophyll at risk. Big issues for agricultural and human settlement. High level of fragmentation with some level of re-sorting will lead to local extinctions. Sea level rising important for mangroves, salt marshes, coastal wetlands.
	Tropical warm-season wet	Moisture Index and Growth Index high in warm season, very low in cool season.	North-west WA, northern NT, and Cape York Peninsula.	Change in fire seasonality and frequency. Potential for spread of exotics from north: high dispersal of exotics during wet season. More intense storms. Saltwater incursions into freshwater swamps. Push for agriculture in north but limitations exist.
	Tropical warm-season moist	Characterized by a long growing season and a cooler dry season than the tropical savannas. Moisture is the main limiting factor to growth and the Growth Index is lowest in spring.	Coast and hinterland areas of Queensland (subtropical in southern QLD)	Increasing fire will become a major issue for composition, structure and function. Increase pressure from agriculture and human settlement. More intense cyclones leading to structural change and establishment opportunities for weeds, but human-induced weeds important. Rainforest especially affected by fire, seasonal drying, and more intense storms. Expansion of horticulture and possibly sugar and biofuels. Species near tops of mountains may be severely affected, but tolerance largely unknown.
	Tropical wet	Moisture Index and Growth Index high all year, J1 has short dry season	Limited areas on the east coast of northern QLD	Increased risk of fire encroaching on rainforests, seasonal drying, affecting floristics, structure and function. Increased storm / cyclone intensity may change structure and favour some species (vines, early successional spp). Threat to tropical mountain species. Higher altitude species.
	Dry	Warm to hot and dry. Moisture Index and Growth Index low all year	Large central portion of the continent. Southern regions wetter in winter and northern regions wetter in summer	Fire important but limited by growth and grazing, both of which are uncertain. More summer and autumn rain may increase suitability for new species from north and new pasture species. Potential for overgrazing high as productivity decreases. Pastoralism may decline and perhaps some retirement of drying areas. Reduced or changed ground and surface water would have big impact on agriculture and refuge-dependent native flora and fauna.

6. BIOREGIONAL SCALE CLIMATE IMPACTS

Contributed by Leanne Webb and Jim Rickets, CSIRO Marine and Atmospheric Research

This assessment produced tables of climate projections for the 85 bioregions in the Interim Biogeographic Regionalisation for Australia (IBRA). Projections for the "standard" high, medium and low greenhouse gas emissions scenarios, at two time steps (2030 and 2070) were calculated using three models for temperature, rainfall, extreme temperatures and snow depth. Annual and seasonal periods were calculated.

6.1 Methods

6.1.1 Australia's Bioregions

A map of the Interim Biogeographic Regionalisation of Australia (Version 6.1) was obtained from the Australian Government Department of the Environment, Water, Heritage and the Arts (http://www.environment.gov.au/metadataexplorer/explorer.jsp). State boundaries were removed from this file before any ArcGIS analysis was carried out on the climate variables.

6.1.2 Climate Projections

OzClim makes use of MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change (http://www.cgd.ucar.edu/cas/wigley/magicc/index.html), a simple one-dimensional atmosphere-ocean model used by the Intergovernmental Panel on Climate Change (IPCC) to estimate projected global warming and sea-level rise from various emissions scenarios at low, mid-range and high climate sensitivity. The latest IPCC scenarios for greenhouse gases and sulphate aerosols are from the Special Report on Emissions Scenarios (SRES) (IPCC 2000). The SRES authors developed a series of storylines, based on assumptions about demographic change, economic development and technological advances, which were then given to modelling groups to estimate emissions for the major greenhouse gases and aerosols.

For this report a low GHG emissions scenario (B1) combined with a low climate sensitivity, a mid GHG emissions scenario (A1B) combined with a mid climate sensitivity, and a high GHG emissions scenario (A1FI) combined with a high climate sensitivity were used to provide a range of results that represent global climate projection uncertainty.

Recent measurements of CO_2 emissions, global temperature rise, sea-level rise (Rahmstorf *et al*. 2007, Raupach *et al*. 2007) indicate that, to date, the high warming scenario (A1FI) is being exceeded.

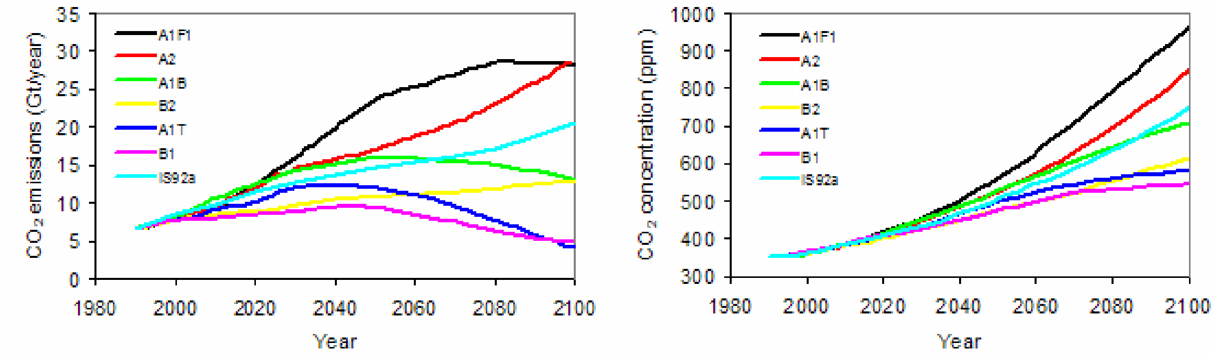


Figure 6.1. IPCC scenarios for CO_2 emissions and CO_2 concentrations to 2100.

6.1.3 Climate Models

For this climate projection assessment we chose to employ three different climate models to allow for an estimation of uncertainty due to climate model variability (Whetton *et al*. 2005). A strategy of using more than one model to capture the range of future change is widely used because many global climate models (GCM) have been developed by different research centres around the world and these models do not (and cannot) take into account all processes (natural and anthropogenic) which affect climate variability and change.

OzClim contains patterns of regional climate change from a selection of different global climate models run by CSIRO and other research centres and archived in the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (http://www-pcmdi.llnl.gov/about/index.php). The GCMs listed in OzClim perform well over the Australian continent. The simulated and observed (1961-1990) patterns of average rainfall, temperature and mean sea level pressure had small error magnitudes and high pattern correlations. For further details see Suppiah *et al*. (2007). The patterns of change can be scaled by different global warming scenarios to obtain scenarios of climate change across Australia for 5-yearly intervals from 2010 to 2100.

The model simulations used as part of the IPCC Fourth Assessment Report (Solomon *et al.* 2007) and contained within the OzClim framework available for use are:

- CSIRO MK3.0
- ECHAM5/MPI-OM
- UKMO-HadGEM1
- CCSM3
- FGOALS-g1.0
- GFDL-CM2.1
- MRI-CGCM2.3.2
- ECHO-G

Three climate models were selected from this suite of models to represent the potential range of climate projections. Projections of annual temperature and annual rainfall using a high GHG emissions scenario and high temperature sensitivity for the year 2100 were compared for the eight available climate models. This combination of projections for the year 2100 was used so as to see the maximum possible climate perturbation and hence model differentiation.

The ECHO model was the coolest/wettest, and GFDL was the hottest/driest. ECHAM5 was selected to represent the mid case due to its similarity to the model average projections in Suppiah *et al*. (2007) and the weighted average (23 models) calculated by Ian Watterson (Unpublished data, Pers. Comm). (See Appendix for more information regarding the selected climate models).

Baseline climate data (1990) were extracted for each region for the climate variables described in Table 6.1. For all of these variables, projections of the data were made using the eighteen projection possibilities: 3 models (GFDL, ECHAM5, ECHO) × 3 scenarios (A1FI, A1B, B1) × 2 time periods (2030, 2070).

Table 6.1. Temporal breakdown of climate data (baseline) presented for the IBRA.

Climate Variable	**Period** – 2030 and 2070
Temperature	Annual
	Summer (DJF)
	Autumn (MAM)
	Winter (JJA)
	Spring (SON)
Rainfall	Annual
	Wet (Nov to Apr)
	Dry (May to Oct)
Snow	Annual only
Temperature > 35°C	Frequency change – spells (>3days)
Temperature > 40°C	
Temperature < 0°C	

6.1.4 Climate data extraction technique

The climate data, representing the various climate variables, emissions scenarios and climate sensitivities, climate models and projected dates, were represented on a 25 km by 25 km grid and this was intersected by the bioregion boundaries (Figure 6.2). Averages of the climate data were then calculated for each bioregion with the climate data weighted according to the proportion of each grid cell lying in the bioregion. Analyses were conducted using ArcGIS 9.0 software. Due to the OzClim grid size, some grids do not overlap the coast perfectly leading to some slight errors in the results (Figure 6.3).

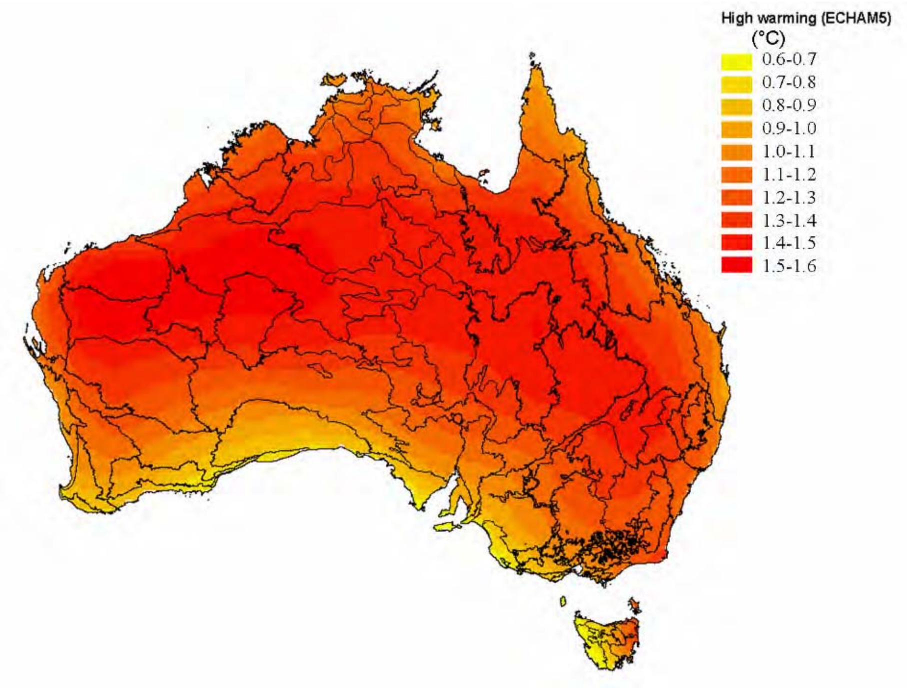


Figure 6.2. Boundaries of the Interim Biogeographic Regions of Australia (IBRA) overlaid over an example of a projected warming map ((2030, A1F1 emissions scenario, ECHAM5 climate model).

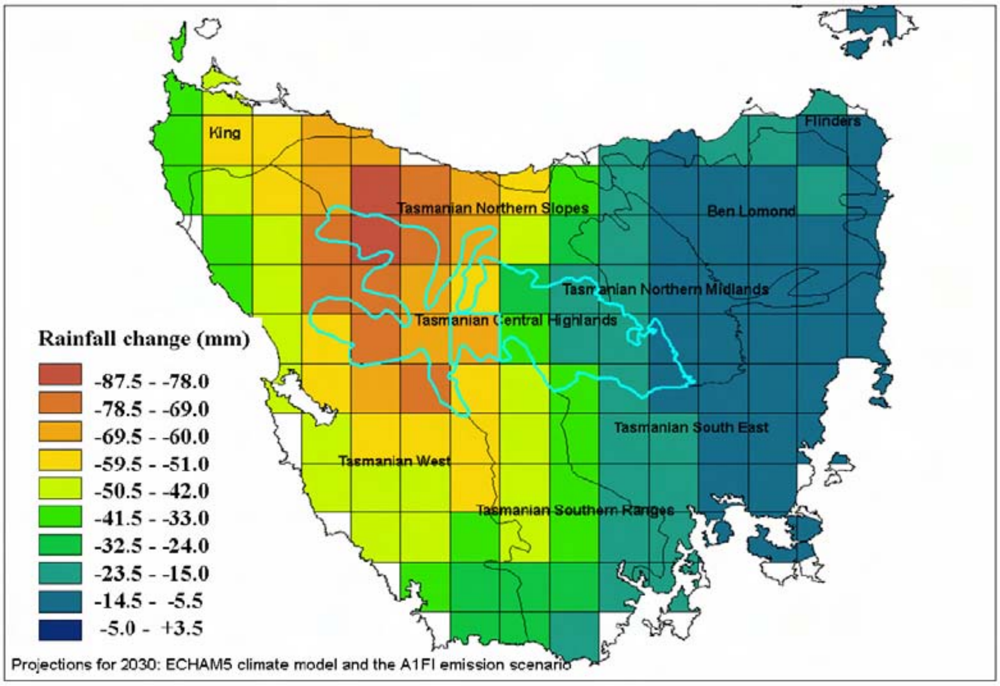


Figure 6.3. Map of spring rainfall change for one model-scenario combination laid over IBRA regions in Tasmania. The climate data for each bioregion was calculated as the average of the data for each grid area-weighted by the proportion of the grid within the region. There are some minor errors in the results due to non-perfect overlap at the coast (depicted by white areas).

6.1.5 Extreme data frequency calculations

Changes to extreme temperatures were calculated from point data, not regional average data. The preferred approach for analysing extreme temperatures is to apply the range of projected change in average temperature to observed daily records for a site then analyse the modified record for extremes in relation to thresholds. This analysis has been applied to annual temperature records to ensure that extremes that occur in the transitional seasons are also captured. This approach is also well justified given that climate models do not give clear and consistent changes in variability and diurnal temperature range.

Projected warming was calculated for each season, climate model, and emissions scenario. Exceedance counts of the threshold values (>35, >40 and <0°C) were undertaken for each available year between 1974 and 2003. A number of regions do not have data to the end of 2003. If a year was incomplete, data was used to the end of the year before.

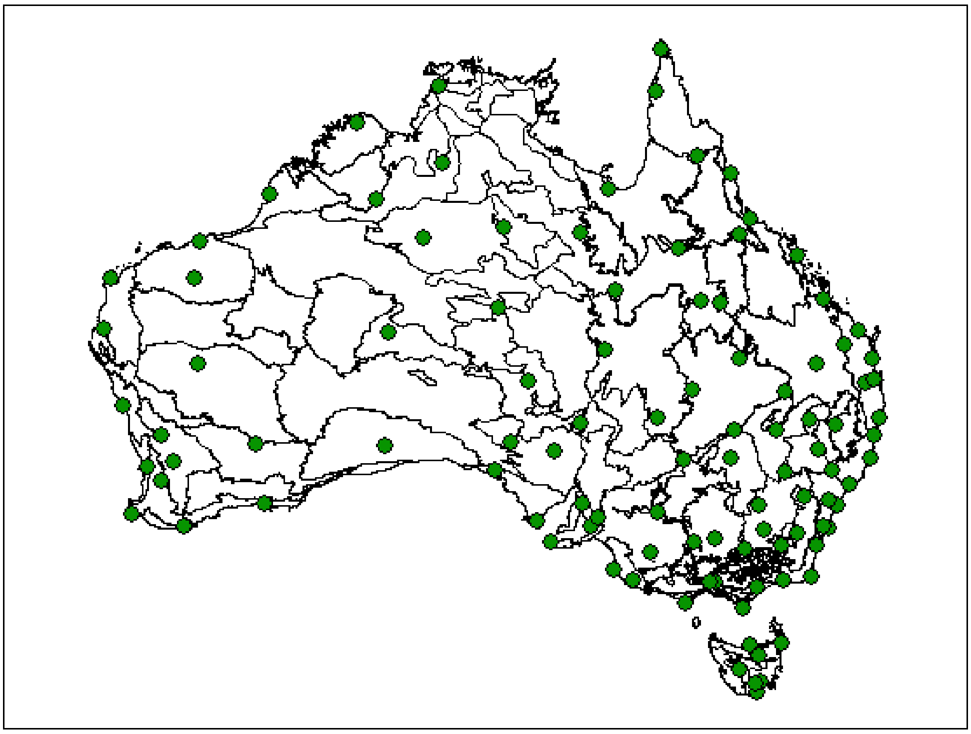


Figure 6.4 Map showing BOM weather stations (green dots) supplying data that were used to calculate the frequency of extreme events, and IBRA bioregions of Australia.

