Bushland and Urban Biodiversity Management in a Changing Climate:

climate change projections and resulting implications for management of biodiversity assets at a local government level in Eastern Suburbs Melbourne.

This paper forms part of the project
*"Bushland management and climate change:
Adapting management practices in response to landscape change"*
as developed by the Eastern Alliance for Greenhouse Action.

This project is funded through the Victorian Government's
Sustainability Fund under the Victorian Local Sustainability Accord.

Updated May 2013

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The Eastern Alliance for Greenhouse Action (EAGA) comprises Booroondara City Council, Knox City Council, Monash City Council, Maroondah City Council, Whitehorse City Council and the Yarra Ranges Shire Council.

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Version Update November 2011

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1. Introduction

"Bushland and urban biodiversity management in a changing climate" is a project implementing the first stage of a program to assist Local Government Authorities (LGAs) to better manage biodiversity assets on public and private land within their jurisdiction.

The objectives of the project are to:

1. document the needs, issues and opportunities for local government to enable them to support species and ecosystems to adapt to climate change – with a strong focus on biodiversity and bushland management on public and private land; and

2. identify knowledge gaps to enable local government to manage public and private land biodiversity in a changing climate.

Project Area
This project looks specifically at the outer Eastern Suburbs of Melbourne, incorporating the council areas of Boroondara City Council, Knox City Council, Maroondah City Council, Monash City Council, Whitehorse City Council and the Yarra Ranges Shire Council which comprise the Eastern Alliance for Greenhouse Action (EAGA).

Project Steps

Step 1: Literature Review for issues around climate change impacts on biodiversity in general and more specifically in the EAGA region. Attached as Appendix A.

Step 2: This Projections Paper that outlines the potential changes to climate in the EAGA region and their possible impacts on biodiversity associated with those changes.

Step 3: An interactive workshop with all EAGA councils to discuss the projections paper in the context of current local government biodiversity asset management to identify the issues, opportunities and knowledge gaps that need to be addressed.

Step 4: Development of an Issues Paper to address what has been learnt in the first three stages of the project and to identify areas for further investigation in a Case Study.

Step 5: Conduct a Case Study with the assistance of ARCUE (Australian Research Centre for Urban Ecology) in order to test the ability of the current knowledge to support changes in biodiversity management and to develop a protocol or tools to help assist local governments.

Step 6: Review the Case Study in relation to the Issue Paper and create a final report to show the outcomes of the project.

The Role of Local Government in Biodiversity Protection

In many cases Local Government Authorities (LGAs) are at the front line of natural resource management on both public and private land, and therefore have a very important role to play in biodiversity management. They are managers of public land, regulators of development and planners for land use and patterns of development. They are also the closest government authority to influence biodiversity protection on private land as leaders demonstrating environmentally responsible behaviours, as support for private land holders in the form of education, training and capacity building, and also as motivators through incentive schemes.

In the Victorian government's "Securing our Natural Future: A white paper for land and biodiversity at a time of climate change" (2009), the roles and responsibilities of LGAs in natural resource management are listed as to:

- Advocate and promote proposals which will benefit the local community
- Plan for and provide services and facilities for the local community
- Provide and maintain community infrastructure in the municipal district
- Undertake strategic and land use planning for the municipal district including: planning for sustainability in nature conservation, energy use and community involvement
- Administrator of Victorian Planning Provisions.

In many cases LGAs work with the State government to manage biodiversity assets, particularly where assets overlap or are connected. Key State government agencies involved in biodiversity management include: Department of Sustainability and Environment, Parks Victoria, Melbourne Water and Catchment Management Authorities.

General descriptors of biodiversity assets which LGAs in the EAGA region may manage include:

- Grasslands
- Bushland Reserves
- Street trees
- Waterways and water bodies
- Roadside vegetation and linear reserves
- Parks and recreation areas with remnant vegetation
- Ecologically mature forests

In some cases biodiversity assets may be seen more simplistically as community assets that add visual amenity or recreational benefits to an area. They may also be seen as community assets that can influence property values, encourage tourism to an area or act as buffers to heat island effects in urban areas. With this wide range of values to biodiversity assets, LGAs face challenges in how they approach the management of these assets.

2. Climate Change Projections for the EAGA Region

Climate projections methodology

It is necessary to consider uncertainty when making climate projections for any given location. Major factors contributing to uncertainty in producing climate projections include:

- difficulties in predicting the level of future emissions growth and global atmospheric concentrations of greenhouse gases (GHG's) and
- variation in the global climate models as they capture the complexities of the climate in different parts of the world.

To address uncertainty in relation to future GHG emissions growth, the Intergovernmental Panel on Climate Change (IPCC) developed a range of potential GHG emissions scenarios for their Special Report on Emissions Scenarios (Nakićenović & Swart 2000). The scenarios were intended to portray a plausible set of future economic and social conditions (or story lines) that described alternative broad development patterns for the world. These alternatives are considered when creating climate projections for this project.

While at 2030 there is little difference in the global warming estimates (and ranges) for the range of SRES scenarios, further into the century the choice of emission scenario can have an impact (Reisinger 2010). For this reason, in the assessment of climate futures for the EAGA region, only one emission scenario, the A1B 'mid-range' scenario, was considered necessary to represent the 2030 period. However, for the outlook periods 2050 and 2070, a lower emission scenario (B1), and a higher emission scenario (A1FI), were selected to represent a range of emissions possibilities into the future. It is interesting to note that since the development of the SRES scenarios, global emissions have been tracking the higher end of the SRES emissions envelope (Manning *et al.* 2010).

To account for the variation in results from different global climate modelling groups from around the world the range of results from 24 climate models were included when producing the climate projections for the EAGA Region. These 24 global climate models, hereafter referred to as 'models', represent the entire set archived in the CMIP3 Multi-Model Dataset at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (see: http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php).

Data presented have been derived using the Representative Climate Futures methodology (Clarke *et al.* in press). Climate Futures for the 5° grid centred on 37.5°S 146.5°E, which includes the EAGA region, are presented. In this study "Most Likely" and "Worst Case" climate futures were considered for the region. The most likely climate future is defined as that represented by the greatest number of models. The worst case is defined as the climate future that would have the greatest impact on ecosystems in the EAGA region i.e. greatest increase in temperature and/or greatest drying.

Climate projections were calculated for the EAGA region for the 30 year climatology centred on outlook periods 2030, 2050 and 2070. Values provided are relative to a 30 year period centred on 1990 (1975 – 2004). The changes summarised below should be interpreted as an overview of projected changes in aspects of the climate of the EAGA region as provided in "Climate Futures for Eastern Melbourne" (CSIRO, July 2010).

Table 1a - Projected future changes in climate for the EAGA region

2030

Medium GHG emission scenario

- **The most likely climate future (14 of18models) is that it will be warmer (with a range of +0.6 to +1.0°C) with little change in annual rainfall (-4.9 to +1.3%). There will be increases in summer maximum temperature and winter minimum temperature of 0.2 to 0.5°C and of 0.2to 0.3°C respectively.**
- The suggested worst-case climate future (4 of 18 models) is that it will be warmer (+0.7 to +1.1°C) and drier (-7.5 to -5.1%). There will be increases in summer maximum temperature and winter minimum temperature of 0.3 to 0.4°C and of 0.2 to 0.3°C respectively.

2055

High GHG emission scenario

- **The most likely climate future (8 of 18 models) is that it will be hotter (+1.7 to +2.5°C) and drier (ranging from little change to drier, -6.2 to -14.0%). There will be increases in summer maximum temperature and winter minimum temperature of 1.1°C and of 0.7°C respectively.**
- The suggested worst-case climate future (2 of 18 models) is that it will be much hotter (+1.6 to 2.5°C) and much drier (-17.2 to -17.5%). There will be increases in summer maximum temperature and winter minimum temperature of 0.7 to 0.9°C and 0.4 to 0.7°C respectively.
- Other climate futures are possible (5 of 18 models) are slightly cooler, 3 of these models are in the drier category and 2 models have little rainfall change. The other 3 (of 18) models are just as hot as the most likely group but have little change in rainfall.