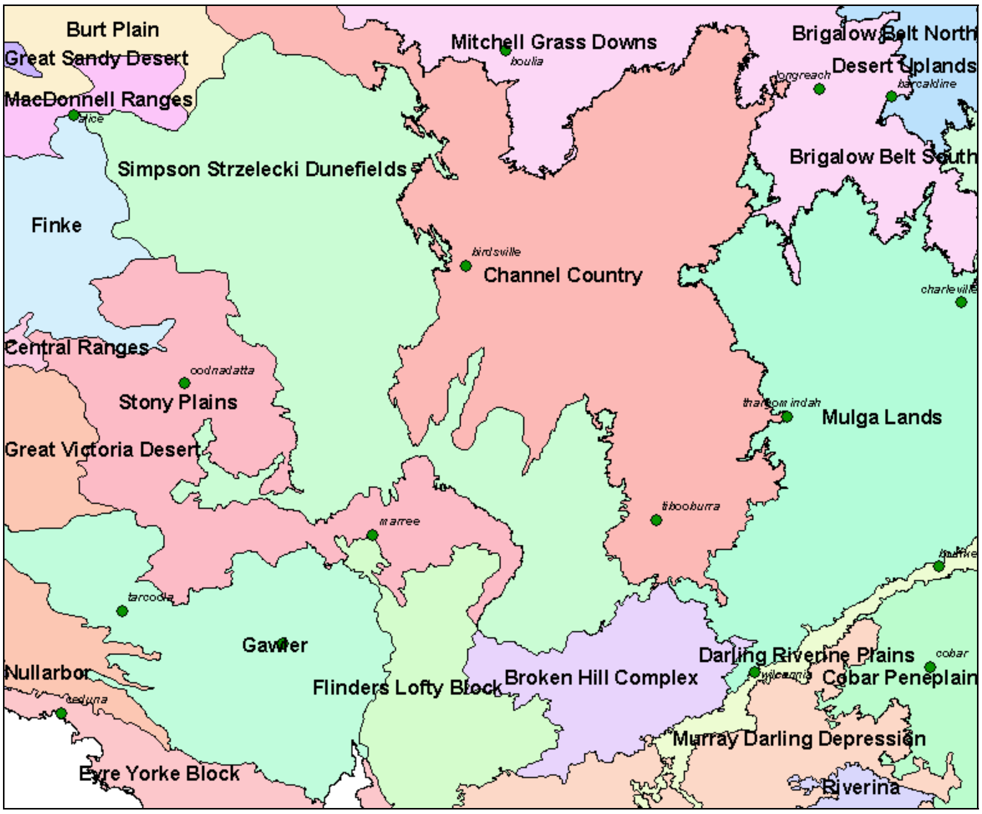


Figure 6.5 Fine scale map showing weather stations (green dots) are not evenly distributed among IBRA regions. Some regions had more than one weather station (e.g. Channel Country), others had no available data (e.g. Simpson Strzelecki Dunefields).

In some cases weather stations were located on the boundaries of two bioregions. These were allocated into one of the bioregions, but not the other (Table 6.2).

Table 6.2. Weather stations on the boundary between two bioregions, with regions into which they were allocated.

Site	Allocated to:	Also on the border of:
Thargomindah	Mulga Lands	Channel Country
Palmerville	Cape York Peninsula	Einasleigh Uplands
St George	Darling Riverine Plains	Mulga Lands
Barcaldine	Mitchell Grass Downs	Desert Uplands

6.2 Results

A database of values for climate variables and number of extreme temperature events for each IBRA bioregion will be available from the Department of the Environment, Water, Heritage and the Arts, when the full CSIRO regional analysis of the IPCC Fourth Assessment Report scenarios is released in October 2007.

Regional patterns of climate change are detailed in Section 3.3.1 in Part A.

The tables below provide summaries of the changes in climate and number of extreme events.

6.2.1 Temperature projections

Projected annual warming for the IBRA bioregions in Australia ranges between 0.8 and 6.2°C by 2070 (relative to 1990) (depending on the climate model, emissions scenario and region). A threshold of 1.5°C warming since 1990 was used to assess the relative climate-sensitivity of each biogeographic region. Global temperatures increased by 0.5°C (range 0.24 to 0.62°C) between pre-industrial times (late 1800's) and the 1990 baseline (Parry *et al.* 2007; Solomon *et al.* 2007; Rahmstorf *et al.* 2007). Therefore, 1.5°C warming since 1990 is equivalent to 2°C warming above pre-industrial levels, which has been identified by some institutions as the level of 'dangerous climate change' (Preston & Jones 2006). We assess how many regions exceed a temperature threshold of 1.5°C warming from 1990 to 2070 for each combination of emissions scenarios and global climate models. Similarly, counts of change greater than 2.5, 3.5 and 4.5ºC above 1990 levels are equivalent to those greater than 3, 4 and 5°C above pre-industrial levels.

With the low (B1) emissions scenario, the threshold of 1.5°C could be exceeded for 40 regions by 2070 (warmest climate model)(Table 6.3). All 85 regions exceeded the threshold in the mid-range (A1B) emissions scenario even with the coolest climate model (ECHO-G). Warming of more than 2.5°C (equivalent of 3°C pre-industrial) by 2070 was projected for 59 of the regions using the mid emission profile (A1B) and the warmest model (GFDL).

With the high (A1FI) emissions scenario all regions exceed the 1.5°C warming threshold with each model. Using the coolest climate model, 83 regions warmed by more than 2.5°C by 2070 (Table 6.3), and 44 regions warmed by 4.5°C or more with the warmest model.

Table 6.3. Number of the 85 IBRA regions exceeding the 1.5°C annual temperature increase (equivalent of 2°C from pre-industrial times) from late 1800's to 2070 under three emissions scenarios (rows) and three models (ranges).

Emissions scenario	1.5°C or greater warming (equivalent to 2°C since late 1800's)	Comment
Low– B1	1-40 regions	All regions exceed 0.8°C warming with coolest model
Medium – A1B	All	59 regions exceed 2.5°C for warmest model 27 regions exceed 2.5°C warming with coolest model
High – A1F1	All	83 regions exceed 2.5°C with coolest model 44 exceed 4.5°C with warmest model

Table 6.4. Number of the 85 IBRA regions exceeding the 1.5°C increase in seasonal temperature from 1990 (equivalent of 2°C increase from pre-industrial times) to 2070 under three emissions scenarios (rows) and three models (ranges).

Emissions scenario	1.5°C or greater warming (equivalent to 2°C since late 1800's)				Comment
	DJF	MAM	JJA	SON	
Low– B1	7-32	0-41	8-32	28-45	Overall summer has largest projected warming ranging between 0.6°C-2.1°C
Medium – A1B	77-85	All	80-84	77-85	Warming 2.5°C or more in up to: 59 (Summer), 56 (Autumn), 52 (Winter), and 63 (Spring) regions
High – A1F1	All	All	All	All	Warming 3.5°C *(4.5°C)* or more in up to: 73 (*43*) (Summer), 72 (*46*) (Autumn), 57 (*31*) (Winter), 69 (*54*) (Spring) regions.

6.2.2 Rainfall projections

The percent change in annual rainfall for the IBRA regions range from 31% wetter to 86% drier (depending on the model, emissions scenario and region). A threshold of 20% change in rainfall since 1990 was used to assess the relative climate-sensitivity of each biogeographic region. The assessment was made separately for each climate model.

The ECHO-G model (wet tending model) projects a wetter future for nearly 60 of the 85 IBRA regions by 2070, the maximum projected increase in rainfall being 31% (all models/scenarios) (Table 6.5). This contrasts with a drier projected future climate for all but one of the regions resulting from projections made using the GFDL (dry trending) climate model. In this case, with a high GHG emissions scenario, more than 60 of the IBRA regions have a greater than 20% reduction to annual rainfall by 2070 (Table 6.5).

Table 6.5. Number of the 85 regions exceeding 20% rainfall change from 1990 to 2070 under three emissions scenarios (rows) and three models (ranges)

Emissions scenario	>20% increase	>20% decrease	Comment
Low– B1	0	0-5	All regions with >20% decreases are with GFDL model
Medium – A1B	0	5-44	4 regions greater than 40% reduction
High – A1F1	0-47	11-62	47 regions with >20% increase are from the ECHO-G model (max 31%) 21 regions showing increases with the ECHAM5 model but they were all <20%

To reduce the confusion over the models showing increases and decreases even for the same region the results are split to show potential for seasonal rainfall increase, then decrease, in Tables 6.6 and 6.7. Fewer regions have projected increases (>20%) in summer rainfall, and by a lesser maximum percent, than in the other seasons (more regions with a wetter projected summer than other seasons). Autumn and winter have regions with the highest drying trend, while spring has many regions affected (>20%) (all regions drier (>20%) with two of the model results with the lowest GHG emissions scenario) but with a lower maximum impact.

The dry season has more regions showing a rainfall decrease (>20%) and few showing a 20% increase compared to the wet season

Table 6.6. Number of the 85 regions exceeding the 20% rainfall *decrease* from 1990 to 2070 under three emissions scenarios (rows) and three models (ranges).

Emissions scenario	>20% rainfall decrease						Comment
	DJF	MAM	JJA	SON	Dry	Wet	
Low– B1	0-7	1-29	10-26	2-37	19-65	7-32	Spring: two models show all regions drier. Max decrease: DJF (73%), MAM (100%), JJA (98%), SON (74%), Dry (100%), Wet (100%)
Medium – A1B	4-25	5-44	14-50	25-67	33-73	13-56	In some regions, some seasons have zero projected rainfall by 2070 with the driest model, although no region has zero annual rainfall.
High – A1F1	7-42	15-56	21-56	32-74	39-79	16-65	

Table 6.7. Number of the 85 regions exceeding the 20% rainfall *increase* from 1990 to 2070 under three emissions scenarios (rows) and three models (ranges).

Emissions scenario	>20% rainfall increase						Comment
	DJF	MAM	JJA	SON	Dry	Wet	
Low– B1	5-31	0-2	2-4	No regions	No regions	1-42	Max increase: DJF (73%), MAM (35%), JJA (36%), SON (8%), Dry (12%), Wet (99%),
Medium – A1B	8-50	0-14	1-9	No regions	0-1	1-57	Max increase: DJF (144%), MAM (69%), JJA (70%), SON (17%), Dry (24%), Wet (193%),
High – A1F1	8-58	0-37	2-9	1-3	2-3	1-59	Max increase: DJF (235%), MAM (114%), JJA (115%), SON (27%), Dry (39%), Wet (317%),

6.2.3 Extreme events

Of 85 biogeographic regions, 54 included one or more sites from which temperature datasets were accessed for calculation of extreme projections. Where more than one site is included in a region, an average value is calculated and is used here for simplicity. The dataset of climate projections (to be released in October 2007) does include the individual site information.

Number of days / spells (>3days) above 40°C

By 2070, expected projected increases in the number of days with temperatures exceeding 40°C was found in all but one of the 54 regions analysed (all models/scenarios). Depending on the climate model, one of the regions may have between 117 and 175 more days per year than present climate averages (about a 500%-800% increase) with temperatures over 40°C (A1FI emission profile).

Only 10 of the 54 regions assessed will not experience an increase in the frequency of spells (>3) of days of temperature greater than 40°C. Ten regions will experience at least 4 more of these spells above 40°C by 2070 even with the lowest warming projection.

Number of days / spells (>3days) above 35°C

Projections indicate that all regions will experience an increase in the number of days where temperature exceeds 35°C. The greatest projected increase is of nearly 300 days in the north of Australia by 2070 (A1FI/GFDL). Sixteen regions are showing an increase of more than 25 days over 35°C, even with the lowest warming projection.

All but 5 regions have a projected increase in the number of spells (>3) of days above 35°C by 2070 (all models/emissions scenarios). 18 regions have an increase of more than 5 spells above 35°C by 2070 with the lowest warming projections. A projected increase of 90 spells above 35°C occurring by 2070 is found for one region in the north of Australia (A1FI/GFDL).

Number of days below 0°C

Of the 54 regions (of 85 biogeographic regions) within which stations used to monitor changes to extreme conditions were found, 36 regions may have reductions in days with temperatures below zero by 2070. The greatest impact, where there is projected to be 86 fewer days per year having temperatures below zero by 2070 (A1FI/GFDL), is found in one region.

6.2.4 Snow Depth

Five biogeographic regions were assessed for projected changes to snow depth (cm). A reduction was projected for all but one of these under all model-emissions scenario combinations. In that region zero change to snow depth was projected. Reductions range from 0.2 to 31 cm across the regions, models and emissions profiles.

PART C:
IMPLICATIONS OF CLIMATE CHANGE FOR AUSTRALIA'S NATIONAL RESERVE SYSTEM

PART C – IMPLICATIONS OF CLIMATE CHANGE FOR AUSTRALIA'S NATIONAL RESERVE SYSTEM

This part of the report discusses the implications for Australia's National Reserve System (NRS) of changes in biodiversity due to climate change. The first section briefly reviews some of the literature on climate change and protected areas. We then offer our own assessment of the implications for conservation and the NRS in Section 8, based on the earlier review and synthesis of changes to biodiversity, insights from the regional analysis, the review below and extensive discussions with reserve managers.

The NRS brings together protected areas managed by the State, Territory and Australian governments, non-government organisations and indigenous landholders into a system of terrestrial protected areas for the conservation of native biodiversity (NRMMC 2004a). Protected areas include National Parks and other types of conservation areas dedicated to the protection and maintenance of biodiversity and formally managed for this purpose. Managing these protected areas as a system allows for the planning and coordination of investment required to achieve strategic conservation objectives. The aim is to protect representative areas of all regional ecosystems, their constituent biota and associated conservation values. It currently comprises 88,436,811 ha, or 11.5% mainland Australian (including Tasmania) (*Personal communication*, Tim Bond, NRS Section, Department of the Environment, Water, Heritage and the Arts).

Fundamental to the development of the NRS is the notion of developing a *comprehensive*, *adequate* and *representative* system of protected areas across Australia; the CAR criteria (NRMMC 2004a). These principles were first articulated in the 1960s and thus have been pivotal for all Australian Governments in reserve system planning and establishment for over 40 years. Current targets for achieving comprehensiveness and representativeness relate to sampling the diversity of native ecosystems in each of the 85 bioregions and 403 sub-regions in the Interim Biogeographic Regionalisation for Australia (IBRA) (currently version 6.1; http://www.environment.gov.au/parks/nrs/ibra/version6-1/index.html). Adequacy relates to ensuring that the size and management of protected areas are sufficient to maintain the viability of species within them.

7. REVIEW OF ASSESSMENTS OF THE IMPACT OF CLIMATE CHANGE ON PROTECTED AREAS

7.1 Are protected areas effective under climate change?

Historically, national parks systems around the world were developed on the assumption that climate and biodiversity were relatively stable. This is no longer valid; therefore it is important to reassess the effectiveness of protected areas given their prominent role in biodiversity conservation (Scott *et al*. 2002; Lovejoy 2005; Gaston *et al*. 2006).

This question, "Are protected areas effective under climate change?", has been addressed by a range of studies, but the question itself is not straightforward; it confuses two fundamentally different concepts:

1. Will climate change reduce the effectiveness of protected areas?

2. Given the impacts of climate change on biodiversity, is use of protected areas an effective conservation strategy?

Most of the literature does not distinguish between these two questions. Much of it focuses by default almost entirely on the first question and arrives at the entirely unsurprising answer that climate change does reduce the effectiveness with which protected areas conserve biodiversity.

However, this conclusion is simply a corollary of the observation that climate change is bad for biodiversity especially in landscapes where it is confined to limited areas of remnant habitat. Some studies conclude from such a finding that "the concept of sustaining species through fixed protected areas may be fundamentally flawed" (Rutherford *et al.* 1999). In contrast, we suggest that such a bold conclusion can easily be drawn when asking the *fundamentally wrong question!* Very few studies have directly addressed the second question, although most do offer some general advice about increasing the effectiveness of protected areas under climate change.

7.2 Will climate change reduce the effectiveness of protected areas?

Many studies addressing this issue have analysed changes in the distributions of species or biomes found in protected areas. Typically many species and biomes are predicted to be "driven out of reserves" by climate change. Araújo *et al*. (2004) predicted that 6-11% of 1200 plant species would be lost from existing European reserve networks in a 50-year period as a consequence of shifts in distributions resulting from climate change. Rutherford *et al*. (1999) estimated that greater than one third of plant species might go extinct within the existing reserves of South Africa under climate change. Scott *et al*. (2002) found that widespread changes in biome distributions in Canada's national parks are likely, including formation of novel biomes in half of the parks under doubled-CO_2 climate change scenarios. Téllez-Valdés & Dávilla-Aranda (2002) found significant reductions in the distribution of the bioclimate habitat of a number of Cactaceae species in a Mexican reserve. Hannah *et al*. (2007) report on modelling of species distributions in three regions globally and found that none would fully meet all conservation targets under moderate climate change scenarios. Hannah *et al*. (2005) suggest communities and ecosystems will become less diverse as they will lose some species, and while other desirable species will theoretically experience increased ranges, they may not actually be able to migrate to reserves because of local geography and landscape barriers such as agricultural and urban areas.

While useful for demonstrating the possible magnitude of impact of climate change on biodiversity at a broad scale, especially when it is restricted to limited protected areas, studies such as these suffer the same uncertainties and shortcomings inherent in most predictions of changes in species distributions (Pearson & Dawson 2003; Ibáñez *et al.* 2006; Brooker *et al*. 2007; see Section 3.3.4 Impacts on populations). In addition, while many studies point out that species might not be able to disperse to new reserves even if suitable habitat is available (Hannah *et al*. 2005; Donald & Evans 2006), the same process may actually enable the persistence of species in their current reserves by restricting the establishment of species that would exclude them through competition or predation.

Simplistic modelling of changes in species distributions distracts attention from the critical questions about vulnerabilities (Ibáñez *et al.* 2006), whether and where abundances will decline, how they will decline (to zero, fewer populations or restricted micro-sites), and what actions might be suitable for maintaining populations? In other words, the process by which species might be "driven out" of reserves, and indeed whether they actually will be, are very uncertain.

Some reserves are dedicated for the purpose of protecting a given species or specific biodiversity value which is likely to be affected by climate change; in such cases analyses of the change may be important and useful. However, in Australia the development framework for the reserve system is based largely on preserving *the diversity of ecosystem types*, not individual species; this is discussed further in Section 8.6 Development of the NRS.

In no way should studies that suggest species might leave protected areas be interpreted as providing evidence that protected areas will intrinsically become devoid of species, that they are in the wrong places, or that they have decreased value as a conservation tool.

7.3 Given the impacts of climate change on biodiversity, is use of protected areas an effective conservation strategy, and how can their effectiveness be improved?