Low GHG emission scenario

- **The most likely climate future (10 of 18 models) is that it will be warmer (+0.8 to +1.5°C) with little change in annual rainfall (-10.1 to -5.1%). There will be increases in summer maximum temperature and winter minimum temperature of 0.3 to 0.4°C and of 0.2 to 0.3°C respectively.**
- In this instance, the suggested worst case climate future is the same as the most likely climate future.
- The other 8 climate models indicate similar temperature increases but with little change in annual precipitation.

2070

High GHG emission scenario

- **In this instance there is no most likely climate future as there is no group of models with a total percentage greater than 27%. For the models to be grouped under most likely, it is necessary for there to be a percentage of 33% or more.**
- The suggested worst-case climate future (2 of 18 models,) is that it will be much hotter (+3.5°C) with much drier conditions (-19.4 to -24.1%). There will be increases in summer maximum temperature and winter minimum temperature of 1.3°C and 0.9°C respectively.
- 13 of 18 models are in the hotter category varying from much drier (4 models), to drier (5 models) to little change in rainfall(4 models)
- The remaining 3 models are in the same temperature category as the worst case but indicate less of a drying trend.

Low GHG emission scenario

- **The most likely climate future (8 of 18 models) is that it will be warmer (+0.9 to +1.4°C) with little change in annual rainfall (-6.2 to -12.1%). There will be increases in summer maximum temperature and winter minimum temperature of 0.5 °C and 0.3°C respectively.**
- The suggested worst-case climate future (2 of 18 models) is that it will be warmer (+1.8°C) and drier (-9.9 to -12.4%). There will be increases in summer maximum temperature and winter

minimum temperature of 0.7 and 0.5°C respectively.

- 6 of 18 models project similar temperature shifts to the most likely climate future, but less drying. The remaining 2 models have similar temperatures to the worst case climate future, again with less drying.

Table 1b - Summary of most likely projected future changes

Temperature

- *Average temperatures will increase in all seasons, most significantly in summer and least in winter.*
- *The frequency of hot days will increase.*
- *The frequency of warm nights will increase in all seasons, but most in summer.*

Precipitation

- *With higher emissions into the future there are likely to be decreases in average rainfall in all seasons.*
- *The majority of the models project greatest percentage decreases in average rainfall to occur in spring.*
- *There will be increases in evaporation across all seasons with most models indicating the largest increases will be in winter.*
- *Projected decreased rainfall and increased evapotranspiration is likely to lead to decreased average streamflow.*
- *The frequency of dry days will increase.*

Relative humidity

- *By 2030 a decrease in annual average relative humidity of around 0.8% (+0.2 to -1.8%) is likely.*
- *By 2050 decreases in annual average relative humidity of around 0.5% (0.2 to 1.0%) and around 2.7% (-2.0 to -3.6%) are likely under low and high emissions scenarios respectively.*
- *By 2070 decreases in annual average relative humidity of around 2.7% and around 4.1% (-1.8 to -5.2%) are likely under low and high emissions scenarios respectively.*

Fire Weather

- *The frequency of weather conditions conducive to high forest fire risk will increase.*
- *The fire season will start earlier and end later in the year.*

Extreme Wind Speeds

- *The majority of models indicate extreme wind-speeds could decrease in spring, summer and autumn and increase in winter.*

Solar Radiation

- *By 2030 an increase in annual average solar radiation of around 0.8% (0.1 to 1.6%) is likely.*
- *By 2050 increases in annual average solar radiation of around 0.9% (-0.1 to 1.9%) and around 2.7% (0.6 to 4.8%) are likely under low and high emissions scenarios respectively.*
- *By 2070 increases in annual average solar radiation of around 0.6% (0.4 to 2.5%) and around 3.1% (0.5 to 5.4%) are likely under low and high emissions scenarios respectively.*

3. Projected Impacts of Climate Change on Biodiversity

Adapted from Campbell et al. 2009, ***Review of the Literature on the Links between Biodiversity and Climate Change: Impacts, Adaptation and Mitigation****. Secretariat of the Convention on Biological Diversity, Montreal; Technical Series No. 42.*

Climate change will have significant impacts on many aspects of biological diversity; on ecosystems, species, genetic diversity within species, and on ecological interactions. The implications of these impacts are significant for the long-term stability of the natural world and for the many benefits and services that humans derive from it.

Because of the importance of these impacts and of climate change itself, there has been a great deal of recent research, which has added to the evidence base.

The evidence for the impacts on biodiversity comes from three principal sources. First, from direct observation of changes in components of biodiversity in nature (either recently or in the distant past) that can be clearly related to changes in climatic variables. Examples include observed phenological changes in bird arrival times and changes in distribution. Second, experimental studies using manipulations to elucidate responses to climate change. For example, examining the effect of increases of temperature on butterfly emergence (Kearney *et al.* 2010). Finally, and most widely, from modeling studies where our current understanding of the requirements and constraints on the distributions of species and ecosystems are combined with modeled changes in climatic variables to project the impacts of climate change and predict future distributions and changes in populations.

Dimensions of climate change in the EAGA Region

Climate change is a diabolical policy problem (Garnaut 2008) that has already had an observed impact on natural ecosystems. Global average temperatures have risen by 0.7°C over the last century and are predicted to continue rising. The IPCC (2007) projects that temperatures are likely to have risen by 1.1°C to 6.4°C by the end of the 21st century relative to the 1980-1999 baseline. Although such projections do not account for mitigation policies, it is widely accepted that temperature rises are likely to surpass the lower bound, particularly as current models do not take into account climate-carbon cycle feedbacks.

Temperature rises are linked to changes in precipitation regimes which can be predicted with less confidence as they are largely influenced by regional processes. Understanding precipitation regimes and their influence is vital for projecting changes in many natural systems (Knapp *et al.* 2008).

According to **Climate Futures for Eastern Melbourne** (CSIRO, July 2010), if emissions continue on the present trajectory , by 2050 the EAGA Region annual average temperatures are most likely to be 1.6 to 2.7°C hotter, with precipitation reduced by up to 13%. By 2070 it is most likely to be much hotter (2.0 to 3.0°C) and drier to much drier, with precipitation reduced between 6% and 21%.

It is also important to recognize that local climatic regimes comprising the full suite of climate variables are what influence the survival of species and ecosystems. With climate change, areas of rare climates are likely to shrink, and may result in the loss of rare endemic species (Öhlemüller *et al.* 2008).

Compounding Factors

Climate change is not the only pressure acting on natural systems and its effects are strongly dependent on interactions with these other pressures:

- Pollution
- Land Clearing
- Land Use Changes
- Overgrazing
- Fire wood collection
- Fragmentation of remnant vegetation
- Introduced exotic weeds and feral animals
- Highly modified hydrology
- Over committed water use
- Widespread use of fertilizer & other chemicals
- Changes to fire regimes
- Urbanisation
- Mining

IMPACTS ON ECOSYSTEMS

The effect of climate change will often be felt when it combines with overlying climate variability to exceed the coping range of a system. Assuming that there is no change in the variability of the climate, if the coping range of the system is optimised for past climate conditions, then conditions outside the coping range will occur with increasing frequency as climate change progresses.

Types of Impacts on Ecosystems

Observational, experimental and modelling work has pointed to several broad types of major changes to ecosystems as a result of climate change.

Ecosystem distribution

Modelling studies combined with experimental evidence of species tolerances point to significant changes in the distribution of some ecosystems, principally due to increasing temperature and altered precipitation regimes. Such changes will happen first at present boundaries between ecosystem types (Thomas *et al.* 2008), and their actual occurrence is dependent on the ability of component species to migrate and to the availability of suitable substrates.

> *For example, there is some evidence of an upward shift of tree species (Beckage et al. 2008). The models project large impacts resulting from pole ward shifts in boreal regions (Notaro et al. 2007; Alo and Wang 2008; Metzger et al. 2008; Roderfeld et al. 2008; Wolf et al. 2008a) and upwards shifts in montane systems, where lack of space at higher latitudes/altitudes may cause some systems to disappear entirely.*

Projected changes in ecosystem distributions vary regionally (Metzger et al. 2008; Pompe *et al.* 2008). There is only very limited scope for changes in distribution of aquatic ecosystems, other than through the local disappearance of some ecosystems (e.g. wetlands; McMenamin *et al.* 2008) or change in physical type (e.g. river channels).

Ecosystem composition

In addition to shifting their location climate change will alter the composition of many ecosystems. Some observational studies have already documented species turnover and attendant changes in species richness within both terrestrial and aquatic ecosystems, especially at temperate latitudes (e.g. Daufresne and Boet 2007; Lemoine *et al.* 2007; Moritz *et al.* 2008), as species less tolerant of new conditions are replaced by those with greater tolerance for warmer and drier conditions and increased fire occurrence. Modelling studies identify many more examples of likely species turnover (Levinsky *et al.* 2007; Buisson *et al.* 2008; Colwell *et al.* 2008; Trivedi *et al.* 2008b).

Rising temperatures are a key factor in such a turnover, but changing precipitation regimes are also important and rising CO_2 concentrations have important effects where they favour C3 plants such as trees over C4 grasses. Their actual occurrence is dependent on the pool of available species and their migration rate (e.g. Colwell *et al.* 2008). In some cases, the arrival of new species has been observed to lead to modest and probably transient increases in overall species richness (Buisson *et al.* 2008) in an ecosystem, but when species with the appropriate tolerances cannot reach a site, loss of intolerant species can lead to an overall impoverishment (e.g. Colwell *et al.* 2008; Deutsch *et al.* 2008; Huntley *et al.* 2008a).

Climate change could bring great confusion to the existing pattern of plant diversity, with scarcely predictable consequences for our ecosystems and mankind (Sommer *et al.* 2010). Site level reductions in species richness are of concern because under changing environmental conditions, multiple species play a role in ensuring that ecosystem processes can continue (Hobbs *et al.* 2007b). Processes potentially dependent on species richness include carbon storage (Bunker *et al.* 2005), so compositional changes may have important feedback effects on climate change. Regional losses in overall species richness can be exacerbated by land-use changes (Higgins 2007).

There is also increasing concern regarding the role of climate change in facilitating the spread and establishment of invasive species, which can have major impacts on ecosystem composition (Hobbs *et al.* 2007b; Hellmann *et al.* 2008; Rahel and Olden 2008; Rahel *et al.* 2008). Climate change has been recognised as one of several interacting factors that can enable native species to become invasive (van der Wal *et al.* 2008).

Ecosystem function

There is also rising concern that changes in species composition also lead to changes in the physical and trophic structure of ecosystems, with resulting further effects on system function and composition. Another structural change that has been observed, induced in experimental manipulations and projected is the invasion of temperate grasslands by woody plants, which is facilitated by increasing CO_2 concentrations (Morgan *et al.* 2007; Bloor *et al.* 2008) and which alters the availability of food for grass-eating herbivores. In other systems, trees may disappear as a result of drought (February *et al.* 2007; Foden *et al.* 2007; Badgley *et al.* 2008) and increase the probability of extinction for herbivores unable to digest C4 grasses, as well as the dispersal and dynamics of other plant species. Advances of the treeline also change the structure of montane systems (Beckage *et al.* 2008).

Climate changes in combination with changes in ecosystem composition and structure have been shown both by modelling and experimentation to lead to changes in ecosystem function. Changes in productivity will result in changes in litterfall and nutrient cycling. Where litterfall increases, it may contribute to increasing respiration and loss of soil carbon (Sayer *et al.* 2007).

Another aspect or attribute of ecosystem function that will certainly be affected by climate change is phenology. Many different approaches have been used to address this issue, but a fully coherent picture of likely responses has yet to emerge (Cleland *et al.* 2007). Long-term observational data play a key role. They show, amongst other things, that in warm temperate forests warming accelerates spring budburst and delays autumn leaf fall (Fujimoto 2008).

Changing climatic variables can have a profound influence on successional processes and community dynamics. The evidence that climate change can profoundly influence host-pathogen dynamics is growing, not only for plant diseases but also for animal and human diseases (Purse *et al.* 2005; e.g. Haines *et al.* 2006).

Enhanced phytoplankton blooms favour cynobacteria, resulting in increased threats to the ecological status of lakes and increased health risks (EEA *et al.* 2008).

Ecosystem services

A final, key property of ecosystems that may be affected by climate change is the values and services they provide to people. These include provisioning services such as fisheries and timber production. Climate change affects the ability of montane and other ecosystems to regulate water flow (Nunes *et al.* 2008; Ruiz *et al.* 2008), and critically reduces the ability of many different ecosystems to sequester and/or retain carbon (Bunker *et al.* 2005; Morales *et al.* 2007; Wang *et al.* 2008), which can feedback to climate change.

Ecosystem Types in the EAGA Region

Grasslands and savannas

According to the IPCC AR4, both tropical and temperate grasslands are sensitive to variability and changes in climate, which are likely to have strong effects on the balance between different life forms and functional types in these systems. The mixture of functional types (C3 and C4 photosynthetic systems) and their differential responses to climate variables and CO_2 fertilisation mean that non-linear and rapid changes in ecosystem structure and carbon stocks are both likely and difficult to predict with any certainty. Rising temperatures are likely to increase the importance of C4 grasses, but CO_2 fertilisation may promote C3 species and the expansion of trees into grasslands. The major climatic effect on the composition and function of grassland and savanna systems is likely to be through precipitation changes and associated changes in fire and disturbance regimes. Modelling has shown major reductions in rainfall as a result of large scale changes in savanna vegetation cover, suggesting positive feedbacks between human disturbance and climate change. The role of temperate grasslands in carbon storage is strongly dependent on rainfall. There are few studies on fauna. The proportion of threatened mammal species may increase by 10-40 per cent; changing migration routes are a threat. Large reductions in species' range size have been projected.

Forests and woodlands

Modelling approaches predict that major changes in global forest cover are likely to occur at temperature rises over 3°C. Mostly they predict significant loss of forest towards the end of the century, particularly in boreal, mountain and tropical regions, but some climate-limited forests are expected to expand, particularly where water is not limited. Recent moderate climate changes have been linked to improved forest productivity, but these gains are expected to be offset by the effects of increasing drought, fire and insect outbreaks as a result of further warming. Estimates of the ability of tree species to migrate are uncertain. Losses of species diversity have been projected. Mountain forests appear particularly vulnerable. Extinctions of amphibian species in montane forests have already been attributed to climate change, and in most cases extinction risks are projected to increase. Substantial changes in the tree flora of Australia are expected (Hughes 1996).

Forests play an important role in delivering a wide range of ecosystem services, including the provision of timber, fuel and other non-timber forest products, carbon sequestration, regulation of hydrological processes and flows and retention of biodiversity. Research suggests that warming and drying climates in combination with land-use change, fire and other pressures are likely ultimately to reduce the capacity for carbon storage in the vital carbon reservoirs of both boreal and tropical forests (Nitschke and Innes 2006; Malhi et al. 2008).

A very important advance since the IPCC AR4 is the recognition that old growth forests continue to store carbon rather than being carbon-neutral (Luyssaert et al. 2008) and that they therefore play a vital role in offsetting carbon emissions.

Mountains

Mountain regions have already experienced above average warming, and its impacts, including water shortages, are likely to be exacerbated by other pressures causing ecosystem degradation, such as land-use change, over-grazing and pollution. There is a disproportionately high risk of extinction for endemic mountain biota, partly because of their restricted geographic ranges and possibilities for migration, which can result in genetic isolation and stochastic extinctions. A reshuffling of species along altitudinal gradients is to be expected from their differential capacities to respond to change. Warming is expected to produce drying due to higher evapotranspiration in many mountain systems, and this will in itself reduce the feasibility of upward movement of treelines.

Inland waters

Inland aquatic ecosystems are highly vulnerable to climate change. Higher temperatures will cause water quality to deteriorate and will have negative impacts on micro-organisms and benthic invertebrates. Plankton communities and their associated food webs are likely to change in composition. Distributions of fish and other aquatic organisms are likely to shift polewards and some extinctions are likely. Changes in hydrology and abiotic processes induced by changes in precipitation as well as other anthropogenic pressures will have large impacts on aquatic ecosystems. Increases in the variability of precipitation regimes will also have important impacts and may cause biodiversity loss in some wetlands. Seasonal migration patterns of wetland species will be disrupted. The impacts of increased CO_2 will differ among wetland types, but may increase NPP in some systems and stimulate methane production in others. On the whole, ecosystem goods and services from aquatic systems are expected to deteriorate.