Many studies conclude that protected areas are essential for the conservation of biodiversity under climate change (e.g. Halpin 1997; Hannah & Hansen 2005; Gaston *et al*. 2006; Lovejoy 2006; Hannah *et al*. 2007). These authors and others suggest however that fixed protected areas must be augmented with, for example, other strategically located reserves, broad-scale connectivity, and sympathetic management of surrounding lands to provide sufficient porosity in the landscape to allow species to disperse and establish with changing environmental conditions. One challenge is to design reserve systems so they are effective now and continue to be effective in the future (Lovejoy 2005).

7.3.1 Species modelling

Most current systematic reserve design does not consider biodiversity changes due to climate change (e.g. Margules & Pressey 2000), and doing so will be challenging (Hannah & Hansen 2005). It would appear there is a clash of paradigms between optimising reserve design based on the diversity and distributions of species (either current or at a time in the future) and accommodating flux in diversity and distributions. A number of studies suggest that modelling the future distributions of species (or biomes) can give a useful indication of where to place reserves so that species can remain protected or of how to manage the shifting distributions of species (Midgley *et al*. 2002; Téllez-Valdés & Dávilla-Aranda 2002; Hannah & Hansen 2005). Hannah *et al*. (2007) also found that designing reserves now to accommodate future and current species distributions was more effective (required less area for a given representation of species, and potentially cheaper) than designing first for current distributions, then later adding new protected areas to accommodate future distributions.

Others however, caution that current models of species distributions are not sufficiently accurate to warrant such use (Pearson & Dawson 2003, 2005; Araújo *et al*. 2005; Ibáñez *et al.* 2006). Furthermore, the data required to undertake bioclimatic envelope analyses will never be available for most species, let alone a sufficiently good understanding of fundamental physiological tolerances, dispersal mechanisms and species interactions that would be required to make better predictions (Halpin 1997; Brooker *et al.* 2007). Finally, if species distributions do change they will do so continuously, hence locating reserves for them will be like “hitting a moving target” (Scott *et al*. 2002); and different species will shift in different directions and at different rates so the proposed task becomes “hitting *multiple* moving targets”.

Again, this suggestion to use projections of species distributions to plan additional protected areas is possibly less applicable to the Australian context where the design process for the NRS is based largely on sampling ecosystem and landscape *diversity* – thus it is more akin to “covering all bases”.

7.3.2 Design criteria

A number of studies have looked at reserve design criteria in relation to climate change. Some emphasise creating overlap between current distributions and the locations of protected areas, and increasing connectivity between protected areas. In contrast, others suggest that protected areas should be widely distributed and should focus on including representative ecosystems rather than establishing large-scale corridors (Araújo *et al*. 2004; Pearson & Dawson 2005). Indeed, Pearson & Dawson (2005) found that a reversal of several standard reserve design criteria may be more effective for accommodating shifts in distributions. Essentially, if the area under reservation (in one or several protected areas) is more spread out, especially in the direction that species distributions will expand, then the greater the likelihood that the some of the distributions will remain in a protected area (Araújo *et al*. 2004). In contrast, standard reserve design criteria seek to increase the size of individual reserves, minimise distances between reserves, increase local connectivity and minimise edge effects.

Underpinning this and similar results is the notion that gradual range shifts are not likely to be the mechanism by which species distributions keep track with climate change, rather only long distance dispersal will be fast enough (Malcolm *et al.* 2002; Pearson & Dawson 2005). Higgins *et al*. (2003) supports the idea that long distance dispersal may be possible and important for many species; they also suggest that morphological dispersal adaptations might give poor estimates of a species propensity for long distance dispersal, as such events are often by non-standard mechanisms. There is not substantial evidence for contemporary distribution shifts via long distance dispersal, but Brooker *et al*. (2007) found lack of available establishment sites (“site occupancy”) can significantly limit the rates of distribution shifts. While these studies are based on species distribution modelling, they are examining general rules and not making specific predictions; hence the caveats on the modelling approaches are less of a concern. It must also be emphasised that the relative importance of gradual distribution shifts and long distance dispersal remain extremely uncertain and will only be clarified by observation over decades of many species and ecosystems. Similarly, these discussions also distract attention from understanding the consequences of altered abundances, changed ecological processes and the causes of vulnerability, issues that are critical for the management of protected areas (Halpin 1997; Brooker *et al.* 2007).

7.3.3 Other suggestions

The effectiveness of protected areas would be increased by completing current reserve system development plans (e.g. NRMMC 2004a; Scott 2005; Lovejoy 2006), including additional reserves and reducing other pressures. The changing nature of species and ecosystems might influence the selection or priority of areas or ecosystems to add to reserve systems. Scott *et al*. (2002) suggested that the establishment of new parks in Canada might focus on biomes projected eventually to have reduced representation as a result of climate change and on maximising the potential of species to respond to climate change through increasing connectivity or by protecting outlying populations. Halpin (1997) suggested addition of redundant reserves and reserves that provide habitat diversity, such as areas with high topographic relief. Many authors also suggest areas acting as refuges from past climate change, climatic variation and disturbance should be reserved as a priority. Brereton *et al*. (1995) found many such areas are already included in the reserve system in Victoria.

To complement the role of protected areas in assisting biodiversity adapt to climate change, it may be necessary to undertake more active interventions; for example, re-establishing areas of habitat, translocating species and more *ex situ* conservation (Rutherford *et al*. 1999; Scott *et al*. 2002; Pearson & Dawson 2005; Lovejoy 2005, 2006). However, there are likely to be undesirable consequences of intensive interventions (Scott *et al*. 2002). McLachlan *et al.* (2007) describe a framework for dealing with some of the risks associated with assisted migration. Community concerns about balancing various risks may play an important role in how such management is conducted (Lovejoy 2005, 2006). Similarly, reserved areas seek to protect representative natural areas for all time, but with climate change it is not clear what we should consider to be a representative natural area (Scott *et al.* 2002).

There will be considerable uncertainty about what interventions might be required because distribution changes are very uncertain and the requirements to ensure adequate protection will change as species and interactions alter in protected areas. Therefore, good monitoring and flexible management, coordination of conservation activities across protected areas and the intervening matrix of agricultural and urban lands and non-protected native habitats, and planning over longer times and larger scales would greatly assist in achieving conservation outcomes under climate change (Rutherford *et al*. 1999; Scott *et al*. 2002; Araújo *et al*. 2004; Opdam and Wascher (2004); Hannah & Hansen 2005; Lovejoy 2005).

Donald and Evans (2006) describe a range of agri-environmental schemes that support farmers to make environmental improvements to their agricultural land in Europe. Where these have been appropriately designed and targeted, they have proved successful in reversing declines in farmland wildlife populations. This “softening” of agricultural land could complement protected area networks by offsetting some of the negative impacts on biodiversity through fragmentation.

8. IMPLICATIONS FOR THE NATIONAL RESERVE SYSTEM

In this section we address key challenges for the National Reserve System (NRS) in Australia that are likely to arise as a result of the many and cumulative impacts of climate change on biodiversity. Many of these issues arise from the way in which climate change may alter the nature and impact of many existing anthropogenic pressures on biodiversity. Therefore, while this report focuses on the implications of climate change on the development and management of the NRS, the discussion is set in the context of the broader implications for the collective of Australia's conservation programs as a whole.

In February 2007 a workshop was held at CSIRO Sustainable Ecosystems, Canberra, which brought together a range of scientists, protected area managers and planners, and conservation stakeholders to examine the potential implications of climate change for protected areas in Australia. The report from the workshop is included in Appendix 4. The discussion in this section has been developed from that workshop and subsequent discussions with other protected area managers and planners. It is also informed by the review and synthesis in Part A and by the regional analysis in Part B of the report.

The discussion below fits into three broad themes covering: implications for conservation in general (Section 8.1-8.5), implications for the NRS (8.6, 8.7), and implications for information needs of conservation (8.8).

A range of management responses will be appropriate for each of the issues discussed; for some issues a comprehensive response would require further research and analysis, however many responses can be commenced with information currently available. At the end of each section we include some suggestions about actions that can be undertaken now, those that agencies could work towards over 5-10 years, and information and research needs. These are summarised in the final section.

8.1 The changing conservation challenge

8.1.1 Changing biodiversity – what are we trying to conserve?

Climate change will lead to many cumulative changes to biodiversity. Critically, the abundances and distributions of species will change, the genetics of populations will evolve, species assemblages will change, and ecosystems will change in their structure and function as well as their composition; some known ecosystem types may disappear and novel ones form. While the details are uncertain, many of the types of changes are not. There will almost certainly be some extinctions, possibly many, although there is contention about how much extinction will occur. The services that ecosystems provide to the Earth System and society will be affected. In any one place, the character of biodiversity will change; the look, sound and smell of familiar places will change as the vegetation, fauna and fungi are all affected.

While change is certain, in assessing the implications for conservation we need to remember that the nature of the change is uncertain. Change could happen via any of the three mental models (or combinations of them) that were described in Section 4.3.

Species and ecosystems undergoing significant change in response to climatic changes is a natural process that has occurred many times in the history of the Australian continent. We should expect many similar changes to occur with contemporary climate change; indeed we should be alarmed if change did not occur. However, there are reasons for society to be concerned about current changes:

- they are unprecedented in their nature and rate, hence they may be outside any “evolutionary coping range” of many species,
- society has caused many other compounding changes (e.g. habitat fragmentation) which may greatly reduce the ability of biodiversity to naturally respond without considerable loss of species and other values,
- the changes are human induced, therefore humanity is responsible for any loss, and
- species and other aspects of biodiversity have many social values, and widespread changes are likely to lead to considerable and compounding societal losses.

The next decades and centuries will see many changes to species and ecosystems that society has not had experience of since the birth of the modern conservation program with the declarations of Kings Park in Perth (1871), Yellowstone National Park in the U.S.A. (1872) and Royal National Park near Sydney (1879). These areas, and many others since, were reserved to preserve their natural and biotic characteristics in the face of landscape modification by human activity.

Fundamental to the vast majority of reserve declarations and conservation programs, is the idea that the basic character of the biodiversity being protected in any area will remain essentially the same over time. This intent is not always explicit: the intent to preserve biodiversity “as is” is often embedded in conservation aspirations, practice and formal processes, despite high-level statements in some programs of the objective to enable natural processes to occur.

For example, many protected areas have been declared specifically to protect certain species or ecological communities. The idea of “communities” as entities to conserve is one largely, but not entirely, connected to a static notion that the fundamental characteristics of biodiversity in any given place should remain the same. The concept of conserving (static) ecological communities is prevalent in societal expectations, planning tools, and legislation (see Section 8.4 Single species and strategic management).

Use of ecological communities was adopted as the basic unit of analysis for biodiversity conservation target setting and planning in Australia largely for administrative purposes: to stratify and classify the Australian environment. This was initially undertaken as an attempt to delineate the breadth and extent of ecosystems across the county using ground surveys and air photos, with vegetation mapping units used as surrogates for biodiversity. Species-driven approaches have become more common as information technology has advanced over the past 20 years. This schism between what actually exists on the ground and how it is represented in planning tools restricts capacity to reliably measure changes to biodiversity in response to climate change to those few sites where long-term biological surveys have occurred.

The static concept of communities is influenced in part by the methodology of using modal values or snapshots in time to characterise each “community”, by the administrative and policy frameworks that enshrine the protection of these modal values of communities in legislation, and by the comparative level of climatic stability over the last century (and preceding 10,000 years).

The idea that ecosystems are dynamic dates back to at least the late 19th century (Whittaker 1953); and some planners and park managers have been addressing dynamic processes in conservation in a practical way for many years: for example, using natural variability in assessing responses to management (Landres *et al.* 1990), considering connectivity of protected areas (Araújo *et al.* 2004), and planning for change within “thresholds of potential concern” (Biggs & Rogers 2003). However, even these exceptional efforts typically focus on repetitive dynamics (e.g. post-disturbance succession, metapopulations, migration), as opposed to the idea of managing continuous directional change. While many “undisturbed” ecosystems have undergone directional change (e.g. Lunt 1998), the rate of natural change has often been so slow that it has not been a challenge for the static intent. However, things are now different. Rapid changes in biodiversity have already been seen over the last 20 years with a relatively small change in climate (0.6 ºC); change in the next 50 years may be five times this level.

The reality of relatively rapid changes in species and ecosystems presents a major challenge to the fundamental goal of biodiversity conservation. Achieving conservation goals will also be challenged by the changing nature and relative risk from different threats, changes to the nature of trade-offs between conservation and other uses, and changing information requirements.

8.1.2 Recalibrating our biodiversity conservation goals

The current goal of preventing change to species and ecosystems is impossible to achieve under climate change; biodiversity managers will now need to choose more actively what it is they are trying to conserve. At one level the new goal can become “to manage the change to minimise the loss in biodiversity”, as opposed to “preventing change”. However, it is still necessary to choose what change is acceptable and what aspects of biodiversity should not be lost.

It is probably reasonable to aspire to:

- prevent places becoming ecologically dysfunctional (e.g. dramatic loss in species diversity, major interruption to the ecological processes of nutrient, carbon and water cycling),
- maintain particular ecosystem services (e.g. carbon storage, water storage and purification, pollination and pest control),
- minimise the number of genes and species that become globally extinct, and
- maintain a diversity of ecosystems.

However, given that changes in abundance and distribution are inevitable, and that different species will respond to climate change in different ways, some other conservation aspirations may become conceptually difficult if not practically impossible (in a natural setting). For example, maintaining:

- specific populations, communities or ecosystems in a given location,
- particular communities and ecosystems anywhere,
- species richness at a given location, or in a region, and
- specific patterns of ecosystems at a landscape scale.

It is often traditional to assume a particular community or ecosystem is necessary in order to conserve the species within it; however, this assumption will be tested as relative abundances change, as species begin to occur in different combinations, and as ecosystem structure and function change. Moving beyond the correspondence between species and communities will be a challenge as conserving ecological communities and using communities in conservation planning has become an important feature of modern conservation. Indeed, recognition of ecological communities and the requirement to conserve them is frequently enshrined in conservation legislation and guidelines.

Deciding what conservation goals are appropriate (or not) will be difficult, and the use of different criteria to make that decision will provide different preferred outcomes. The exact nature of the changes that happen will have an impact on what might be acceptable and will certainly affect what is feasible. Preserving some characteristics of biodiversity (e.g. maintaining particular species, communities and ecosystems in specified places) will, over time, require more intensive management and may become more akin to gardening than nature conservation (e.g. Hobbs 2007). The details of future changes, hence what is and is not feasible, are very uncertain; indeed they always will be. Therefore the setting of suitable conservation goals needs to become an on-going process that is responsive to new information. Ultimately it is a societal issue to decide what changes are and are not desirable, and it will probably require extensive community debate informed by different scientific perspectives on what changes might occur.

This need to reassess the goals of conservation applies equally to the NRS as it does to conservation *per se*. In particular, individual protected areas will see considerable changes in the character of the biodiversity within them, including changes in relative abundance, changes in ecosystems, and the disappearance of some species and arrival of others. These are all changes that currently might be regarded as undesirable in an individual protected area. However, at the scale of the system of protected areas within a bioregion, or across the NRS as a whole, such changes might not necessarily indicate significant biodiversity loss was beginning to occur.

The challenge for reserve system planners and park managers will be to learn how to monitor and anticipate changes, and to assess when management intervention might be required to reduce the risk of some loss, and also assess possible unintended consequences of intervention. The community as a whole needs to decide how much loss might be acceptable.

8.1.3 Adopting dual conservation goals

As the task of the NRS and biodiversity conservation more generally evolves into one of managing change to minimise loss, it may be useful to explicitly recognise two distinct conservation goals, both of which must be adopted (Table 8.1):

i. to facilitate natural changes in species and ecosystems including natural adaptation to climate change, and

ii. to preserve elements of biodiversity that are both particularly valued and threatened.

Table 8.1. Examples of contrasting management required for goals of facilitating change and preserving vulnerable elements of biodiversity under climate change.

Facilitate change	Preserve elements
1. Allow change to occur	1. Prevent change from occurring
2. Establish new habitat with species adapted to future climates	2. Establish new habitat with local species and provenances
3. Encourage new native species to establish (disturbance, seeding, connectivity)	3. Discourage and reduce establishment of new species (reduce connectivity, control species)
4. Allow fire regimes to change	4. Maintain historic fire regimes
5. Manage new flow regimes (less water to all wetlands)	5. Maintain existing flow regimes (possibly in only a few wetlands)
6. Remove barriers to dispersal	6. Assist dispersal to new sites
7. Control exotic pests and weeds	7. Control exotic pests and weeds
8. Reduce habitat loss	8. Reduce habitat loss

The rationale for facilitating change is that, in the long term, having species change in synchrony with climate change will decrease their likelihood of becoming threatened. Facilitating change includes explicitly “allowing” change to happen (rather than seeking to prevent it), removing institutional and biophysical barriers to change, and possibly proactively creating environmental or biotic changes to enable other changes to occur. In general facilitating change will involve less-intensive and landscape-focussed management. However, it may include some single species programs (e.g. assisted dispersal or establishing new “future-adapted” populations); maintaining and restoring habitat to facilitate establishment of new populations and movement of species; and management of threats. The goal of facilitating change could be regarded as the “default” conservation goal, and the goal of preserving could be regarded as the “safety net” that almost certainly will be needed (Brereton *et al.* 1995).

The preservation goal is in recognition that society is not prepared to let some elements of biodiversity become extinct if it can be prevented. Preserving valued and threatened elements of biodiversity will typically involve intensive and species-focussed management, quite possibly in perpetuity, and may involve conservation in botanical and zoological gardens and other intensive programs. It would frequently involve attempting to limit the impact of other species (native and exotic) that are adapting naturally to climate change; for example fencing to control predators and herbivores, and spraying to control the establishment of some plant species. Such activities are akin to *reducing* ecological connectivity (See 8.5.2). Preservation activities may also include attempting to retain historic fire, grazing and river flow regimes.

It is likely that in most cases intensive management will be targeted at protecting individual species or groups of species that are all similarly threatened, but it is possible that there may be demand to preserve particular communities or ecosystems in certain places for societal reasons. Deciding which elements of biodiversity are particularly threatened and of high enough value to society to be worth preserving will require input from scientists (what is threatened), managers (cost of preserving) and the general community (the value to society). Currently, much of the information required for such input will be new information that must be collected in the context of the likely impacts of climate change. Existing information that is based on a static view of biodiversity or on superficial understanding of climate impacts will have limited applicability.

In many cases management objectives would be similar for the two goals (e.g. controlling exotic pests and weeds, reducing habitat loss). However, in some cases the two goals will be mutually contradictory: the types of management activities used may be similar (e.g. fire management, habitat restoration, control of undesirable species) but the implementation may differ significantly depending on whether facilitating change or preserving current biodiversity is the goal (Table 8.1). It is because of this tension that it is important to articulate that the two goals are in fact different; increasingly management plans will need to specify which goal is to be applied for each management unit in a region. This could well require significantly more detail in planning than is currently specified, and will require more and different information.

8.1.4 Other challenges conserving changing biodiversity

As well as the need to reassess the goals of conservation programs, the changing nature of biodiversity will lead to a range of other challenges for conservation programs. These may include:

- **Operational problems**, where tried and tested approaches for the on-ground management of native ecosystems or species of conservation significance are no longer appropriate given changing environmental conditions and the changing nature of threats.
- **Management problems**, where knowledge or tools do not exist to address new issues. For example, where managers don’t have the experience to deal with changing threats; or they are not provided with the capacity to learn about changes that are occurring in their areas,

including some level of anticipation about how biodiversity may change and about future threats.

- Similarly, **adaptive management**, while eminently sensible, may be less useful when the responses to alternative management actions might be longer than several planning cycles (due to the noise of climate and site variability and delays in ecological responses); the information feedback may be too slow (much management will have had to have taken place without it), and the information itself may be out-of-date (as the climate and biota will have changed even more).
- **Planning problems**, where it is unclear what conservation objectives and targets are appropriate due to lack of knowledge, information and guidelines. For example, whether or not a given ecological change should be facilitated or retarded (e.g. increasing or decreasing connectivity); and what premium should be placed on connectivity in conservation landscape design (Araújo *et al*. 2004; Pearson and Dawson 2005).
- **Conservation ethics problems**, where the consequences of acting and not acting both have potential significant and unknown consequences. Increasingly situations will arise where the precautionary principle is difficult to apply. For example, is translocating a species precautionary where one does not know if it is actually doomed *in situ*, nor that it will not have negative impacts in its new location (McLachlan *et al.* 2007)? Risk management and risk reducing (e.g. not relying on one strategy) may become more appropriate.
- **Methodological problems**, where current planning concepts and tools are no longer appropriate. For example, planning based on the idea of fixed communities, with stable species abundances, and biodiversity being in equilibrium with the environment and other species; and the use of static lists of species, communities and ecosystems, with fixed benchmarks (e.g. pre-European extents of vegetation types; see also Section 8.4.2 Planning concepts).
- **Institutional problems** arising from mismatches between current legislation and guidelines and new objectives and realities. For example, when desirable change in an ecosystem or species resulting from natural adaptation is legislatively regarded as “undesirable” change (e.g. change in the composition of communities); or when changes in ecosystem processes that may be acceptable from the perspective of biodiversity conservation are not desirable from other societal perspectives (e.g. increased fire frequencies).

Biodiversity planning and management decisions will have to be made with longer time horizons and more uncertainty. Increasingly risk reducing, risk management and other anticipatory approaches will become more applicable.

8.1.5 A need for “new eyes”

It is clear that understanding the likely changes to biodiversity and the implications for protected area management, and conservation more generally, will be challenging for many people involved in or concerned about biodiversity conservation. A “cultural change” is required in order to achieve the change in conservation planning and practice required to effectively facilitate natural adaptation and preserve valued and vulnerable species. One way to achieve this cultural change is to build the capacity of people to observe the changes around them and assess the consequences. This requires a reasonable concept or mental model of the different types of changes that might occur both with and without climate change so that they are better equipped to interpret what they see (and hear and read). Some suggestions about the possible implications may also help them make their own judgements about the consequences and possible responses. A primary goal of this report has been to assist in building that capacity among protected area managers.

Priorities for *The changing conservation challenge*

Actions that can be undertaken now:

- Improve the understanding of the scale, types and implications of ecological changes due to climate change among managers, policy developers, researchers, and the general community.
- Explore the implications of change by asking questions such as: "how will this be affected by …?" In particular, ensure consequences of changes in species abundance, changes in species interactions, and different types of distribution shift (e.g. the three mental models) are all considered, not just gradual distribution shift.
- Review policies, guidelines and legislation to make them consistent with the reality of constantly changing biodiversity.
- Facilitate a national conversation about new goals – what to keep, what to let change?

Actions that agencies could work towards over 5-10 years:

- Implement the dynamic goal – decide how to choose when to facilitate change (and how) and what to preserve intensively (and how).
- Involve the community in the setting of conservation goals, especially where trade-offs are encountered, for example between facilitating change and preserving vulnerable elements, or when translocation is considered. Broad consultation needs to be ongoing and to evolve as new information becomes available.
- Implement monitoring programs designed to help implement management plans.

Information and research needs:

- Provide information products and consultative processes about types of change that might be experienced and their implications.
- Provide model and observational information about changes in species and ecosystems, and the implications for conservation.
- Develop new planning processes and information to implement new conservation goals (e.g. the dual goals: facilitate change and preserve vulnerable and valuable elements of biodiversity).

8.2 Dealing with changing threats

Climate change will significantly alter the nature, mix and impact of many threats facing biodiversity nationally, in many regions and for individual protected areas. Climate may affect the threats themselves, e.g. changing weed, pest and pathogen growth rates, abundance or distributions; or it may affect the sensitivity to threats, e.g. environmentally stressed organisms being more susceptible to pathogens or less able to compete for resources. For example, altered interactions between frogs and chytrid fungus, with changes in both host susceptibility and pathogen activity potentially involved, are among the first extinctions attributed to climate change (Pounds *et al*. 2006).

Climate change will also interact with existing threats such that the combined impacts of threats and climate change impacts may be greater than the sum of the two separate impacts. For example, habitat fragmentation combined with shifting species distribution; human extraction of water combined with reduced rainfall and increased evaporation; and reduced habitat area combined with pressure from new predators. Therefore protected area managers are likely to be faced with new and evolving threats, increasing uncertainty about their potential impacts and changing effectiveness of different management approaches.

Changing threats will have consequences for prioritisation of the development of the NRS and for reserve management. In many situations reducing threats might be the most effective option for increasing the ability of species to adapt to climate change. Threat assessment in Australia has typically been limited or at scales that are not particularly useful for prioritising investment. As threats begin to change, being able to anticipate threats better may become more important, especially where early action (e.g. inclusion in the NRS) might reduce the impact of emerging threats or where new threats are not correlated with land prices (with implications for the cost of acquiring new protected areas). Assessments of future threats can be undertaken through qualitative and quantitative modelling (e.g. Sections 5 and 6), combined with monitoring and experimental work to provide information to help calibrate the models.

In order to understand how threats may be affected by or interact with climate change it will also be useful to examine how threats or their impacts have been affected in the past by climate variability. For example, the distributions of many species, including pests and weeds, can alter considerably during floods, droughts and fires.

As well as trying to predict how threats will change, monitoring will be very important for updating knowledge about changing threats and for rapidly detecting new or changing threats that have not been anticipated. In addition, as unanticipated threats are likely to develop especially at the regional scale, management systems may need to become increasingly responsive to observations and well designed monitoring to ensure actions can be taken before the impacts of emerging threats become overwhelming.

As most threats operate at landscape scales and across all tenures, it would be sensible to continue and enhance the integrated bioregional approach to include anticipating future threats, monitoring threats and developing strategic responses (see Section 8.5)

Priorities for *Dealing with changing threats*

Actions that can be undertaken now:

- Conduct assessments with available information of changing threats including how they may change, especially the four wicked threats (following section).
- Explore the consequences for biodiversity and management of emerging threats.

Actions that agencies could work towards over 5-10 years:

- Conduct regular re-assessments of changing threats at regional scales, and ensure they inform management plans, development priorities, other conservation programs and monitoring programs.
- Develop management plans that anticipate threats but also responded flexibly to the emergence of unexpected threats and new information.
- Address skill and resource requirements for dealing with emerging threats.

Information and research needs:

- Develop models and gather data needed for detailed assessments of threats at national and regional scales
- Design monitoring to detect changes in threats.

8.3 "Wicked" threats

Many threats will change, however there are four threats that are likely to be particularly important and difficult to manage: the arrival of new (native and exotic) species, altered fire regimes, changing land use, and altered hydrology. Each of these threats already has a significant impact on biodiversity in many regions, the nature of each is likely to be altered by climate change, and there is a strong human dimension to each which may exacerbate its impact on biodiversity. Each of these threats has significant implications for management or development of the NRS, and for conservation more generally. However, addressing these threats will be complicated for society: the nature of the problems may not be well defined; there are likely to be contradictory and possibly evolving criteria against which solutions might be judged; for each threat there are probably no general answers (each threat will have to be addressed case-by-case, region-by-region, species-by-species); and simple solutions are likely to cause other problems – hence the label "wicked" threats (Rittel & Webber 1973).

8.3.1 New species arrivals

Climate change will lead to changes in the abundance and distribution of many species; this means some previously absent species are likely to arrive in protected areas and regions, and previously sparse or low-density species may increase in their abundance. Some of these "new" species will be native species spreading from their current distributions; others may be exotics spreading from naturalised populations, "escaping" from agriculture or gardens, or dispersing from elsewhere. New species could have considerably variable ecological impacts when they establish: they may establish in low density, or become a dominant; they may out-compete present species, become valuable food or habitat, or be significant pests or predators; they may have relatively little impact at the ecosystem level or may transform composition, structure or function in some way. Each of these impacts could be judged as being desirable or undesirable depending on the circumstances and the choice of criteria. There are unlikely to be clear correlations between the different impacts that could help managers decide how to respond to newly establishing species. It will not always be the case that new native species will be benign or desirable, and exotics invasive and undesirable; nor will only species that establish in large numbers have important ecological impacts; and a new species may simultaneously have some positive impacts and other negative ones.

It is likely that many exotic species that are currently recognised as problems will increase in their distributions as the climate changes and there may be significant advantages in anticipating the spread of these species (Sutherst *et al.* 2007). However, many other species will also change their distributions and a small proportion of these may have considerable impacts. There are many examples of native species that have historically changed their distributions or abundances in response to agriculture, urban development, and possibly climate change or variability. Some of these changes are relatively benign but some have socially undesirable impacts; for example new fruit bat colonies, exclusion of species by bell miners, noisy miners and currawongs, and vegetation thickening. Societal responses to "disasters" that may become more frequent under climate change may also increase the likelihood of new species being spread and becoming established at times of biological release, for example: fire control activities, clean-up after storms and floods, and distribution of drought feed.

It may actually be desirable for some new species to establish, either for their own conservation or to provide habitat for other species. Where such cases can be identified it may be possible to actively facilitate their establishment; for example with seeding or plantings, and translocation of animal species. However, experience suggests that translocation is intensive, has low success and frequently has unforseen negative consequences, and there will almost always be a high level of uncertainty about how necessary it is (McLachlan *et al.* 2007).

In general, there will be very low predictability about which species might disperse and establish rapidly in new areas and what impacts new species might have. In the absence of good ecological knowledge of individual species, information about phylogenetic relatedness and species functional types may provide some predictive ability. In particular, focussing on functional responses to changes in seasonal growth patterns in a region may give some insight to the types of new species that might establish and from which regions or directions they might come; a similar approach was used in the regional assessment in Section 5. Only from widespread monitoring will it become clear whether new and rapidly expanding species are more likely to originate from distant populations via long distance dispersal, or from the expansion of low density or cryptic populations that are already within the region (Section 4.3 Three alternative mental models). If new species are more likely to arise from local populations, prediction and early control may be easier than if species are dispersing from distant populations.

Protecting more habitat, more diverse habitat, and more redundant populations and ecosystems would be likely to decrease the probability that a new species might have a significant impact on the whole population of a species, the entire distribution of an ecosystem, or all protected habitat in a region. In addition, proposals to increase habitat connectivity should be assessed carefully as they it may also increases the likelihood of the spread of unwanted new species (Section 8.5.2 Connectivity and climate change).

Given the uncertain and variable impact of new species establishing in a region, it is difficult for managers to know how to respond to the actual or likely arrival of a new species. We currently do not have clear conceptual frameworks or heuristics that managers can readily use to assess the consequences and desirability of newly establishing native species and to identify suitable management responses. In theory, the procedures used to assess the risks of potential introductions of exotic pests and weeds could incorporate future climates and be used for native invasive species (Sutherst *et al*. 2007). However, there are many practical, legal, ecological and ethical differences between the potential introduction of an exotic species and the unassisted spread of a native or naturalised species. For example: there will be no proponent to facilitate an assessment, no regulator to make determinations, much weaker management options (i.e. control *in situ* rather than preventing entry), and any assessments would most likely be in response to an *observed* arrival not a *proposed* arrival. There is likely to be very poor information about the future extent and consequences of native species spreading, and about the consequences of trying to stop it spread (e.g. if it disappears from its existing distribution). Finally, if the spreading species is native, there are no clear and overriding conservation principles to guide any decisions: with the new conservation goal of “managing change” the default action should presumably be to “let” the new species establish, however this would clash with a precautionary approach of not allowing changes with potential and unknown impacts; and it is not clear how positive (providing food and habitat) and negative impacts (competition for space and resources) should be compared.

Until a cultural change occurs, with the general community accepting the reality that there will be considerable changes in species abundances and distributions, many changes are likely to be judged as undesirable even if they are essentially inevitable or have low probability of resulting in loss of other species. A balance needs to be found somewhere between "all change is undesirable" and "all changes in native species are acceptable". To facilitate this cultural change and development of a suitable response framework, we suggest Australia needs to have a major "national conversation" over the next decade about this issue.

In the mean time, managers need guidance and in some cases revised legislation and targets to assist them with this already occurring phenomenon. Further research and monitoring is required about species movement and establishment, the predictability and management of potential transformer-species, effects of altered ecological interactions between species, and the role habitat heterogeneity may have in ameliorating the impacts of new species..

Priorities for managing *New species arrivals*

Actions that can be undertaken now:

- Begin a national conversation about reacting to and managing the movement of native species around the landscape and between regions.
- Increase restrictions on the entry of new domestic, horticultural and agricultural species.
- Adjust expectations, goals and legislation to accommodate new arrivals and their impacts.
- Control potential source populations of sleeper pests and weeds.

Actions that agencies could work towards over 5-10 years:

- Increase the redundancy and diversity of ecosystems that are protected.
- Develop a framework for assessing the consequences and management of new native and exotic species arriving in regions that considers their positive and negative impacts.
- Develop observation or monitoring programs for recording arrival of new species and assessing changes in species abundance.
- Plan for protection of things affected by new arrivals, if warranted.
- Monitor any obvious future "problem" species.

Information and research needs:

- Assess potential for stable populations of problems species to expand.
- Assess the potential impacts of new species and changing abundances on ecosystem processes.
- Assess the role of habitat heterogeneity and landscape connectivity in mediating the spread and ecological impacts of new species.
- Record observations in all regions of species movements, and assess whether local or inter-regional movements dominate and how frequently significant impacts on ecosystem processes occur.
- Identify the locations from which new or expanding species might come.
- Provide general ecological knowledge about species movement and establishment, the predictability and management of potential transformer-species, and effects of altered ecological

interactions between species.

8.3.2 Altered fire regimes

Climate change will alter many of the factors that affect fire regimes: fuel production, structure and water content, frequency of high fire danger weather and thunder storms providing ignition. Fire regimes are characterised by the intensity, frequency and seasonality of fires (Whelan 1995). Changed regimes can affect the composition, structure and function of ecosystems, which can feed back to affect fire regimes. Nutrient and water balances can also be affected. Changed fire regimes can also have impacts on urban areas and infrastructure, and public safety. Some regions can expect increased fire frequencies and changes in seasons suggesting more intense fires, and other areas may experience reduced fire risk due to reduced litter growth with increased moisture stress (e.g. see regional analysis in Section 5). Actual changes in fire frequencies and risk will depend in part on how litter production is affected by the counter-balancing impacts of increasing CO_2, increasing evaporation and altered rainfall.

Fire risk and behaviour may also interact with human land uses. For example, some forestry practices increase the flammability of forests by introducing more flammable forest species or more flammable stand structures (Thompson *et al.* 2007). Such practices could then increase the extent and frequency of fires by increasing the flammability of the less-fire-prone parts of the landscape that separate the naturally-more-fire-prone parts, effectively increasing the fire-connectivity of the landscape. Similarly efforts to increase habitat connectivity may increase the extent of fires and therefore decrease the diversity of fire histories in a landscape.

Some of the impacts on biodiversity of increasing fire regimes may be reduced by protecting additional examples of habitat, especially remnants that are isolated from other areas of native vegetation and therefore less likely to burn at the same time. Similarly, protecting diverse habitats and landscapes, which may be more likely to include unburnt patches and variable fire histories, may also help.