IMPACTS ON SPECIES

Climatic change has already caused changes to the distribution of many plants and animals, leading to severe range contractions and the extinction of some species. The AR4 states, with very high confidence, that observational evidence from all continents and most oceans shows that species are being affected by regional climate changes, particularly temperature increases (Rosenzweig *et al.* 2008). Changes have occurred in terrestrial and marine ecosystems; they include phenological changes (for example in leaf unfolding, flowering date, migration and time of reproduction), species distributions, community structure, species interactions, changes in ecosystem functioning and productivity, including shifts from cold-adapted to warm-adapted communities (e.g. Edwards and Richardson 2004; Rosenzweig *et al.* 2008). Most of these changes are in the direction expected with warming temperature (Rosenzweig *et al.* 2008). Some species are unable to disperse or adapt fast enough to keep up with high rates of climate change and these species face increased extinction risk (Menendez *et al.* 2006), and, as a result, whole ecosystems, such as cloud forests, may cease to function in their current form. Here recent observed and modelled climate change impacts on species, including changes in species' distributions and population changes are reviewed.

Changes in Distribution

Climatic conditions, such as temperature and precipitation, determine suitable habitat for certain species, such as Australian Eucalypts (Hughes *et al.* 1996) and kangaroos (Ritchie and Bolitho, 2008). Rapid changes in climatic conditions are therefore likely to change the geographic extent of species distributions, resulting in latitudinal and/or altitudinal shifts and/or contractions of species' ranges. Many eucalypt species will have their entire present day populations exposed to temperature and rainfall regimes under which no individuals currently exist (Hughes *et al.* 1996). Bioclimatic modeling predicted an average reduction in northern Australian kangaroo distributions of around 48% in response to increases of 2.0°C. At this temperature, the distribution of one (*Macropus antilopinus*) was reduced by close to 89% (Ritchie and Bolitho, 2008).

Documenting incipient range shifts requires intensive surveying and resurveying at high spatial resolution. The global mean velocity at which temperature zones are expected to shift has been found to be 0.42 km per year, but this varies with topography as temperature decreases rapidly with altitude (Loarie *et al.* 2009). In flat areas the temperature velocity may be up to 1.26 km per year. The survival of individual species may depend on their capacity to keep pace with moving climates and whether or not habitats are sufficiently connected to allow migration. Refugia may be found on South-facing slopes, which are cooler than Northern aspects (Ashton 1976, quoted in Nitschke 2007).

Southward shifts

Meta-analyses of observed impacts on species found that there have been significant range shifts towards the poles in the recent past (Parmesan and Yohe 2003; Root *et al.* 2003). Recent observational evidence for more species, including plants (Colwell *et al.* 2008), invertebrates (Hickling *et al.* 2006; Franco *et al.* 2006; Mitikka *et al.* 2008), and vertebrates (Gaston *et al*. 2005; Hickling *et al.* 2006; Hitch and Leberg 2007; Lemoine *et al.* 2007; Sorte and Thompson 2007; Schliebe *et al.* 2008) strengthen these findings of substantial latitudinal shifts of range boundaries, centres of occurrence and abundance.

Altitudinal shifts

New observational evidence backs up findings that species tend to move upwards to higher elevations with increasing temperatures. Up-slope shifts have been observed for plants in Europe (Kullman 2007; Lenoir et al. 2008) and North America (Kelly and Goulden 2008). Butterflies ranges have shifted upwards by over 200 m in 30 years in Spain, consistent with shifts in isotherms (Wilson *et al.* 2005; Wilson *et al.* 2007). Temperate mammal, South East Asian bird, and Madagascan amphibian and reptile ranges have shifted up-slope (Parmesan 2006; Peh 2007; Moritz *et al.* 2008; Raxworthy *et al.* 2008). Observed altitudinal shifts for species on mountains and in grassy habitats were larger than in other species (Lenoir *et al.* 2008).

Range contraction

With species distributions shifting polewards and up-slopes, the ranges of many species may contract, if current and projected ranges do not overlap and species are unable to migrate. Interactions between climate change and landscape changes will impede range shifts, resulting in range contractions and potential extinctions (Carroll 2007). Jetz *et al.* (2007) have projected that 5 per cent of all land bird species will suffer range reductions of more than 50 per cent by 2050. This is particularly severe for species with limited dispersal abilities, e.g. reptiles and amphibians (Hickling *et al.* 2006), plants (Huntley 2007), species with slower life history traits (Lenoir *et al.* 2008), and range restricted species such as mountain top specialists, e.g. high elevation mammals as land area declines with increasing elevation (Moritz *et al.* 2008). Some stream fish are projected to suffer significant range contractions (Xenopoulos *et al.* 2005; Xenopoulos and Lodge 2006), whereas other cool- and warm-water fish are likely to colonise newly suitable sites, resulting in dramatic changes in species composition (Buisson *et al.* 2008).

In addition to direct impacts on species, distribution changes are likely to result in the disruption of biotic interactions and networks when interacting species have responded differently to warming, with important ecological and evolutionary consequences (Parmesan 2006; Lenoir *et al.* 2008). There is some suggestion that novel biotic interactions could lead to decreased biodiversity in the future (Shuttle *et al.* 2007; Liow and Stenseth 2007) or engender more complex responses (Tylianakis *et al.* 2008) possibly dependent on co-factors such as dispersal ability (Brooker *et al.* 2007).

Changes in Population Status

The AR4 stated that up to 30 per cent of higher plant and animal species would be at high risk of extinction with a warming of 'only' 1.5-2.5°C over present temperatures. Many species have suffered population declines that have been attributed to the effects of climate change, acting through a range of mechanisms. However, other species have increased in both abundance and breadth of distribution.

In the absence of migration, 10-50 per cent of plants are likely to disappear.

According to Levinsky *et al.* (2007) up to 9 per cent of European mammals risk extinction, whereas 70-78 per cent may be severely threatened (losing over 30 per cent habitat) under one IPCC scenario, assuming no migration. Where unlimited migration is assumed such figures fall to 1 per cent and up to 46 per cent respectively. Endemic species were predicted to be most affected where no migration was assumed, and species richness was dramatically reduced in the Mediterranean region. Jetz *et al.* (2007) and Sekercioglu *et al.* (2008) evaluated exposure of all 8,750 land bird species to projected climate and land-use change scenarios; both conclude that 400-900 species are projected to suffer dramatic range reductions by the year 2100. Worldwide, every degree of warming projected a nonlinear increase in bird extinctions of about 100-500 species (Sekercioglu *et al.* 2008). The Orange-bellied Parrot is projected to become extinct in the wild within five years due to reduced availability of seed resulting from diminished freshwater inflows to the salt-marshes where the species feeds (Dooley 2010). Only 21 per cent of the species predicted to become extinct are currently considered threatened with extinction (Sekercioglu et al. 2008). More severe impacts are projected for the tropics, e.g. 74 per cent of rainforest birds of north-eastern Australia are predicted to become threatened within the next 100 years (Shoo *et al.* 2005).

Sinervo *et al.* predict that 6% of lizards will be extinct by 2050 and that figure will rise to 20% by 2080 (Sinervo *et al.* 2010). Synchronous declines in 11 snake populations in five different countries are thought to be attributable to a widespread common cause, such as climate change (Reading *et al.* 2010).

Climate change will severely affect biodiversity by 2100; however, in the near future land-use change may lead to yet greater species loss (van Vuuren *et al.* 2006; Jetz *et al.* 2007). Interactions among species, as well as those between climate change and other pressures that may threaten species, such as habitat loss, need to be included in models (Carroll 2007).

Mechanisms or causes impacting species in relation to climate change

Although considered separately below, these factors also interact and impact on species.

Temperature

Temperature can affect species range, life cycles and even cause direct death in individuals.
Some species' ranges appear to be limited by variation in temperature. Of 819 species of Eucalypts in Australia 53% currently have ranges spanning less than 3°C (mean annual temperature), 41% have a range of less than 2°C and 25% less than 1°C (Hughes *et al.* 1996).

Some species are directly impacted by temperature. For example, temperatures exceeding 42°C killed over 3500 individuals of Australian flying-foxes in nine mixed-species colonies (Welbergen *et al.* 2008). The early emergence of the common brown butterfly around Melbourne is causally linked to rising temperature associated with anthropogenic climate change (Kearney *et al.* 2010). Lizards appear to be susceptible to increasing temperature linked to climate change, with 6% of species expected to be extinct by 2050 (Sinervo *et al.* 2010).