Fire management strategies and protocols that have been adapted to contemporary fire regimes may become less applicable as fire regimes change. In recent fire seasons there were various press reports and anecdotes of "unprecedented fire behaviour", including recently burnt areas carrying fire again. Changed fire behaviour, especially intensity and frequency, can dramatically affect vegetation composition and structure.

Increased fire risk could readily lead to community demands to increase hazard-reduction activities. Attempting to keep bushfires to historic frequencies or intensities through frequent fuel reduction could lead to ecological impacts much greater than those that might be expected from natural change in fire frequency. Similarly, reactive or emergency fire management using mechanical fire breaks that are poorly planned, located and constructed may introduce weeds at times that are ideal for their establishment, and erosion hazards when soil cover is low. Recognising and accepting the inevitability of changing fire regimes and managing the consequences may be more productive and effective for biodiversity managers and the general community than constantly trying to suppress all fires through broad-scale hazard reduction (Whelan 2002a,b).

Priorities for managing *Altered fire regimes*

Actions that can be undertaken now:

- Expect fire regimes to change and understand that the consequences must be managed.
- Consider consequences for biodiversity of both altered fire regimes and human responses to them.
- Give increased priority to habitat protection of some isolated examples of habitat, and high priority to more diverse habitats, to increase the availability of unburnt habitat and diverse fire histories.

Actions that agencies could work towards over 5-10 years:

- Anticipate changing fire regimes, assess conservation implications and develop management responses.
- Develop and implement strategic responses to altered fire regimes that consider the implications for biodiversity and other assets.
- Increase the redundancy of ecosystems that are protected in the NRS.

Information and research needs:

- Assess how fire regimes may change regionally including interacting impacts of: CO_2, temperature and rainfall impacts on fire weather, litter production, vegetation feedbacks, etc.
- Provide information on the impacts of altered fire regimes, and the design of landscapes (e.g. habitat heterogeneity, connectivity and isolation) required to ensure availability of habitat with suitable fire histories for persistence of sensitive species.
- Processes for improving fire management.

8.3.3 Land use change

Climate change, including changes in CO_2, temperature, frost and the seasonality, amount and variation in rainfall, are likely to lead to changes in productivity of agriculture (including grazing on rough and improved pastures, broadacre cropping, semi-intensive cropping, and horticulture) and forestry which will almost certainly lead to significant land use changes. There will be productivity increases in some areas (leading to expansions in agriculture) and reductions in others (leading to contractions), and changes in relative productivity (leading to switches between crops, cropping systems and cropping seasons). Many of these changes in land use will have impacts on biodiversity.

Where productivity decreases there may be opportunities to expand the NRS or establish sympathetic management. There may also be considerable risks, e.g. severe degradation may result if grazing pressure is not reduced in line with any reductions in rangeland productivity. Where productivity increases or land use intensifies, there are likely to be significant threats to biodiversity through loss of remnant woody vegetation, loss of native grasses, herbs and forbs through cultivation and fertiliser, disturbance of soil biota, and so on.

One of the greatest threats could arise from conversions of high-rainfall permanent grazing lands in southern Australia to cropping; many of these pastures have high frequencies of native species that provide critical habitat for ground feeding and nesting birds and other species. As much of this land is already cleared there may be no institutional barriers to conversion to cropping should climatic conditions allow. These impacts could happen at the regional scale through to the within-paddock scale. Similar conversions may happen to the permanent pastures in areas that are currently too dry to crop that may get wetter, possibly including inland margins of the cropping belt in eastern Australia and in parts of northern Australia (see the regional analysis in Section 5).

Reductions in water availability for irrigation in southern Australia may also see investment in development of irrigation in the north, with direct impacts on the cropped areas, consequent impacts on rivers, wetlands and estuaries, and likely introductions of new weeds and pests. This expansion of irrigated agriculture could have flow-on impacts leading to further intensification of dryland cropping and grazing in the north.

Further expansion of coastal development in Australia is clearly a pressure on biodiversity; rising sea levels and changed cyclone regimes will add to this pressure in some areas. Rising sea levels will see salt marsh communities increasingly squashed between urban development and ocean; and efforts to secure coastlines may lead to direct damage to highly confined coastal ecosystems (e.g. dune fields, rocky shores).

If a bio-energy industry takes off in Australia, scaled up biomass production could affect biodiversity conservation considerably in a positive manner (should cleared agricultural land be used for native biomass production) or a negative manner (should diverse native vegetation be cultivated and replaced with native or exotic monoculture).

The feasibility of some of these land use changes can be assessed with various production and economic models, however climate is only one of many uncertain drivers of agricultural productivity making accurate prediction over decades tentative.

Priorities for managing *Land use change*

Actions that can be undertaken now and work towards over 5-10 years:

- Anticipate changing patterns of land use, including agricultural, forestry, (including potential biofuel and biomass), and urban (including peri-urban and “tree-change” trends and projections) land uses.
- Consider consequences of possible land use changes for biodiversity.
- Plan strategic responses to land use change and develop priorities for protected areas and the design of off-reserve conservation to ensure key ecosystems are protected.

Information and research needs:

- Provide quantitative information required to assess the potential for land use changes.
- Monitor land use changes and impacts on biodiversity.

8.3.4 Altered hydrological systems

Climate change will alter the dynamics of surface and ground waters, and plant and animal requirements for water. These changes will affect aquatic species and many other species dependent on rivers, wetlands, floodplains and groundwater for food, water or habitat. Human extraction of water and modification to flow regimes has already had a considerable impact on biodiversity in many systems; the combination of climate change impacts and human impacts could be much greater than the sum of each. In addition, efforts to further secure water resources for irrigation and urban consumption will almost certainly have additional impacts on biodiversity, e.g. reduced environmental flows, new dams and brine outflow from desalination plants.

Managers of wetlands and floodplains will increasingly find it difficult to provide sufficient flows (amounts, frequencies and durations) to maintain the natural character of systems (e.g. Macquarie Marshes and River Red Gum forests in NSW). In many systems environmental flow allocations are much less than natural flow regimes, and additional allocations are expensive to purchase. Decreasing inflows would greatly reduce management options. Managers may increasingly need to choose which wetland ecosystems they wish to maintain and which they sacrifice.

Locations with reliable surface waters and accessible groundwater may be important drought refuges and staging posts for mobile native species. Such places could become both more important for conservation if the climate becomes more variable and more vulnerable to changes in rainfall and hydrological cycles. More frequent or permanent drying of wetlands may lead to expansion of grazing, pasture improvement or cropping into areas of locally productive and unique habitat. Such drying or conversion of wetlands would make remaining refuges even more valuable for biodiversity.

Responding to and managing the impacts of changed water regimes are made especially complicated by the dynamics of water, and the societal dimension of water including multiple trade-offs with many different human uses, rapidly increasing human use, historical over allocation, uncertainty about ecological impacts, high level of social and political contention and rapidly changing institutional arrangements.

Priorities for managing *Altered hydrological systems*

Actions that can be undertaken now:

- Anticipate changes of changing rainfall, run off, evapotranspiration etc, and consider consequences for terrestrial and aquatic biodiversity.
- Develop a framework for incorporating wetlands, groundwater dependent ecosystems and freshwater habitats into the NRS.
- Ensure allocations for environmental flows are not reduced disproportionately by climate change.

Actions that agencies could work towards over 5-10 years:

- Prioritise the use of environmental flows given the expectations of changing availability.
- Plan strategic responses and develop priorities for protected areas, design of off-reserve conservation to protect key ecosystems.

Information and research needs:

- Continue to explore issues surrounding societal dimensions of water including multiple trade-offs with many different human uses.
- Investigate the role of hydrological connectivity in the landscape at multiple scales.

8.3.5 Surprises and nasty synergies

As well as these four threats that to some extent can be anticipated, protected area managers are likely to be confronted with many unexpected changes and threats. Some of them may require management responses, some may alter future development priorities, and with others there may be no real options other than to observe significant changes occurring.

Mass mortality of architectural species

Climate change will lead to declines in the abundance of many species. If such species have a dominant structural role in an ecosystem then, the decline may be very dramatic and perhaps confronting to managers and visitors to protected areas, especially if they occur rapidly with extreme events. Coral bleaching is a well known, understood and predictable example. The impact of the 2003 bushfires in the Australian Alps provides a good terrestrial example: wildfire associated with severe weather resulted in the mass mortality of canopy species in some locations. The impression is particularly stark in parts of Victoria where almost no trees survived. Such events would have occurred in the past, and regeneration is occurring from seed and surviving trees. However, the impact of the fires will be evident for decades; and if there is a second event before new recruits have matured, flowered and set seed, then the character of these forests may be changed for thousands of years.

In recent years the drought-related death of large numbers of mature canopy trees of various species in some communities of the South East Forests of NSW provides another example. In the short term these species are likely to persist, but if the events driving mass mortality become more frequent then their abundance may decrease dramatically and they may become restricted to certain micro-habitats. These examples suggest that changes to the fundamental defining characteristics of native ecosystems may become more common. Conservation responses could include ensuring areas containing micro-habitat that supports the species during extreme events (refuges) are protected, this could include additional reservation in subregions or regions were the climate or fire history is different. The current development framework for the NRS would probably already target such areas (see Section 8.6 Development of the NRS).

Synergistic interactions

These surprises could become a major concern for biodiversity conservation if there were flow-on impacts on many interacting species. For example, if the species being affected is a dominant source of habitat and food, especially for locally endemic wildlife. Similarly, dramatic changes in ecologically important species that are less visible are also possible; for example, changes in species regulating nutrient cycling (e.g. detritivores, mycorrhizal fungi and bacteria), species affecting hydrology (e.g. deep rooted species), or predators, diseases and pathogens. Managers should expect to see unpredicted synergistic interactions leading to impacts on many other species; and they will probably be very hard to predict and manage.

Priorities for managing *Surprises and nasty synergies*

Actions that can be undertaken now:

- Expect the unexpected.
- Give increased priority to protection of some isolated examples of habitat, and high priority to more diverse habitats.

Actions that agencies could work towards over 5-10 years:

- Develop management plans that can respond rapidly to emerging threats.
- Increase redundancy of protected areas in the reserve system to spread risks.

- Develop monitoring programs that allow results and observations from different regions to be coordinated so emerging trends can be detected as early as possible.
- Develop the capacity of managers to detect potentially important ecosystem changes and share these with other managers and researchers.

Information and research needs:

- Continue to model and explore possible new interactions and threats.
- Investigate how landscape structure, including habitat diversity and connectivity, may affect the incidence and impact of dramatic changes to species and ecosystems.
- Monitor changes and emerging threats.

8.4 Single species and strategic management

8.4.1 Institutional tensions

Most conservation in Australia occurs through strategic management and investment (e.g. NRS, controlling grazing, restricting land clearing) and through single species management (e.g. threatened species recovery, pest and weed control). They are both effective and have important roles. However, there is often a trade-off between them in terms of investment, and they may clash in terms of conservation objectives. Strategic management largely aims to prevent species becoming threatened, and is probably very cost effective in that regard. Management of at least some species, although expensive, is always likely to have a high societal priority. However, there is recognition that intensive management for all threatened and endangered species would be very resource intensive. Climate change is likely to affect the practical demand for and conceptual feasibility of both strategic and single species management, and has the potential to exacerbate some of the tensions between the two.

As climate, biodiversity and threats all change, greater efforts to build the resilience of species and landscapes and efforts to facilitate adaptation would lead to increased demand to develop the reserve system, other forms of habitat protection and reduce threats. On the other hand, there are almost certain to be more species that become threatened as a result of climate change (despite efforts to facilitate their adaptation), leading to increases in the number of species listed as vulnerable or endangered, which may suggest an increased demand for resources for threatened species programs.

While more resources in total may be warranted, the increased tension should be anticipated and managed. This may require revision of legislation, guidelines and targets for species protection. The tension is likely to be played out at various scales, from allocations to the NRS and national threatened species programs, to setting the priorities for works programs at the individual reserve level. An additional call on resources may come from demands for revegetation to establish landscape connectivity, and for *ex situ* conservation and translocations as a “last feasible action” for some species; both of these actions are logical but expensive and uncertain in both effectiveness (Will they succeed? What are the possible risks?) and necessity (Will there actually be significant loss without them?). A bioregional approach to biodiversity management (better coordinating conservation and NRM programs) and incorporating likely changes in biodiversity may reduce the risk of such tensions and increase the likelihood of finding synergies between single species and strategic conservation goals.

Priorities for *Institutional tensions*

Actions that can be undertaken now and could work towards over 5-10 years:

- Anticipate the changing demands on different programs managing biodiversity and threats.
- Review procedures (legislation, guidelines, etc) to ensure a strategic balance is maintained between protecting habitat (e.g. developing the reserve system) to reduce threats and increased demand for resources for threatened species programs.

Information and research needs:

- Provide information about how biodiversity will respond to climate change, and how to reduce the negative impacts via strategic and single species approaches.
- Explore methods for developing synergies between strategic and single species conservation through bioregional planning.

8.4.2 Planning concepts

The fact that species will respond individually to climate change, and the composition and identity of communities will change, affects the relevance of information at different ecological scales, and leads to somewhat of a conundrum about single-species information.

It is clear that there will never be enough species-level information to enable planning based on requirements and responses of individual species, nor enough management resources to manage most species individually. In response to this, ecological community-level approaches have become the norm for much conservation planning and management; for example the bioregional framework used in the NRS. As species abundance and distributions continue to change it will become even more difficult to obtain and use single species information.

However, at the same time, information about surrogates (e.g. indicator species, communities and ecosystems) will increasingly become less representative of individual species. Understanding how biodiversity is responding to climate change, what aspects of biodiversity will be threatened and what management approaches might be suitable are essentially single species questions; the answer for one species will not be the same as for another.

Therefore at a time when single species information is going to be less available and harder to obtain, it is going to become much more important. The bioregional framework of the NRS essentially uses diversity of ecological communities at two scales as a surrogate for diversity of species. Such an approach would appear to be more robust than surrogates based on the identity of ecosystems and communities, but careful monitoring will be required to ascertain the extent to which this is true in the future.

There is also a risk that in attempting to rapidly generate information about how individual species will respond to climate change, information that is very uncertain or easily misinterpreted will be made widely available. Indeed this is already evident with much of the volume of analyses about potential changes in species distributions and the use of this information to predict failings of protected area systems. Such analyses often have a false air of precision and can distract attention from equally plausible impacts and consequences that are less amenable to mathematical treatment and colour mapping.

To address the issue about the relevance of different types of information and management approaches, it may be useful to be clearer about the roles of different information in the conservation planning "value chain". In a static world, species, community and ecosystem objectives would be largely synonymous, hence there would be less need to be precise about the scale of the information. But as biodiversity changes, greater precision of meaning and intent is required. In the following hypothetical example each step leads directly to the one below, but each step focuses on a different scale and uses different types of biodiversity (and other) information (Fig. 8.1); details would vary between settings.

- Knowledge about biodiversity, how it is distributed and functions, and how it may respond to climate change at species, ecosystem and landscape level.
- A conservation goal of "minimal species loss" might be set given concerns about potential extinctions and realities about ecosystems changing.
- Conservation planning procedures might be developed at the community scale (e.g. bioregional framework) as a suitable surrogate for diversity of species.
- Data on species abundance and distributions and environmental parameters is required to spatially model communities and set priorities.
- Regional management targets are determined in terms of species to control, properties to acquire, landscape features to conserve.
- The management output is inclusion in the reserve system of ecosystems with reduced threats.
- From a conservation perspective the output is a diversity of habitats have been protected and made available for biodiversity.
- And the national conservation outcome is that many species survive.

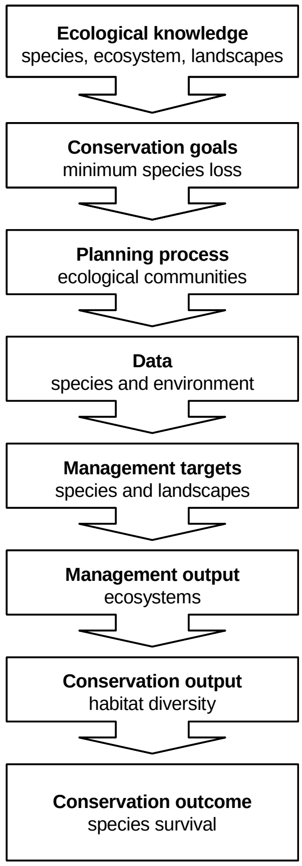


Figure 8.1. A hypothetical conservation planning "value chain" showing the use of different types of information at each stage of the process.

This example illustrates how contemporary or historical species, community and ecosystem level information, as well as information about landscapes and properties, can contribute to the process of protecting species. In this example changes in communities and ecosystems due to climate change do not alter the validity or utility of the historic information about them. Furthermore, in this example, changes in communities and ecosystems should not be regarded as indicating that the species level goal cannot or has not been met.

Priorities for *Planning concepts*

Actions that can be undertaken now:

- Be aware of how changes in biodiversity and threats affect and does not affect various planning concepts.

- Ensure stakeholders (policy, managers and society) understand the difference between conservation outcome and process, and the information requirements of different steps in the conservation planning "value chain".

Actions that agencies could work towards over 5-10 years:

- Develop more robust concepts and processes, where necessary; for example increase emphasis on habitat diversity at multiple scales.

Information and research needs:

- Analyse the effectiveness of habitat diversity at multiple scales as a surrogate for conservation planning in the face of climate change.
- Avoid the risks of rapidly generating poor quality information about how individual species will respond to climate change.

8.5 Bioregional and landscape conservation

8.5.1 A coordinated approach

Biodiversity conservation in Australia is delivered through a wide range of programs, including publicly managed protected areas, private protected areas, sympathetic management of agricultural lands around ecologically sensitive areas, habitat restoration, fire management, pest and weed control, species translocations and *ex situ* conservation. All of these activities are likely to be affected by climate change. Increasingly, as species and ecosystems change and move, the complementary aspects of different programs will become important in the achievement of overall conservation goals at landscape scales (Hannah *et al.* 2002). Therefore, there will be increased benefits from coordinating various aspects of these different conservation programs.

The bioregional framework used in the NRS is based on preserving a high diversity of ecosystems types and variation within ecosystem types within each IBRA region. The biophysical underpinnings of the framework mean that a diversity of landscape types will also be protected which will help maximise the opportunities available for conserving native species now and under changing climatic conditions (See 8.6 Development of the NRS). The framework is supported by all Australian Governments and the recent *Directions for the National Reserve System, A Partnership Approach* (NRMMC 2004a) contains a specific commitment for the development of bioregional plans to guide the further development of the NRS. The bioregional framework could also provide a suitable platform for developing regional biodiversity strategies with coordinated goals and investments across the NRS and other programs. Delivery would then be via a diversity of approaches, with different programs setting targets at their own relevant scales, e.g. catchment scales for CMAs or Landcare groups. The bioregional scale would be suitable for:

- setting strategic goals for conserving habitat and species,
- assessing the condition of biodiversity, e.g. extent of ecosystem types protected, condition and trend of vegetation, conservation status and trends of different species,
- assessing and prioritising threats to biodiversity,
- determining priority ecosystems and species based on their regional level of protection and threat,

- planning major activities in a landscape context, e.g. protecting habitat, restoring habitat, managing connectivity, managing hydrological impacts, controlling weeds and pests,
- setting regional scale objectives and targets (with delivery targets set at the relevant scale of each conservation program), and
- monitoring, evaluation and review of different programs.

A key feature of bioregional plans should be some degree of anticipation of change in biodiversity over 50-100 years, including how species and ecosystems might change, how land use may change, what new threats may emerge, and what elements of regional biodiversity may become particularly vulnerable in the future. This would help ensure regional strategies and program-level plans all contribute towards the two overarching goals of facilitating change in biodiversity and preserving elements of biodiversity that are valuable and threatened. Similarly, monitoring the changes over time in species, ecosystems and threats, and assessing the impact of climate change and other pressures, would be most productively coordinated at the bioregional scale (Hannah *et al.* 2002).

Biodiversity will increasingly become dynamic in space and time, however the locations of protected areas and most other lands managed for conservation are fixed in space. Long-term bioregional strategies could become the mechanism for managing changing biodiversity with fixed areas, as opposed to the sometimes suggested objective of moving protected areas to keep up with biodiversity. This scale would allow for assessments and planning of landscape conservation objectives which frequently span tenures and catchments including providing connectivity and building resilience (see below) (Hannah *et al.* 2002).

The bioregional scale would also be suitable for assessing the efficiency of different conservation programs, and comparing how effective different programs are at contributing to broad-scale biodiversity conservation targets. This is especially important with the growing number of alternative conservation delivery models, including private conservation trusts and government incentives for biodiversity management on private land.

By providing a diversity of habitats the NRS provides a good foundation for conserving biodiversity as species and ecosystems change; however coordinated efforts of the other conservation programs, including NRM and species management, will be critical in facilitating the changes and managing threats to reduce overall pressures on biodiversity. Some states, including Queensland and NSW are already conducting some level of bioregional assessment and planning. The regional impacts assessments provided in Part B of this report a methodology and some information for helping anticipate impacts on biodiversity at the bioregional scale.

8.5.2 Connectivity and climate change

Assessments of the impact of climate change on conservation frequently call for increased connectivity to allow the movement of individuals and facilitate the shifting of species distributions (e.g. Halpin 1997; NRMMC 2004b; Hannah & Hansen 2005; Lovejoy 2006). The bioregional scale would be well suited for planning such connectivity using the full portfolio of conservation programs.

Increased connectivity, at various scales, would no doubt assist the expansion of some species distributions, and increase the viability of some populations facing decreasingly favourable environmental conditions (e.g. increased fire, reduced primary production and food availability) by increasing the effective area of habitat available to them. However, there may be circumstances when connectivity is undesirable for the conservation of some vulnerable species. The distributions of many species are set in part by competition, predation and parasitism by other species (e.g. Austin 2005). In such cases, a species distribution would be reduced by any expansions of the *other* species, and it will be reduced faster if the other species expand faster.

The Australian Alps provides a cogent example of where mammalian herbivores could have a dramatic effect on the floristics of alpine herb fields that were naturally mainly grazed by insects. Increasing the rate at which new herbivores establish in the Alps could increase the decline of the many alpine herb species. For most species, the extent to which biotic or environmental factors contribute to distribution boundaries is not known; however, many animal species that are threatened or have gone extinct have done so largely as a result of the impact of introduced species.

Increasing connectivity, in particular connecting isolated patches of habitat, might also facilitate the spread of fire. This could lead to more extensive fires and more uniform fire histories resulting in reduced opportunities for fire sensitive species.

Reducing connectivity is actually a mainstay of many threatened species programs, through placing populations on isolated islands, fencing, baiting in buffer zones, etc. In general, where species are potentially vulnerable due to their restricted distributions or limitations to any distribution shifts (e.g. species on mountain tops, or adjacent to coasts, deserts or urban areas), increasing connectivity may be more likely than not to increase their rate of decline.

For species whose distributions are apparently not constrained it is still not immediately obvious that increasing connectivity will have an overwhelmingly positive impact. The outcome will depend very much on which model of change (Section 4.3) happens to dominate in each specific situation. If the dominant impact is from large "transforming" impacts from a small number of species rapidly establishing beyond their historic ranges, then increased connectivity might not be advantageous. If however the dominant impact is from gradual changes in distribution and abundance, then connectivity will have more positive impacts. For many species such gradual changes in distribution are unlikely to be fast enough to track shifting bioclimatic habitat (Pearson & Dawson 2005; see also discussion of Rates of distribution change in Section 3.3.4 Impacts on populations). Strategies to protect more diversity of habitats, and promote successful long distance dispersal (e.g. distributed rather than clumped protected areas, or translocation) may be more effective than increasing connectivity to enable gradual distribution shifts (Araújo *et al*. 2004; Pearson & Dawson 2005).

Connectivity between different types of habitat and different patches of habitat is however important for many species providing access to resources, increasing effective habitat availability, facilitating population processes, enabling hydrological processes and buffering the impacts of disturbances (Soulé *et al.* 2004). Fragmentation of habitat (reducing connectivity) is a major cause of biodiversity decline (Beeton *et al.* 2006). Maintaining and increasing habitat connectivity (at multiple scales) may increase the viability and resilience of populations and therefore increase the chance they will survive added pressures of climate change.

Therefore careful assessment of the possible risks as well as advantages of connectivity may be warranted before substantial efforts are made to increase connectivity, particularly in relation to species of high conservation value or that are dependent on climatic refuges. Knowledge about which models of biodiversity change predominate in different regions will come with concerted monitoring of the changes to species and ecosystems as they occur across the country. Landscape-scale adaptive management experiments of the impact of increasing connectivity would also help identify if connectivity, and what sort of connectivity, facilitates movement of different types of species. Such monitoring and experimentation will be necessary to identify situations where connectivity is beneficial or not.

8.5.3 Resilience and climate change

Many native species are particularly resilient in the face of disturbance; their relative abundances may vary considerably through time but they have traits enabling them to persist. For example, arid zone plant species that flush and bloom after infrequent wet periods and tropical and sub-tropical rainforests that recover readily from cyclone damage. There are also examples of natural resilience being broken down by altered environmental conditions; for example, arid zone mammals becoming especially vulnerable in drought refuges due to exotic predators; and some "fire-adapted" species may be sensitive to increased or decreased inter-fire periods.

There are frequent calls to increase the resilience of biodiversity in the face of climate change, e.g. in the *National Biodiversity and Climate change Action Plan 2004-2007* (NRMMC 2004b). However, it is not always clear how "resilience in the face of climate change" may differ from generally reducing threats and increasing connectivity. There are three scales at which it might be useful to think about resilience, biodiversity and climate change.

- **Resilient species** are those that are able to survive changes to the environment and other species either because they are not sensitive (strictly this is resistance not resilience) or they adapt by evolving, changing behaviour, or shifting distributions, etc. Management to increase the resilience of species might include reducing other threats (see Sections 8.2 & 8.3 on threats), reducing changes in disturbance regimes, increasing the number of populations that are protected, increasing the area and diversity of available habitat, and possibly increasing (or decreasing) connectivity to other suitable areas of habitat. It may also be necessary to intensively provide habitat through translocation to new sites in the wild or zoological or botanical gardens.
- **Resilient landscapes** might be defined as those that manage to maintain landscape-scale ecosystem processes and a diversity of healthy ecosystems, even if the identity of the ecosystems and constituent species change. Lack of resilience might be indicated by significant reductions in: species richness, functional diversity, functional redundancy, beta diversity (the turnover of species between ecosystems) and the diversity of ecosystem types, and changes in ecological process (beyond those in line with changing environmental conditions). Resilience would probably be increased by enhanced connectivity (facilitating species turnover), reducing the incidence of species that lead to monocultures or are suppressing diversity (although the emergence of new ecologically or structurally dominant species is to be expected), and allowing disturbance regimes to change (facilitating changes in ecosystems) but maintaining a diversity of disturbance regimes. With this definition of landscape resilience, transformation of an ecosystem from one type to another might not be considered lack of resilience. Our notion of the resilience of a landscape may be influenced by historic patterns of climate and climate variability (e.g. last 200yr); the resilience may change with rapid climate change.
- **Resilient social-ecological systems**, in the context of conservation, might be ones where the interactions between societal use and natural ecosystems are not greatly altered by climate change. Indications of low resilience might include loss of ecosystem services (e.g. hydrological regulation, carbon storage, pollination, pest control services), or changes in the balance between productive and conservation activities and benefits (e.g. decline of harvested populations, loss of agricultural productivity and land abandonment, lost conservation value due to intensification or spread of agriculture). Resilience might be increased by providing economic opportunities in conservation management (e.g. incentives to conserve on agricultural land or allowing "sustainable" economic returns form conservation lands),

limiting land use change, and allocating property rites to the environment (e.g. environmental flows).

In each of these cases, the bioregional scale would be appropriate for monitoring and assessing resilience and developing strategies to increase it and manage possible trade-offs between resilience at the different scales.

8.5.4 Refuges and climate change

Many species persist during periods of climatic stress and other disturbances in particular parts of the landscape. Such refuges (sometimes referred to as “refugia”) may be topographically diverse, wetter and less fire prone, or have reliable access to surface or ground water. Species may persist in refuges for short periods (e.g. droughts) or thousands of years (during cool or warm extremes of the glacial cycles). An essential feature of an ecological refuge is that it will be source from which new populations will be founded once the stress has passed (Mackey *et al.* 2002). Many commentators recommend climate refuges be protected as a measure to protect species under climate change. In the current context, it is not immediately clear if and when the stress of climate change will pass. It may do so if deep emission reductions are implemented, or when the next glacial phase commences (Mackey *et al.* 2002); but it would not be prudent to plan conservation on the basis that “normal” climatic conditions will return.

There are a range of issues related to refuges that are relevant to understanding how biodiversity may respond to climate change and planning biodiversity conservation under climate change. What places might offer higher levels of species persistence under climate change (whether species re-radiate from these or not)? What areas may be the sources from which species radiate as a result of climate change? How should refuge areas be protected?

Are there places in the landscape where some species will contract to as the climate changes (where are the future refuges)?

It is frequently expected that many species will be increasingly restricted to cooler and wetter locations in Australia as the climate warms and landscapes dry. This is very likely for some species. However, there will be considerable variation among species in their ecological requirements and how they respond to climate change, so the characteristics of refuges and their actual locations will vary among species. Not all species will contract to refuges, many will expand or persist locally. The phenomenon of species contacting and becoming constrained to particular locations where they can persist through some level of climate change may occur at various scales; e.g. behind a rock, into a gully, over a hill, the top of the mountain, the next mountain range, the coast, the next river system, and so on.

Generally, it will be hard to predict which widespread species might become dependent on refuges in the future and what characteristics those refuges might have. In the case of species already confined to “climatic islands” (e.g. alpine areas, wetlands, patches of habitat that are relicts of past climates), it may be easier to predict whether they are likely to expand or be further constrained. Although it may be difficult to distinguish between climatic and other limits (e.g. soils) on historic (and future) species distributions.

Many likely changes to species and ecosystems in response to climate change do not equate to distribution changes along climatic gradients. In these cases, refuges (areas offering higher levels of persistence) will be defined by the various change processes, more than climatic considerations, and will vary between species and regions. For example:

- Fire or storm frequency increase – refuges will be local in scale and occupied for the short to medium term, and their locations might vary between disturbance events. The potential availability of such sites might be increased by increasing "redundancy" (multiple examples of habitat types so not all are affected by a single event) and landscape heterogeneity (topography, soils, vegetation patterns, fire management practice).

- Changed species interactions especially from new species arriving in a location – refuges will be places where the new species don't get to, can't establish, or are controlled. Again, increasing redundancy and diversity will increase the likelihood of such refuges existing. Where feasible refuges might be made more effective by controlling unwanted species.

- Changed land use – refuges will be places where land use does not change for biophysical, socio-economic (land holders don't want to change for amenity or economic reasons), or institutional reasons (prohibition on certain land uses). Refuges from land use change can be provided by protecting additional habitat (through reservation or stewardship incentives) in regions identified as susceptible to threatening land use change.

- Hydrological change – refuges will be places with reliable surface or ground water, less disturbed landscape hydrology, less water extraction and better managed environmental flows.

Past (glacial) refuges will probably be future refuges, but the nature of the pressures is different, and there are additional pressures under contemporary global change, so past refuges will not be sufficient. Past drought and fire refuges will remain very important, especially as these disturbances are expected to become more intense or frequent in many regions. Such refuges that are in good condition will be even more important as the overall availability of refuges is reduced by direct human activities (e.g. habitat loss, grazing) and the level of climate change (e.g. usually-perennial water dries up).

For many current and future stresses, human activities may play a much greater role than natural geographic and climatic characteristics in defining future refuges, both in terms of the pressure from which refuge is sought, and in determining the location that is free from that pressure (e.g. protected habitats, road verges, travelling stock routes, distance from sources of exotic species, fire management, hydrological management). In general large areas and diversity of habitats will provide increased opportunity for species to persist through disturbance or periods of stress (Halpin 1997). However some species (e.g. some specialists) may require particular macro-scale geographic or climatic characteristics, and for some stresses (e.g. fire, invasive species) *decreased* connectivity may be a critical defining characteristic of refuges.

The only viable refuges for some species under climate change may be highly managed environments of zoos, botanical gardens, domestic gardens, and managed urban bushlands; pessimistically, the ultimate refuges may be gene and seed banks.

Where might species that do well under climate change emerge from (what refuges are they currently in)?

As the climate changes there are likely to be some species that are favoured and expand in their abundance and distribution. Some may become the dominant species in Australian ecosystems in the future – the eucalypts, acacias and spinifexes of the next millennium. Many expansions are likely from the boundaries of already well established populations. At a continental scale, Soulé *et al.* (2004) argue that the extensive savannas and other ecosystems of northern Australia may be important sources of radiating species. Where changes are dominated by landscape drying and increased climatic variation, species from arid regions may become more dominant. It has also been suggested that areas supporting higher primary productivity may be important sources of future radiations (See Appendix 4, Workshop Report).

In many regions there may be species that are persisting outside their optimal bioclimatic habitats and that expand as the climate becomes more suitable for them. They may currently be persisting in small populations, low abundance or in pockets of specific habitat. Many native species do exist in low abundance or small populations, and it is possible that some of them may respond in this way. It is also likely that some exotic species that are currently confined to domestic gardens may spread into the wild as a result of climate change. Similarly some agricultural and roadside weeds may also respond in this way. If species are not currently reasonably widespread, it may be difficult to predict their ecological requirements and whether they are likely to expand or not. Species that do spread from local populations due to favourable environmental conditions could be expected to expand and establish in a region faster than species spreading from other regions.

In analyses of which "new" species might expand in a region, it will therefore be important to consider not just species that may disperse from other regions as their bioclimatic envelopes change, but also species that expand locally. They may come from small, possibly unknown, populations in the wild or from highly altered parts of the landscape. Thus human activities as well as landscape features and biogeographic history may determine the sources populations of rapidly expanding species under climate change.

Enhancing and conserving refuges

Many authors suggest climate refuges should be reserved as a priority. In many cases, where such areas are readily identifiable, they are already likely to be a high conservation priority and either already reserved (e.g. Brereton *et al*. 1995) or unavailable for reservation due to conflicting land uses. In Australia, protecting climate refuges has been a priority for some time due to their importance for the protection of primitive species of Gondwanan origin, endemic species and ecosystems of high conservation significance in Australia's increasingly more arid climate (ANZECC 1999).

In addition, the process used to develop the NRS selects for diversity of ecosystems within regions, hence many past and potential future refuges would be identified as a priority to included by virtue of being different from other ecosystems in the regions (see Section 8.6.1, Comprehensiveness and Representativeness). It may however be warranted to provide extra priority or protection (e.g. large areas or greater redundancy) to such refuges if they can be identified. For other species, and where specific refuges can not be identified, placing increased emphasis on landscape diversity may increase the opportunities available for species in the face of various disturbances and pressures.