Precipitation

Changes in precipitation can affect species range, spatial patterns and abundance and life cycles.
Species may also be limited in range by rainfall. 23% of Australian Eucalypt species have ranges than span less than 20% variation in mean annual rainfall (Hughes *et al.* 1996).

Precipitation and its seasonality and, in particular, droughts, have been shown to reduce populations of mammals and birds.

> *For example: In the critically endangered Helmeted Honeyeater (Lichenostomus melanops cassidix) of Yellingbo in the Shire of Yarra Ranges, the timing of egg laying became earlier and there was a possible reduction in the mean number of eggs laid per breeding season corresponding to a reduction in rainfall and mild warming (Chambers et al. 2008).*

Precipitation has been shown to explain spatial patterns of bird abundance in Australian tropical rainforest (Williams and Middleton 2008), and abundance of swamp antechinus (Magnusdottir et al. 2008). Droughts can cause resource bottlenecks (i.e. lack of insects, nectar or fruit) to tropical birds in Australia (Williams and Middleton 2008). Ongoing drought is also reported to be a major factor in the loss of large numbers of trees in Melbourne's parks and gardens (Cooke 2010).

Extreme events

Extreme temperature or precipitation events can have more significant impacts on species than gradual climatic changes due to direct loss of individuals or changes in breeding capacity.
Extreme temperatures exceeding the physiological limits of species have caused mortality in Australian flying-fox species (Welbergen *et al.* 2008). Floods have caused catastrophic, species-specific mortality in desert rodents resulting in rapid population and community-level changes (Thibault and Brown 2008). Interactions of extreme events with phenological changes can

result in reduced fecundity.

Competition/encroachment

Species competition can be increased through changes in species range and life cycles.

The difference in response to climate change between different functional groups may potentially increase competition within ecosystems, e.g. grasslands (Cleland *et al.* 2006), which may impact on population status. Early successional species can germinate at higher soil temperatures and may thereby increase in importance within a habitat (Colwell *et al.* 2008). Experimental work has also supported the potential role of CO_2 enrichment in promoting woody plant invasion of grasslands through its effect on competitive interactions between grass and tree seedlings (Bloor *et al.* 2008).

Pathogens, parasites and pests

Increases in diseases and changes in distribution increase impacts on species.

Climate change impacts on the complex interactions among host, pathogen and environment are poorly understood. However, there is some evidence that climate change is causing impacts on species by changing disease distributions and their severity, as species are stressed by increased temperatures. The evidence that climate change can profoundly influence host–pathogen dynamics is growing, not only for plant diseases but also for animal and human diseases (Purse *et al.* 2005; e.g. Haines *et al.* 2006).

Pounds *et al.* (2006) found that amphibian declines have already been caused by climate change largely through increases in disease. This study is supported by a number of other studies (Alford *et al.* 2007; Fisher 2007; Laurance 2008; Muths *et al.* 2008). The effects of climate, disease and other factors causing amphibian declines are not mutually exclusive. The largest study of global amphibian declines to date implicates climate change as a factor in amphibian decline, but stresses the importance of characteristics of the host, as well as other threats. In the 2,454 species that declined between 1980 and 2004, small range size, habitat loss, and extreme seasonality in precipitation contributed to the risk of decline (Sodhi *et al.* 2008).

There is some evidence from paleontological studies that pressures on plants may increase with climate change. Amount and diversity of insect damage to plants increased in association with an abrupt rise in atmospheric CO_2 and global temperature that occurred 55 million years ago (Currano *et al.* 2008). This increase in insect damage can change predictions of future forest composition (Wolf *et al.* 2008b).

Food supply

Changes in food supply composition or availability can impacts on the direct survival of species.

There may be both direct effects of climate change on the food supply for some species, and indirect effects such as through fire. Increased levels of atmospheric CO_2 may boost plant growth but the nutritional quality of vegetation may be reduced so that koalas, greater gliders and other marsupials will no longer be able to survive on gum leaves (Gleadow 2010; Foden *et al.* 2009; Hume 2008).

Shifting species distributions, changes in numbers of individuals, or even changing environmental conditions could have a knock on effect for species relying on those species as food. Changes in the abundance of prey species due to climate change can cause changes in predator numbers (Ims and Fuglei 2005; Carroll 2007). Changes in range may expose prey species to novel predators. In the Australian Alps, kookaburras are hunting at higher altitudes than before, preying on alpine skinks that fail to recognise them as predators (Low, T., in Steffen *et al.* 2009).

Phenological changes

Changes in the phenological cycles of species can lead to population declines due to lack of food resources or interruptions in reproductive cycles.

Climate change impacts on the timing of many natural events have been documented for many species. Several hundred papers have been published documenting phenological changes for plants and animals which have the potential to affect species' populations directly or indirectly. Most of this research comes from the northern hemisphere and the number of Australian studies documenting changes in phenology is still relatively small (Chambers, Hughes and Weston 2005; Chambers 2009).

Reviews of reported climate change impacts on plant phenology support the IPCC AR4 conclusions of advanced leafing, flowering and fruiting (3-5 days per °C temperature increase) and delays in autumn events (Menzel *et al.* 2006; Cleland *et al.* 2007; Bertin 2008; Fujimoto 2008). In southeastern Australia flowering dates in four perennial species were found to be up to 46 days later over a 20 year period (Keatley *et al.* 2004). Another study of 65 native species over 24 years found that 8 species flower an average of 1.7 days per year earlier while 5 flowered an average of 1.8 days per year later (Keatley and Hudson 2007). As plants are finely tuned to the seasonality of their environment, shifts in timing of plant activity provide most compelling evidence that they are affected by climate change (Cleland *et al.* 2007). Increased temperature and summer rainfall have been related to earlier flowering in two eucalypt species and later flowering in two others (Keatley *et al.* 2002). The influence of temperature on flowering in four Eucalypt species was identified and shown to be non-linear while rainfall was not a significant predictor (Hudson *et al.* 2009). A large proportion of the observed variability in life cycle events can be attributed to climate change (Van Vliet 2008). Experimental results indicate that increased temperature is the driver of advancing first flowering in temperate grassland of Tasmania, and not elevated CO_2 levels (Hovenden *et al.* 2008).

There is ample evidence showing that the timing of reproduction of insects, birds and amphibians is influenced by spring temperatures (e.g. Gordo and Sanz 2005; Gaston *et al.* 2005; Both *et al.* 2006; Dolenec 2007; February *et al.* 2007; Parmesan 2007). However, given Australia's high level of endemic species, already adapted to a highly variable climate system, the phenological changes, and drivers for these changes, seen in the Northern Hemipshere may not be directly transferable to Australian species (Chambers 2009). Nevertheless, pairing dates of lizards have been found to be earlier when winters were warmer and drier (Bull and Burzacott 2002) and changes of timing of breeding in Australian Magpies were linked to climate variables, including the Southern Oscillation Index (Gibbs 2007). The common brown butterfly around Melbourne has been shown to emerge from its cocoon 10 days earlier than it did 65 years ago (Kearney 2010).

Changes in phenology have been linked to population declines, potentially due to direct impacts, e.g. reduced number of eggs laid by the Helmeted Honeyeater (Chambers *et al.* 2008), or due to decoupling of species interactions (e.g. food, pollinators). In general it is uncertain how species will respond in terms of phenology when they reach temperature thresholds.

Migration

Changes in distance travelled and arrival and departure times for migration of bird species can have an impact on their access to food supplies and their reproductive success.

A number of studies have reported variation in timing of migration among bird species, showing earlier spring arrivals for birds (Green and Pickering 2002; Norment and Green 2004). Earlier arrivals and later departures with differences between short and long distance migrants have been reported in southeastern Australia (Beaumont *et al.* 2006). In a semi-arid region of Western Australia earlier arrivals have been generally linked to increasing maximum and minimum temperatures (Chambers 2005) while migration timing shifts in southwestern Australia showed a stronger relationship to rainfall than temperature changes (Chambers 2008). Birds may be able to adjust migration schedules phenotypically to tune their arrival dates optimally to meteorological conditions at the beginning of the breeding season. Changes in arrival times could have consequences on birds' fitness and reproductive success.