A particular conservation problem arises for species that are already restricted to confined habitats as a result of warming since the glacial maximum 11,000 years ago or continental drying over the last 15 million years. Many such species may find themselves particularly threatened with continued warming and drying. In addition, the locations in which they are found may become important habitat for other species that are affected by climate change in adjacent areas. Hence managers may be faced with a dilemma of choosing between managing these places (in as much as they can) to maintain the current relictual populations (which may indeed be doomed), or managing the areas to facilitate the expansion and establishment of new species that may become restricted to these locations (see Section 8.1.3, Adopting dual conservation goals).

Priorities for *Bioregional and landscape conservation*

Actions that can be undertaken now:

- Start developing a biodiversity conservation plan for each bioregion that:
    - outlines regional habitat protection and threat abatement priorities,

- considers anticipated future changes in biodiversity, land use and threats, and
- includes coordinated targets for biodiversity and NRM programs intersecting the bioregion.

Actions that agencies could work towards over 5-10 years:

- Implement bioregional scale monitoring and evaluation programs to detect changes in biodiversity and assess the effectiveness of conservation programs.
- Develop plans for assessing and protecting key habitats (including known and likely refuges), landscape diversity and broad-scale ecological processes.
- Assess which species may expand in regions, considering local species in small populations and habitat pockets, species in urban and agricultural areas, and species in neighbouring regions.

Information and research needs:

- Design bioregional observation and monitoring programs to track changes in biodiversity and detect new threats.
- Investigate methods for building resilience at multiple scales and identifying refuges.
- Investigate the positive and negative consequences of habitat connectivity for the maintenance biodiversity under climate change.

8.6 Development of the NRS

Development of the NRS is the process of improving the *comprehensiveness, adequacy* and *representativeness* (CAR) of the reserve system by formally protecting additional targeted areas that meet specific ecological and management criteria (NRMMC 2004a). Guidance for the selection of areas for inclusion in the National Reserve System has been developed cooperatively with State and Territory governments and published in the *Australian Guidelines for Establishing the National Reserve System* (ANZECC 1999). These contain a series of goals including:

- to contain samples of all ecosystems identified at an appropriate regional scale,
- to contain areas which are refuges or centres of species richness or endemism,
- consider the ecological requirements of rare or threatened species and rare or threatened ecological communities and ecosystems, in particular those listed in the *Environment Protection and Biodiversity Conservation Act 1999* and other State, Territory and local government legislation or policy instruments, and
- take account of special groups of organisms, e.g. species with specialised habitat requirements or wide - ranging or migratory species, or species vulnerable to threatening processes that may depend on reservation for their conservation.

A suite of administrative and policy processes result in additions to the NRS. Each State and Territory has a modest ongoing reserve acquisition program where proposed additions are assessed in a bioregional framework which considers the extent to which the full diversity of ecosystem types, and the diversity within ecosystems in each bioregion. Similarly, the Regional Forest Agreement process saw many additions to the NRS using the JANIS reserve criteria with a focus on forests ecosystems (Joint ANZECC/MCFFA National Forest Policy Statement Implementation Sub-Committee; NRMMC 2004a). In recent times, through Australian Government funding programmes under the Natural

Heritage Trust, new major players within conservation NGOs and philanthropic organisations have emerged, and the role of Indigenous Protected Areas on Aboriginal lands has grown. All have contributed to the comparatively rapid growth and expansion of the NRS (Sattler & Glanznig 2006).

How might climate change affect the current process for developing the NRS and its ability to protect biodiversity?

8.6.1 Comprehensiveness and Representativeness

Comprehensiveness and representativeness are based on sampling the diversity of ecological communities at two scales: diversity of ecosystems types and diversity within ecosystem types across their geographic ranges. If biodiversity was static and ecological communities were synonymous with species, then such a process would aim to ensure that the majority of species were protected within one or more reserves.

However, under climate change species will respond in different ways: changes in abundance and distribution of species will affect the composition and structure of communities. Some communities will expand, others will contract; most will change in their nature, some will dissolve and new ones will form. Attempts over the years to model the distribution of native communities provide some insight into the complexity of what changes may occur. For example, in forest ecosystems, canopy trees, shrubs and other species within the ground layer respond to variations in environmental conditions at different scales. Micro-topographic changes can lead to substantial changes in the shrub and ground layer composition.

From one perspective, this presents both practical and conceptual problems for the reserve system: individual protected areas could well cease to protect the communities (and species) they were dedicated to protect, and the basic planning objects of the system (specific ecological communities) might cease to be recognisable.

However, the challenge for a reserve system under climate change is to protect *with fixed areas* as many species as possible *as they change in abundance and distribution*. By sampling a diversity of communities (at two scales), the comprehensiveness and representativeness processes of the NRS are also sampling the underlying geographic diversity of the landscape (including soils, geology, topography, micro-climate) that largely gives rise to the diversity of ecosystem types within regions. Thus, a set of areas that samples a high diversity of communities now will probably also capture a high diversity of communities under future climates, even if the composition of the communities is different in the future.

While there is no guarantee that all species will be able to survive the continual process of abundance and distribution changes brought on by climate change, the current process will ensure that a high diversity of habitat types are available providing as many opportunities for species to survive as possible. In that context, i.e. providing *opportunities for species*, the comprehensiveness and representativeness processes are a very good foundation for building a protected area system that is particularly effective and resilient under future climates; indeed it would be far more so than a reserve system that focussed, for example, on just protecting areas containing endangered species. Araújo *et al*. (2004) also found that reserve designs based on representativeness approaches were more effective under climate change than ones based on clustering.

Therefore, the design process of the NRS, if fully implemented, would probably ensure that a high diversity of ecosystem types and variation within ecosystems are represented within protected areas. We are aware of no other process that could provide better future protection of biodiversity with the same resources. Thus, the NRS planning process is extremely well suited for strategically designing a system of protected areas that remains effective under climate change. However, this conclusion needs to be reassessed on an ongoing basis as changes occur and data become available. In addition, the strategic design needs to be fully implemented in order to achieve this outcome, hence the urgency of advancing development of the NRS (NRMMC 2004a; Gilligan 2006; Sattler& Glanznig 2006)

However, providing habitat diversity alone is no guarantee that species will be able to establish in those habitats. While a large number of different ecosystem types may be preserved in the future, these ecosystems may not contain the same diversity of species that is currently preserved. Increasing the likelihood that these opportunities for species can be realised, and species diversity maintained, may require connectivity at the landscape and regional scale, control of threats to species, and possibly some species translocations (including seeding) or resource provision (e.g. access to water points, habitat restoration). Such outcomes could be the focus of coordinated efforts of different conservation programs (as discussed above). Ensuring that large areas and numerous samples of ecosystem types are protected would also increase the likelihood of species successfully establishing (see adequacy below).

While the current design process for the NRS aims to develop an effective and resilient reserve system, there are significant gaps in the reserve system that are currently the focus of development activities outlined in the *Directions for the National Reserve System* (NRMMC 2004a). Many reserves are in the NRS due to the history and pattern of land development (the land that was not suitable for agriculture) rather than through strategic acquisition. Therefore more productive areas are less well represented in the reserve system; in some landscapes, such areas may support greater diversity and be more resilient. As ecosystems and species continue to change, the gaps in the NRS will become even more evident; and climate change may affect the prioritisation of that development process.

Addition of land to the reserve system is limited largely by the availability of suitable properties for purchase. Initially, the most accessible additions were suitable crown lands that could be converted to conservation reserves. More recently, the NRS increasingly relies on purchasing properties that contain priority ecosystem types. One limitation to this approach is that land is often more expensive in regions where the threat of habitat loss is greatest, e.g. areas of high agricultural productivity and urban development.

Future decreases in agricultural productivity in some regions (due to climate change and other drivers) may provide new opportunities for additions of under represented ecosystems through acquisitions or other incentive based programs. Many threats are likely to change considerably with climate change (see Sections 8.5 & 8.6 on threats). In some situations, inclusion in the NRS might directly remove a threat (e.g. land use change) or increase the ease with which it can be managed (e.g. altered fire regimes, capping bores, reducing grazing pressure). Such regions or ecosystems could become higher priorities for development of the NRS.

Some other criteria that could be used for setting priorities for development of the NRS given climate change include: areas with greater primary productivity, very large tracts of largely intact native habitat, and areas that offer potential for increasing regional and landscape connectivity (Appendix 4 – Workshop Report). It has also been suggested that increased emphasis should be given to areas that may act as refuges. In some landscapes, areas with greater primary productivity could become important as future evolutionary source areas. In many regions, climate change is expected to lead to more frequent and hotter droughts, and more frequent fires, therefore areas that include drought and fire refuges will be increasingly important for conserving sensitive and mobile species. Such areas could also possibly act as longer term refuges and future source areas should climate change stabilise.

Many areas of high productivity or containing refuges will be picked up *implicitly* through the current process of sampling regional and sub-regional communities; Brereton *et al.* (1995) found many potential climate change refuges in Victoria were already in the reserve system. Very large tracts of land will possibly provide the best opportunities for species and ecosystems to respond to climate change, thus they may maintain species diversity much more effectively than smaller and scattered areas. As discussed, increasing connectivity may also increase the viability of populations and facilitate species dispersal and establishment in protected areas.

Priorities for *comprehensiveness and Representativeness*

Actions that can be undertaken now:

- Communicate to stakeholders the effectiveness of the bioregional framework for protecting habitat and species under climate change.
- Maintain a priority on protecting habitat and landscape diversity; and reassess the priority on individual species (e.g. threatened spp) especially if they are committed to extinction, although such an assessment is extremely difficult to make.

Actions that agencies could work towards over 5-10 years:

- Complete the NRS based on the bioregional framework for comprehensiveness and representativeness.
- Examine risks and opportunities from land use change and assess how other changing threats might alter development priorities.
- Provide additional protection for fire and climate refuges.

Information and research needs:

- Monitor to ensure the ecosystem representativeness for protecting habitat does provide opportunity for species under climate change.

8.6.2 Adequacy

The adequacy criterion of the NRS is the extent to which the protected areas are sufficient to ensure the long-term viability of the populations within them. Factors that may contribute to viability may include the size of reserves, the number of populations included in reserves, the spatial arrangements (e.g. connectivity of reserves, populations or different types of habitat), habitat quality and threats.

Species have different ecological and population dynamics; therefore the requirements for viability, and the level of adequacy provided by any one or group of protected areas, can be expected to vary between species. Interactions between species may complicate any simple relationships between the factors listed above and the actual viability of populations. Thus climate change can be expected to affect both levels of adequacy but also the concept of adequacy.

Climate change will alter the nature of threats, species ecology and population dynamics, species interactions, species distributions and ecosystems as a whole (thus habitat). It will also alter land use and ecosystems in neighbouring areas and environmental variability that will contribute to viability. Therefore the adequacy of protected areas in a region will almost certainly be affected by climate change (Araújo *et al.* 2004); and in most cases species will be facing increased variability and threat which will decrease their viability and the adequacy of the protected areas in which they live. In general, it can be expected that greater conservation effort may be required to ensure current levels of adequacy are maintained for given species; this might include: increasing the number of protected populations, the size of habitat areas, decreasing threats, and more "sympathetic management" in adjacent areas.

If climate change leads to species changing their distributions, then assessing *future adequacy for a species* will require consideration of the core habitat areas and protected areas where the species might contract or shift to in the future (and whether or not they might be able to get there) (Hannah *et al.* 2002; Araújo *et al.* 2004; Hannah & Hansen 2005). Furthermore, assessing *future adequacy for a protected area* or set of protected areas will require consideration of which species (current and new arrivals) that might occur in those protected areas in the future. Predicting such distribution changes is very difficult.

If a species is essentially committed to extinction in the wild because its environmental requirements will cease to occur and it cannot adapt, then no amount reservation will be adequate for it; likewise there are some species that will require no level of reservation to conserve them.

Traditionally, the adequacy concept has been applied to communities as well as species; but with climate change existing communities will dissipate and new ones will form; and some of the constituent species might be highly viable and others not able to adapt. So it is conceptually unclear what "adequate to conserve communities" might mean.

The adequacy criterion is still poorly defined from an operational perspective in the NRS (a new framework for assessing adequacy is currently being developed), so there is no current mechanism for formally assessing how climate change might affect adequacy or for assessing what changes in management or reserve design might be required to maintain a given level of adequacy. Changes in species and communities due to climate change make the task of developing an operational framework for adequacy both more difficult conceptually and more urgent. Protected areas will need to be adequate for existing species and adequate for future species that might have different requirements for area, resources or mix of habitats.

Rather than asking how much climate change might decrease (or increase) adequacy, the key challenge in evaluating adequacy under climate change and in developing the new adequacy framework is to assess what factors will be important in determining adequacy as climate, species and ecosystems change. It may be useful to think about adequacy from species, landscape and social-ecological systems perspectives in line with the discussion on resilience above (Section 8.5.3). Additional factors that might then be incorporated in assessments of adequacy might include the extent to which broad-scale ecological processes are maintained, maintenance of functional diversity, habitat diversity including the proximity of high productivity sites and potential refuge sites. In some situations, increasing connectivity will increase adequacy, but it must also be remembered that increasing connectivity to predators, competitors and fire will decrease viability of some populations.

Priorities for *Adequacy*

Actions that can be undertaken now:

- Develop a framework for assessing the adequacy of protected areas in a bioregional context.

Actions that agencies could work towards over 5-10 years:

- Refine the adequacy framework to accommodate the ever-changing nature of biodiversity and threats due to climate variability, climate change and other pressures.

Information and research needs:

- Investigate the requirements for maintaining resilience of species and ecosystems under climate change.

8.7 Management of protected areas

In the near term, climate change will probably pose more of a challenge for management of individual protected areas than for the future development of the reserve system. Managers will be directly confronted with changing biodiversity and threats, and inconsistencies between the new realities of climate change and current set of goals, guidelines and legislative responsibilities. There will also be the need for new types of information and the capacity to use it.

Park managers will be faced with the challenge of managing changing species and ecosystems. They will often be the "front line", observing what changes are actually occurring, and they will have to implement the paradigm switch from the current conservation goal (preserve biodiversity as it is) to the dynamic goal of "managing the change to minimise the loss". In doing this they will need to decide:

- Which changes are acceptable in the context of long-term continuing changes in biodiversity, and how to facilitate change where needed?
- Which changes are likely to lead to unacceptable loss of biodiversity values, and what responses are suitable?

These decisions will largely be different from current management decisions, they may be outside the existing experience of managers, and initially they may not accord with guidelines and institutional procedures. Indeed managers will probably experience the main impacts of institutional lags in response to the new realities of climate change while society considers the implications, as conservation goals are formally revised and legislation and guidelines are amended, and as new relevant information emerges.

Managers will also be faced with new and changing threats. It may be possible to anticipate some of these threats, but that is an additional task and requires information not currently available. In addition, management will need to be responsive to other threats that are not predicted. Current management approaches to dealing with existing threats, which are based on extensive experience, may become less applicable as the environment, biodiversity and threats change continuously. In some situations approaches will evolve as changes occur gradually. However, some changes may require new approaches, knowledge and information that might be based less on experience and more on monitoring and modelling. Responses to management will also become more uncertain, suggesting a greater role for monitoring, research and formal adaptive management approaches.

Climate change will also affect visitor management in protected areas, for example due to increased fire risk and reduced water availability. In many areas there may also be demand to reduce dispersal of pests, weeds and diseases, for example with more vehicle and boot wash-down facilities and exclusion zones.

In summary, protected area managers will directly face many of the changes to biodiversity and threats, and will have to deal with the implications, possibly before their agencies and society have understood the changes and their consequences, and before policies have been suitably revised. Depending on the actual rate at which changes occur this will be a considerable challenge. An understanding of what changes might occur in their regions would help managers interpret the changes they observe and consider the implications (see 8.1.5 A need for new eyes), and would help build their capacity to adapt their management. However, managers will also need institutional support in the way of revised guidelines, resources, appropriate information, and tools for dealing with uncertainty.

Priorities for *Managing protected areas*

Actions that can be undertaken now:

- Build capacity for manages to observe and anticipate the impacts of climate change in their regions, and assess the implications for management; including information about possible changes and implications and time to observe and analyse.
- Revise management guidelines to accommodate expected changes in biodiversity.

Actions that agencies could work towards over 5-10 years:

- Develop processes and guidelines to implement the twin goals of facilitating adaptation and preserving vulnerable and valued species.
- Maintain or build flexibility in management programs and allocate sufficient resources to accommodate emerging issues.

Information and research needs:

- Provide information about expected and observed changes in biodiversity and threats.
- Develop appropriate tools for dealing with uncertainty and helping managers avoid threats.

8.8 Information needs

Information is currently a constraint to management of individual protected areas and to conservation at the continental scale. Some protected areas do not have accurate species lists let alone knowledge about long-term trends or seasonal ecological requirements. Continentally and in many regions there is poor information about the distribution of habitat types and their condition, and there are few assessments of threats at scales that are useful for planning and management. Climate change is likely to increase information requirements as more up-to-date information will be required due to constant change, and different types of information will be needed to anticipate future trends. Managers, planners, researchers and the general community will all need new information to fulfil their respective roles. Acquiring much of this information will require carefully designed and concerted monitoring programs. Increasingly planning will need to consider future changes, the details of which will be uncertain; management that is designed to generate good quality empirical information and that is responsive to such information (i.e. *active* adaptive management) may be increasingly appropriate.

We suggest the community (including researchers and managers) are a long way from having a workable understanding of the nature of how biodiversity will respond to climate change, what changes are currently occurring and the full implications for conservation and society. As discussed in Section 4.3 (Three alternative mental models), patterns of change and conservation outcomes could vary considerably depending on which change processes dominate in different situations. Balanced information about possible changes and vigorous community, scientific and policy debate about the emerging issues is required, with regular updating as more information, and more relevant information, becomes available. To inform the development of better understanding of current and future changes, debates about their implications for biodiversity conservation, and assessments of adaptation options, we suggest as a priority that information in needed about changes in species abundance, species interactions and ecosystem process to complement the more readily available information about species distribution changes.