Resource availability

Phenological shifts in species can impact on availability of food resource and reproductive cycles.

As phenology advances in response to climatic warming, there is potential for development of a mismatch between the peak of resource demands by reproducing animals and the peak of resource availability. Phenological shifts have reduced the floral resources available to pollinators, resulting in a decreased diet breadth of the pollinators, and disruption of plant-pollinator interactions (Memmott *et al.* 2007).

Growth

There is some evidence that climate change may affect species growth which could therefore impact on populations. Changes in precipitation and temperature have also resulted in changes in biomass of trees (Lapenis *et al.* 2005).

Fecundity and reproduction

There is some evidence that fecundity is affected by climatic variation and may therefore be affected by long-term climate change. For the critically endangered Helmeted Honeyeater of central southern Victoria, Australia, climate also plays a role in the timing and success of breeding. During the period 1989 to 2006, the timing of laying became earlier and there was a possible reduction in the mean number of eggs laid per breeding season (Chambers et al. 2008). Lizards that have live offspring, which is common in Australian alpine species, tend to have lower body temperatures than those which lay eggs and have almost double the risk of extinction (Sinervo *et al.* 2010).

Sex ratios

In many egg-laying reptiles, the sex of offspring is determined by the temperature experienced during a critical period of embryonic development. Increasing air temperatures are likely to skew offspring sex ratios in the absence of evolutionary or plastic adaptation.

Dispersal

Changes in climate can affect the dispersal ability of species leading to species declines, particularly in populations that are slow to adapt.

There is evidence that climate can directly affect the dispersal ability of species, thus facilitating or hindering range shifts and ultimately contributing to population status. Several species have increased their dispersal potential through phenotypic and evolutionary processes which are linked to climate (Thomas *et al.* 2001; Møller *et al.* 2006). Changes in dispersal may also be age dependent. Duckworth (2008) reports that older populations tend to be less dispersive than new ones. A long-term study on the impact of temperature change on lizards showed juvenile dispersal declined dramatically over 16 years, correlated with a rise in spring temperature during development. This is likely to elevate the extinction risk of meta-populations (Massot et al. 2008). Indeed there are similarities between meta-population dynamics and dispersal dynamics which suggest that 'colonising' species are more likely, to expand their ranges in response to climate change than less dispersive species or be faster at doing so (Duckworth 2008).

Characteristics and factors contributing to vulnerability or resilience

The IPCC AR4 estimated that 20-30 per cent of species assessed would be at risk of extinction if climate change leads to global average temperature rises greater than 1.5-2.5°C. Preliminary analyses on the susceptibility of species to climate change according to their biological traits, suggest that for birds and amphibians as many as 35-70 per cent may be susceptible to climate change (Foden *et al.* 2008), and has added to our understanding of the characteristics that contribute to species' risks of decline or extinction.

Species with small ranges are at particular risk (Walther *et al.* 2005; Pompe *et al.* 2008; Sodhi *et al.* 2008), as are those with fragmented or isolated populations (Peter 1999).

Mallee Emu Wrens are found to be absent from habitat within 16 years of a fire (Brown 2009). Species that require late-successional habitat in ecosystems that are intolerant of fire or drought are at high risk from climate change and its interaction with fire (Nitschke and Innes 2006). Limited dispersal ability is also a key risk factor (Foden et al. 2008).

Genetic Diversity

Climate change impacts also affect genetic diversity and its maintenance. Genetic diversity is important both in its own right and in determining the resilience of species to the impacts of climate change and other pressures (Botkin *et al.* 2007). For example, experimental work has shown that eelgrass communities are much more resilient to increased temperature when they include high genetic diversity (Ehlers *et al.* 2008). In this example genetic diversity within a single species is crucially important for continued ecosystem function. Individual plant traits can also strongly influence the biogeochemical cycling of carbon, and differences in inter- and intra-specific responses to elevated CO_2 affect not only physiology and growth, but also higher order biotic interactions and lifetime fitness, ultimately leading to new ecosystem assemblages (Bradley and Pregitzer 2007).

Despite its importance, relatively little effort has yet been devoted to investigating the impacts of climate change on genetic diversity. One clear impact is in the fragmentation of populations when their habitats are fragmented by climate change, as in moist mountain ecosystems surrounded by drying lowlands.

IMPACTS ON ECOLOGICAL INTERACTIONS

As is clearly illustrated above in the sections on ecosystems and species, climate change is likely to affect ecological interactions, including competition, disease and host-parasite interactions, pollination, predator-prey interactions and herbivory. Experimental work has also supported the potential role of CO_2 enrichment in promoting woody plant invasion of grasslands through its effect on competitive interactions between grass and tree seedlings (Bloor *et al.* 2008). Differences in phenological responses between different functional groups may potentially increase competition within grassland ecosystems (Cleland *et al.* 2006). The greater effect of warming in suppressing productivity in more species rich experimental communities (De Boeck *et al.* 2008) has been attributed to negative impacts of intense inter-specific competition for resources under conditions of high abiotic stress.

There is ample evidence that warming will alter the patterns of plant, animal and human diseases.

Recent evidence suggests that mismatches in phenological responses to climate change between plants and pollinators may significantly affect their interactions (Bertin 2008). Modelled phenological shifts in response to climate change reduced the floral resources available to 17-50 per cent of all pollinator species. Reduced overlap between plants and pollinators also decreased diet breadth of the pollinators (Memmott *et al.* 2007). These patterns could lead to the extinction of pollinators and/or plants and disruption of their interactions.

There have been suggestions that climate change may affect predator-prey interactions. Changes relate from either direct effect of climate change on prey/predator numbers which then has knock-on effects on the other species (Ims and Fugelei 2005; Carroll 2007) or through conditions making prey more/less vulnerable to predators (Post *et al.* 1999; Schmitz *et al.* 2003).

Interactions between herbivores and plants are also likely to change as a result of climate influence. Recent observations of herbivore damage on plant fossils suggests that herbivore pressures on plants may increase with climate change; the amount and diversity of insect damage to plants increased in association with an abrupt rise in atmospheric CO_2 and global temperature that occurred 55 million years ago (Currano *et al.* 2008; DeLucia *et al*. 2008). On the other hand, as for pollination, phenological changes arising from climate change may cause decoupling between herbivores and their plant resources. Climate change has been blamed for the extreme severity of a recent mountain pine beetle outbreak in British Columbia, which has effectively turned the forest from carbon sink to carbon source (Kurz *et al.* 2008a). In northern Europe, damage of northern birch forests caused by leaf-chewing and leaf-mining insects is projected to be at least double with expected climatic warming (Kozlov 2008). This increase in insect damage can change predictions of future forest composition (Wolf *et al.* 2008b). On the other hand, climate change can cause reductions in overlap between herbivores and their host plants (Schweiger *et al.* 2008). The effects of climate change on ecological interactions like these are a large part of the key to understanding the likely effects of climate change on both species and ecosystems.

At present it is not possible to look at phenological changes for any dependent species in Australia as we currently have no information. This lack of data severely limits our ability to accurately model species outcomes under a changing climate. In order to better model, understand, and manage Australia's natural systems, improved observation networks are urgently required (Chambers 2009).

FEEDBACKS TO CLIMATE

Natural ecosystems are an integral part of the carbon cycle. The relationship between climate and biodiversity is not linear; and climate change impacts on natural ecosystems can exert significant positive feedbacks to the climate system. Greenhouse gas emissions from land-use change have been estimated to account for 20 per cent of all anthropogenic emissions (IPCC 2007); an estimate that could be amplified by climate change. This feedback cycle is not incorporated into current climate models, but is an area of growing research; particularly following concerns over the continued climate change mitigation capacity of ecosystems such as forest reported in the IPCC AR4. Climate-ecosystem feedbacks have been implicated in droughts in Western Australia (Chapin *et al.* 2008).

It is generally agreed that one of the main feedbacks to the climate system will be through the increase in soil respiration under increased temperature.

Loss of vegetation can also influence the surface albedo, providing further feedbacks to climate. In addition, it has been suggested that impacts of climate change on temperate forest could reduce its capacity to act as a carbon sink (Gough *et al.* 2008); through processes such as increased severity of insect outbreaks (Kurz *et al.* 2008a).

Indeed, although ecosystems are currently acting as a carbon sink to sequester 30 per cent of anthropogenic emissions, global scale climate scenario modelling suggests that the terrestrial biosphere will become a carbon source by 2100, largely due to the increased soil respiration and the dieback of the Amazon. It has been estimated that increased carbon sequestration may lead to an increase of N_2O emissions in grassland (*Kammann et al.* 2008).

Recent evidence supports the findings reported in the AR4 that impacts of climate change on ecosystems are likely to be amplified by positive feedbacks. Further research incorporating such feedbacks into climate models is required (Chapin *et al.* 2008).

CONCLUSION

The main lesson from recent research on the impacts of climate change on biodiversity is that many of the key findings at the time of the IPCC AR4 have been strengthened, with a greater range of evidence, including observational evidence, to support them. While there are some specific areas where new understanding has emerged or the balance of evidence has shifted, the larger scale picture is one of increased support for earlier findings.

This review found compelling evidence from current trends that ecosystems are starting to respond in terms of their distribution, composition, structure and function to the changes in temperature, precipitation and increased CO_2 levels that are occurring. Experimental studies as well as modelling studies have given an indication of what changes may occur (or continue to occur) in the future. Together these studies indicate that some ecosystems may shift poleward or upwards in mountainous regions. Indeed there are already indications of uphill migration of some treelines. Changes in species composition and richness have been documented and are likely to become more widespread. Novel interactions between species may form or invasive species may become established. Such changes in species composition could lead to changes in the physical and trophic structure of ecosystems, with resulting effects on system function and composition. Furthermore, recent findings suggest that the impacts of climate change on ecosystems are likely to be amplified by positive feedbacks.

Nevertheless, more research is needed in certain areas. Experimental studies are extremely useful in determining the effect of climate change on aspects of ecosystem composition, structure and function. However, the time needed to evaluate responses in such experiments, as well as expense, limits the number of studies in this field. Furthermore, changes in greenhouse gas levels are occurring over time frames that are difficult to simulate in experimental studies. Dynamic vegetation modelling has helped to improve our understanding of potential effects of climate change on ecosystems though there is still progress to be made in these models (Prentice *et al.* 2007). Work on the impact of climate change on freshwater ecosystems is starting to emerge. For instance, linkages between climate impact on aquatic systems and invasive species are only starting to be analysed (Rahel and Olden 2008).

At the species level, there are numerous correlative modelling studies simulating the potential impact of climate change on their distribution. For the most part, evidence from observations corroborates the projected poleward expansion of many species. Changes at the trailing edge of species distributions are less well documented though some recent examples reviewed have indicated contraction at the southern margin of many northern hemisphere species. However, detailed effects of changes at the leading and trailing edge of species distributions is an area that needs to be further researched (Thuiller *et al.* 2008). To ensure more realistic projections of the impact of climate change on populations, metapopulation dynamics, species' dispersal ability and demography would need to be incorporated into classic static species distribution models. Scientific research is moving forward in this area with the use of combination or framework models (del Barrio *et al.* 2006; Keith *et al.* 2008; McRae *et al.* 2008) and mechanistic models (Kearny *et al.* 2008). Such models may also help improve our understanding of the effect of climate change on species abundance (Green *et al.* 2008; McRae *et al.* 2008). Land use is rarely incorporated in these modelling studies, yet is likely to impact species' responses to climate change and/or interact with climate change.

Phenological changes are already being observed and mismatches in phenological responses to climate change between species (e.g. plant-pollinator relationships) may significantly affect their interactions and potentially lead to their extinction. Climate change is also likely to affect ecological interactions, including competition, disease and host-parasite interactions, pollination, herbivory and predator-prey cycles. There is ample evidence that warming will alter the patterns of plant, animal and human diseases. Numerous modelling studies project increases in economically important plant pathogens with warming, and experimental studies show similar patterns. However, there are fewer studies examining effects on predator-prey cycles or other ecological interactions. Species are likely to respond individually to climate change (Huntley *et al.* 2007), as they have in the past (Willis *et al.* 2007), and therefore novel interactions may occur with unknown effects.

Despite its importance, relatively little effort has yet been devoted to investigating the impacts of climate change on genetic diversity. Further research is needed to broaden and deepen our understanding of the role of genetic diversity in resilience to climate change and the degree to which that diversity is under threat from climate change and its interaction with other pressures.

The literature reviewed indicates that climate change is already impacting biodiversity from the ecosystem to the genetic level and feedbacks from ecosystem changes to the climate system could have serious implications, though there is some uncertainty in this area, such as turning current carbon sinks into sources. This suggests that adaptation and mitigation strategies will be increasingly important in the future.

4. Biodiversity conservation in a changing climate

From Steffen et al., A strategic assessment, 2009

Even with a rapid and vigorous level of global action to reduce greenhouse gas emissions, we are committed to continuing climate change for the rest of this century and beyond, and to a global average temperature of nearly 2°C or higher above pre-industrial levels. To avoid an escalating loss of biodiversity and the consequent disruption to the ecosystem services on which our society depends, Australian managers and policy makers must undertake a vastly enhanced conservation effort.

Biodiversity conservation in a changing climate requires a re-evaluation of what we are managing for. The rate of change within natural systems could be very swift compared to the past and the magnitude of change could be large. Management approaches that seek to maintain current spatial arrangements are counterproductive. Management objectives will need to be reoriented from preserving all species in their current locations to maintaining the provision of ecosystem services through a diversity of well- functioning ecosystems.

Concepts such as resilience and transformation provide positive, proactive avenues for reducing the vulnerability of biodiversity to climate change. The emphasis is on making space and opportunities for ecosystems to self-adapt and reorganise, and on maintaining fundamental ecosystem processes that underpin vital ecosystem services.

Progress in biodiversity conservation over the past several decades provides a solid base on which to tackle the climate change threat. A blend of existing and new policy and management strategies and tools is required. They can be grouped into three areas: (i) building resilience; (ii) proactive interventions; and (iii) flexible policy and management approaches.

BUILDING RESILIENCE

Maintain well-functioning ecosystems

With decades or centuries of projected climate change that is significant in magnitude but uncertain in detail, the single most important adaptation strategy is the maintenance of well-functioning ecosystems. However, a key question is when, under climate change, does maintenance of resilience of existing ecosystems become counterproductive and facilitation of transformation into new ecosystems become more appropriate? Better regional and local monitoring is required to inform such decisions.

Protect a representative array of ecosystems

The principle of representativeness – representing all biodiversity in appropriately managed systems – remains essential. However, under a rapidly changing climate, the purpose may change – to represent as many different combinations of underlying environments and drivers, rather than specific arrays of current species. Nevertheless, the National Reserve System remains the pillar of biodiversity conservation in the 21st century, and needs to be strengthened with ambitious conservation targets and the means to achieve them.

Remove or minimise existing stressors

Climate change exacerbates the effects of many existing stressors, which continue to be the biggest threat to Australia's biodiversity. Accelerating the control or elimination of existing stressors offers an extremely low-risk, high-payback starting point in building resilience of natural systems to climate change.

Build appropriate connectivity

With increasing pressure on species to migrate in response to a changing climate, and for ecosystems to disassemble and reassemble, there needs to be a greater focus on achieving appropriate types of landscape and seascape connectivity to 'give space for nature to self-adapt'. A key strategy is to integrate all types of protected areas into a single national system, and to facilitate better integration of off-reserve conservation with protected areas.

Identify and protect refugia

There is a need to ensure that key sites likely to provide refugia in the face of climate change are identified and included in reserves or otherwise managed to protect their values.

PROACTIVE INTERVENTIONS

Implement eco-engineering

Although costly and not always successful, eco-engineering may nevertheless constitute a necessary response in a few specific cases. For example, re-establishing keystone, long-lived or structuring species may allow ecological systems to self-organise around critical elements, or the use of provenances and species for the anticipated climatic conditions may help forests regenerate after successive fires.

Preserve genetic stock

As a last resort, species may need to be preserved outside an ecosystem context; for example, in zoos and seedbanks. However, such last-resort, ex situ methods should be seen in no way as substitutes for conserving species in well-functioning ecosystems.

FLEXIBLE POLICY AND MANAGEMENT APPROACHES

Reconsider management objectives

A changing climate is driving change in species distributions, and in the composition and functioning of communities and ecosystems. These dynamics must be recognised in conservation management. For example, there may be a need to reconsider what is 'native' versus 'invasive' as species increasingly move around the landscape. Groups such as migratory species may require different strategic approaches.