In general, while we have a good understanding of the many types of changes that might occur at all levels of the cascade of impacts (e.g. Section 3), specific information is lacking for most species, ecosystems and regions. In many regions poor understanding of core biological and ecological characteristics (e.g. which species are present, in what abundances and how they interact) will be a major constraint. In almost all regions there is likely to be poor understanding of change processes (e.g. the sensitivity of different species to environmental factors; the affect of different types of species on ecosystem function; the dynamics of population, evolutionary and ecosystem change; the role of habitat diversity in species persistence). Similarly, in most regions there is currently a poor understanding of how ecosystem processes might change. We qualitatively assess the potential for change in some processes for ten broad zones in Section 5, but more quantified assessments at a variety of scales would be possible and useful. As discussed above, further assessment of the societal implications of changes in biodiversity are needed, including reassessment of the core goal of conservation (e.g. “managing the change to minimise the loss”, Section 8.1), through specific challenges (e.g. the four “wicked” threats, Section 8.3), to community preferences for specific outcomes (at the scale of individual species, protected areas and places). Likewise, there is a requirement for ongoing scientific and policy assessments of conservation goals, program design and implementation.

It will also be important to understanding current and future changes in climate, including extreme events and the spatial detail of change. However, increased resolution and precision of climatic information is of limited value when it is not matched by accuracy, or when uncertainty about the implications of a given level of climatic change dominates, as is the case for biodiversity conservation in most regions.

It is important that additional information is:

- at the right scale,
- available to managers and planners,
- in a useful format, and
- used by managers and planners with the necessary skills.

Much of the desired information will not be available when needed, nor in the detail or with the level of accuracy that might be desired. Therefore managers and planners will need tools to assist them working with partial or surrogate information. This will require some risk management. Until prediction improves markedly, it may be useful to develop planning techniques using scenarios of possible biodiversity changes and regional scales.

New approaches to predicting the possible impacts of climate change on species and ecosystems would be very useful complements to species-distribution level predictions. Candidate approaches include using information about functional types, architectural species, ecological responses, evolutionary processes and ecological resources including productivity. Information about phylogenetic relationships might also be useful for predicting the ecological responses of species; however the availability of taxonomic skills in Australia is a constraint. To continue to usefully inform conservation planning and management, research on species-level predictions needs to address dispersal issues (both barriers to it and long distance dispersal), species interactions including competition, actual physiological responses (rather than correlations), abundance changes (especially at the “rear edge”) as well as distribution changes, the dynamics of change, the role of habitat heterogeneity (as well as climatic gradients), and confounding of potential and realised niches (Halpin 1997; Hampe and Petit 2005; Pearson & Dawson 2003, 2005; Ibáñez *et al.* 2006)

It is critical that new (and old) modelling approaches are complemented with survey information about species presence and abundance and ecosystem processes, and monitoring of how species and ecosystems are changing in terms of abundance, composition, structure and function as well as distributions. Modelling and monitoring programs should also be closely linked to management and policy development to ensure consistency and efficiency of program design, adequate resourcing, and effective analysis and adoption. Given the uncertainties and rapid developments of new techniques, it is also important that multiple approaches are supported. Observing and analysing historical changes associated with variation in climate between years (and regions) might be an effective way to learn about the sensitivities of particular species or processes to climatic factors. However, such variations do not include the direct impacts of elevated CO_2 concentration on plant growth and composition, which will be very important. In addition, observed short-term biotic responses to climatic cycles might not reflect long-term changes due delays in responses (e.g. decline or evolution) and non-linear impacts.

In particular, consideration should be given in the selection of protected areas and design of management plans to testing unknowns and ensuring that monitoring and evaluation yields information that is of high quality (e.g. statistically robust) so that valid inferences can be made from it to guide future management; in other words, the implementation of *active* adaptive management principles. Similarly, observations, surveys and monitoring programs can be greatly enhanced by well designed coordination of efforts across species, ecosystems and regions; this would increase statistical power (the ability to make a rigorous inference from the data) as well enable comparisons among species, ecosystems and regions.

Priorities for *Information needs*

Actions that can be undertaken now:

- Provide information for protected area managers, policy makers and researchers about the possible impacts of climate change on biodiversity and implications for conservation.
- Undertake baseline surveys to improve knowledge of biodiversity in less well studied regions and of less well studied systems (e.g. soil biota).

Actions that agencies could work towards over 5-10 years:

- Establish nationally coordinated observation and monitoring programs to identify changes in biodiversity, arrival of new species, fire regimes, land use change, altered hydrology and other threats.
- Implement monitoring and planning with biodiversity surrogates that are robust under climate change, possibly including habitat diversity.
- Establish statistically robust management experiments to assess the impact of habitat heterogeneity and connectivity on species responses to climate change.

- Trial habitat modification aimed at increasing *in situ* species persistence
- Trial species translocations to assess risks.

Information and research needs:

- Investigate community attitudes and values about biodiversity in the context of future changes.
- Design monitoring programs and management experiments to improve the understanding of how species and ecosystem are responding.
- Mine past observation data and species records for information about the sensitivity of species and ecosystems to climatic variability.
- Investigate the impacts of climate change on ecosystem processes.
- Improve species level impact modelling, including CO_2 impacts, abundance, species interactions, dynamics of change, ecological processes of population contraction and expansion, dispersal and landscape heterogeneity.
- Conduct experiments into the responses of species and ecosystem to climate change.
- Investigate and develop biodiversity surrogates that are effective under climate change.

8.9 Summary of management priorities

Management actions that could be undertaken to address the implications of climate change for the NRS and biodiversity conservation can be can be summarised in terms of four priorities:

1. Understand how biodiversity will respond to climate change and the implications for conservation,
2. Protect more habitat and more diverse habitat,
3. Manage habitat to reduce threats, and
4. Manage landscape-scale issues.

Many of these priorities could be planned and implemented at the bioregional scale through coordination of the efforts of the NRS, stewardship and incentive programs, and other conservation programs. Some actions under these priorities are already underway or could be commenced now; others would require new information, policy development and community debate over the coming decade.

8.9.1. Understand how biodiversity will respond to climate change and the implications for conservation

In order to plan effective actions to minimise the impact of climate change on biodiversity it is critical for managers, planners and researchers to have a good and broad understanding of the nature of the changes that might occur. While reduced uncertainty would help with planning, there will always be considerable uncertainty about the magnitude of future climate change (due to indeterminate emissions policy and behaviour, and complexity of the Earth System) and its impact on biodiversity (due to the multitude of species, the complexity of interactions and limited knowledge). Effective planning and adaptation actions can however proceed with limited knowledge and uncertainty about what is known. Some of the risks and barriers associated with that can be reduced by ensuring decisions are based on a broad understanding of likely impacts as opposed to a detailed but narrow understanding of the changes that might occur. Detailed analyses can help explore the magnitude of some changes and can contribute to integrated analysis of broader changes; but there is a real risk in rushing into adaptation actions on the basis of detailed information about one aspect of change that may prove not to be the most significant from a conservation perspective. This is typified by calls for increased habitat connectivity based on the idea of a need to facilitate the migration of species, because habitat connectivity can have clear risks in some circumstances, and in many situations climate related changes to other threats are likely to be more significant than shifting bioclimatic envelopes. An early task for conservation stakeholders is to reassess the core objectives of biodiversity conservation in a changing world, this can only be done effectively with a broadly informed community.

Knowledge of the impacts and implications of climate change will evolve over the decades with more observations, further experimentation and improved modelling. Conservation efforts will be more effective if the new information is of high quality and relevant to management and planning.

Priorities

Provide information to protected area managers, strategic planners, policy makers, researchers and the general public about the likely changes to species and ecosystems that could result from climate change and the possible implications for conservation. Provide regular updates of observed changes and refinements of anticipated changes in different ecosystems and regions.

Encourage debate within the general community, policy research communities about the changing nature of biodiversity conservation and the need to reformulate the core conservation challenge, e.g. “Managing the change to minimise the loss”, and implement it via revised goals, e.g. “1. Facilitate change and adaptation”, and “2. Preserve vulnerable and valuable elements of biodiversity”. In particular, facilitate a “national conversation” about suitable management responses to the arrival of native species from other regions that have undesirable impacts on local biodiversity or society. Conduct on-going assessments of community attitudes to help inform trade-offs between the different conservation goals.

Develop methods and programs to improve the capacity of managers and planners in agencies to learn about the impacts of climate change and their implications through their own observations, research and experimental (adaptive) management, and information from elsewhere. Design observation and monitoring protocols relevant to climate change that can be easily and usefully incorporated into core monitoring and evaluation programs, and that combine observations from across the country to increase the ability to detect trends early and compare regions. Initial candidate areas could include information about changes in vegetation structure, arrival of new species (e.g. what types of species, where did they establish, under what conditions, from where did they probably come, what impacts are they having), altered fire regimes, land use changes and altered hydrology.

Improve knowledge about biodiversity responses to climate change through observation and monitoring, modelling of species and ecosystems processes, and experimentation. In particular:

- seek to improve species level modelling (incorporating CO_2 impacts, abundance changes, species interactions, dynamics of change, ecological processes of population contraction and expansion, dispersal and landscape heterogeneity),
- develop models of ecosystem process under climate change, and
- explore ways to integrate species level and ecosystem information, e.g. using functional types.

Conduct quantitative analyses at continental, agro-climatic zone, biome and bioregional scales of the likely changes in species, ecosystem processes and threats due to climate change, including consideration of climate variability and landscape heterogeneity. Use these to inform assessments of the vulnerability of biodiversity and the potential for management interventions in each bioregion. The methodology used in Section 5 could be further developed for this purpose.

Investigate the role of landscape structure in mediating the responses of species to climate change, including patterns of land use, connectivity, landscape and habitat diversity and hydrological function. Similarly investigate the influence on fire regimes of landscape structure, altered seasonal growth patterns, CO_2 impacts, vegetation feedbacks, and possible changes in key fuel species.

Analyse potential land use changes resulting from climate change and other drivers, and the threats and opportunities for biodiversity conservation that may arise. In particular, assess possible transitions from grazing to cropping, intensification of grazing and changes in rangeland productivity. Explore habitat and species protection mechanisms to complement protected areas, especially in areas where opportunities for reservation are limited.

Assess the potential for exotic species to become invasive or ecologically significant under climate change. Potential sources of future pests and weeds include: currently invasive species, exotic species that are currently stable in the wild (sleeper populations), and exotic species currently restricted to human dominated landscapes within regions (e.g. domestic plants and animals, and agricultural plants and weeds).

8.9.2. Protect more habitat and more diverse habitat

Protecting habitat is essential for conserving species. In general, the greater the area of protected habitat, the greater the likelihood of populations of species persisting. And if a greater diversity of habitat is protected, then a higher diversity of species is likely to be conserved. Under the changes and uncertainties of climate change, especially in combination with other human pressures, protecting large areas of habitat and a diversity of habitats both become even more important for conserving species. Currently the NRS includes over 88 Mha, but many ecosystems and bioregions are very poorly represented in protected areas. The bioregional framework, incorporating the IBRA scheme and CAR (comprehensiveness, adequacy, and representativeness) criteria, has been used to strategically develop the NRS for over a decade. This framework, particularly the design of the comprehensiveness and representativeness criteria, is well suited for developing a protected area system that is robust under climate change. As species and ecosystems change, the NRS is likely to continue to provide habitat for a high diversity of ecosystems and species. Indeed no other practical planning framework could reasonably be expected to provide better protection; in particular, habitat protection processes that target threatened species will be particularly vulnerable climate change. However, the NRS will not be effective unless the strategic habitat protection targets are met. As is regionally applicable, this could include further public purchases of protected areas or various types of enduring habitat management arrangements on private land. Not all species will survive climate change within protected habitat and intensive management may be required to conserve some species.

A diversity of habitat not only provides opportunities for a diversity of species it also is likely to provide heterogeneity that is important for persistence of species in the face of climatic variability and recurring disturbances both of which can be expected to alter with climate change. Thus under climate change, habitat and landscape diversity are possibly even more important for species persistence than over the last few thousand years.

Priorities

Complete the habitat protection goals of the NRS using bioregional framework (IBRA and CAR criteria). Management primarily for the purposes of biodiversity conservation (either on public or private land) offers the best protection for species, however in some regions it may be necessary or more efficient to implement habitat protection arrangements that allow for a diversity of outcomes.

Place extra weighting on the diversity of habitat, both within individual protected areas and within bioregions, when assessing potential additions to the NRS and other conservation actions (design of incentives and offsets).

Use anticipated changes in species, ecosystems and threats to prioritise habitat protection programs. Species in areas facing greater levels of change (e.g. significant changes in seasonal growth patterns or landscape hydrology) may be in greater need of additional habitat protection. For example, the analysis in Section 5 suggests the ‘Temperate cool-season wet’ and ‘Temperate subhumid’ agro-climatic zones might be facing relatively more changes than some other zones.

Complete development of a process for assessing how potential additions to the NRS contribute to the *adequacy* of the system taking into account future change in the abundance and distribution of species and changes in ecosystem types.

Complete development of a framework for strategically protecting wetlands, groundwater dependent ecosystems and freshwater habitats in the NRS and via other programs.

Where there is demand to conserve species that are unlikely to survive in the wild, areas of more intensively managed habitat might be required. Establish broad community consultation to help inform decisions about which species to protect.

8.9.3. Manage habitat to reduce threats

Reducing threats to biodiversity, both in protected areas and the boarder landscape, will greatly increase the adequacy of protected areas to maintain the viability of species. The nature and impact of threats will change in many protected areas with climate change placing additional demand on the resources and skills of managers. A focus on reducing threats may be especially important in areas where there are concentrations of particularly vulnerable species, for example in drought and climate refuges or where species are restricted to specific and disappearing habitats (e.g. wetlands, tops of mountains). In addition, in some protected areas it may be possible to manage the changes in habitat that occur as climate change progresses to maintain its suitability for key species.

Priorities

Revise guidelines and policies for management of protected areas to be consistent with revised conservation goals and anticipated changes in species, ecosystems and threats. Ensure protected area managers have adequate resources to build capacity to interpret changes and to enable flexible and effective responses to emerging threats.

Develop plans for implementing revised conservation goals in each region and protected area; including, for example, which management units are to be managed to “facilitate change and natural adaptation” and which are to be managed to “preserve vulnerable species”.

Develop strategic plans for managing key changes and threats in bioregions, including arrival of new species, altered fire regimes, changed land use in and around protected areas and altered hydrology. In some situations limited action may be required, especially where habitat heterogeneity and redundancy buffer the impacts of threats, but where changes have clear undesirable impacts on other aspects of biodiversity actions to manage the threats may be required. Priority bioregions for early development of such plans could include those in the ‘Temperate cool-season wet’ and ‘Temperate subhumid’ agro-climatic zones as well as previously identified key regions (e.g. Kakadu, Australian Alps).

Resource and implement plans to manage threatening processes. Where feasible, control potential source populations of potentially invasive exotic species. Increase restrictions on the entry of exotic domestic, agricultural and horticultural species to Australia and their distribution around the country.

8.9.4. Manage landscape-scale issues

Protecting a diversity of habitat will not be sufficient to conserve many species especially under climate change. There are a range of important ecological processes that occur at landscape or broader scales that may be affected by habitat fragmentation and the spatial arrangement of landscapes. Movement of individuals between habitats and regions is important for many species. The scales of movement vary from patch to continent and daily to decadal. Habitat connectivity (varying from contiguous habitat to spaced “stepping stones”) may be critical for facilitating movements in many species. As species bioclimatic envelopes shift under climate change the distributions of many species are expected to change. Distribution changes will be facilitated by connectivity of habitat as well as distribution of habitat across the landscape, although the nature of connectivity that might be required would vary significantly among species.

Hydrological flows between parts of the landscape, along the surface or through aquifers, are a critical component of the functioning of many terrestrial landscapes in Australia. Flow regimes are also clearly critical in wetland and riverine systems. In such systems alteration of habitat in one part of the landscape can critically affect ecological processes elsewhere.

The spread of fire, affecting its extent and the frequency of fire, can be affected by the spatial arrangement of different vegetation types and land uses in a landscape. Managing vegetation patterns at the landscape scale may be an effective way to minimise the impact on biodiversity of an increased frequency for fire at the regional scale.

Priorities

Develop a framework for considering landscape processes (including fire, movement of organisms, hydrological flows) in assessments of potential additions to the NRS and in other habitat protection programs. This should consider the positive and negative consequences of different levels of connectivity. In particular, it is probably most suitable to seek a range of levels of connectivity among habitat, from isolated patches through to contiguously connected networks of habitat.

Where desirable, protect existing habitat connectivity (i.e. reduce habitat fragmentation) especially where different types of habitat and landscape elements are connected. Identify areas in the landscape that may be particularly important for the persistence of species during periods of stress (e.g. drought and fire refuges), ensure threats are managed in those areas, and ensure species continue to have access to and from them.

Minimise interruptions to landscape-scale hydrological processes that might arise from significant changes in vegetation structure (e.g. establishment of plantations). Ensure environmental flow allocations are not disproportionately reduced as a result of climate change.

Increase the suitability of habitat in the regions between protected areas (and particularly adjacent to protected areas) by facilitating land use practises that are more sympathetic to native biodiversity. For example, low grazing pressures, native pastures, leaving dead trees and fallen timber, reduced fertiliser use, maintenance of paddock trees, and preservation of creeks and wetlands.

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