Uncertainty about future climate projections is no excuse for delay

There is high confidence in climate projections (especially temperature) to 2030 or 2040;

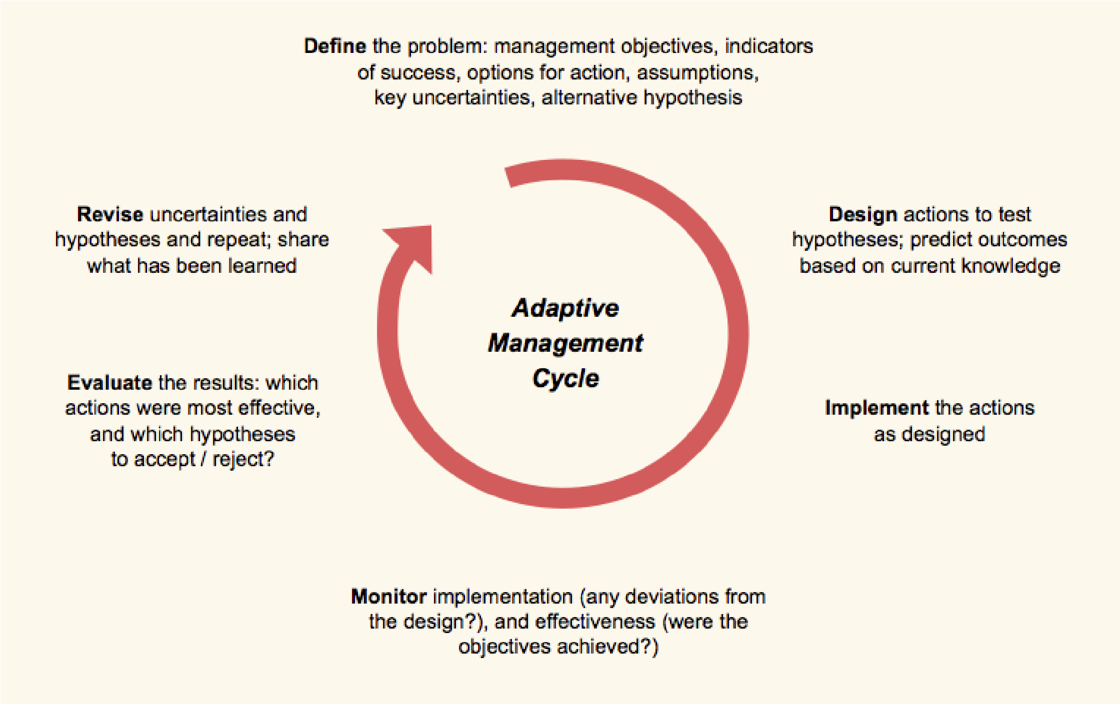
actions taken now will be valuable out to mid-century at least. For the more distant future, spreading risk by adopting a range of conservation strategies, coupled with active adaptive management, is an effective way to deal with the uncertainty of climate projections in that time frame.

Focus more on risk assessments

Climate change presents new and bigger risks for biodiversity conservation at species, ecosystem and process levels. For example, risk assessment at a species level can identify vulnerabilities and help shape appropriate management options; risk assessment at the taxonomic group level (e.g. through Action Plans) can identify individual species or groups of species on which to focus attention. Risk assessment at the landscape scale will allow identification of management options that improve resilience and maintain ecosystem function.

Implement active adaptive management

The linear approach of research–policy–management–outcome needs to be replaced by an iterative, cyclical approach in which biodiversity outcomes are appraised – leading to new research, and adjusted policy and management (Figure). Such an adaptive, cyclical approach needs high quality information, based on monitoring and experimentation.



Source: Murray and Marmorek (2004).

Figure 1 – A visual representation of active adaptive management, an iterative approach built around explicit, experimentally based development of plausible management options.

Build consensus

To achieve widespread, effective implementation of an enhanced conservation effort, we need to transform the way that societies think about and value the biotic world around them. The increasing urbanisation of the Australian population means that most of the public know less and less about the significance of biodiversity in providing services to their everyday lives. Strengthening their support for maintaining biodiversity is critical for dealing with the climate change threat, and ultimately for their own long-term well-being.

Seize opportunities from mitigation

Carbon trading and offset schemes, probably the most common climate mitigation approach in landscapes, offer an opportunity to promote sequestration in biomass while simultaneously benefiting biodiversity. For example, revegetating degraded landscapes with complex forest ecosystems, rather than with fast-growing plantations, creates good biodiversity outcomes while eventually storing more carbon.

The current policy and institutional landscape is changing rapidly, with simultaneous trends towards both centralisation and decentralisation. This state of flux provides opportunities to explore alternative institutional architectures and modes of policy delivery that can provide the flexibility needed to deal with a changing climate. Such reforms could include a regionally differentiated and integrated system with enhanced local rights and responsibilities, together with greater coherence at the national level and across jurisdictions. Such changes to our biodiversity management policies, legislative frameworks and institutional structures will provide the agility required to respond to rapid change and to align with a changed emphasis in management objectives.

Community recognition of the threat of climate change to biodiversity is growing rapidly, providing an opportunity for Australian society to re-examine its level of commitment to, and resourcing of, the conservation of the continent's unique biotic heritage. By any measure, Australia's natural capital has suffered from depletion and under-investment over the past two centuries. Significant new funding strongly focused towards on-ground biodiversity conservation work – carried out within an active adaptive management framework – is essential to enhance our adaptive capacity to deal with the climate change threat as well as existing stressors.

Innovative regional approaches to build adaptive capacity for more effective biodiversity conservation can make use of some of the major socio-economic trends sweeping across Australia. For example, in the south-east, the abandonment of marginal agricultural areas, and an influx of retirees and escapees from urban areas, provides new opportunities for integrating biodiversity values into these changing landscapes. More generally, integrated response packages – in terms of governance, education, investment sources and action plans for biodiversity conservation – can be tailored to the demographic, land use, climatic and socio-economic trajectories of specific regions around the country.

Climate change is a daunting challenge for biodiversity policy makers, managers and researchers. However, it also provides opportunities. Preparing for climate change might catalyse a transformation that is required to achieve a turnaround in the ongoing decline of Australia's biodiversity. Conservation of biodiversity is increasingly becoming a mainstream activity of governments, businesses, landowners, Indigenous Australians and community groups, and there have been some notable conservation successes over the past couple of decades. Recognition in the community of the threat of climate change to biodiversity is growing rapidly, providing an opportunity for Australian society to re-examine its level of commitment to, and resourcing of, the conservation of the continent's unique biotic heritage in a rapidly changing world.

5. Recommendations (Adaptation to changing climatic conditions)

In recent decades a number of scholarly articles have appeared in the literature recommending measures to adapt conservation to climate change. In a systematic review of the literature focused on adaptation strategies (Heller and Zavaleta 2008) it was found that while the range of recommendations in the literature is great (see Table 2), four consistent, broad themes emerged for conservation stakeholders to apply to climate change planning and adaptation:

1. the need for regional institutional coordination for reserve planning and management and to improve landscape connectivity;
2. the need to broaden spatial and temporal perspective in management activities and practice, and to employ actions that build system resilience;
3. the need to incorporate climate change into all conservation planning and actions, which will require increased research and capacity to forecast future conditions and species responses and to deal effectively with unavoidable uncertainty; and
4. the need to address multiple threats and global change drivers simultaneously and in ways that are responsive to and inclusive of diverse human communities and cultures. Action along each of these fronts will involve difficult tradeoffs, barriers to implementation, and collaboration across diverse actors.

In December 2009 the Victorian Government released "**Securing Our Natural Future**, A white paper for land and biodiversity at a time of climate change". This was followed in May 2010 by "**Biodiversity is Everybody's Business**, Victoria's Biodiversity Stategy 2010 – 2015 (Consultation Draft)". Many of the goals and outcomes proposed in these documents are included in, similar to or consistent with Heller and Zavaleta. For example, a goal in Chapter 2 of the white paper includes "building ecosystem resilience" and "improving connectivity" which are included in the first and second of Heller and Zaveleta's "four broad themes" (as noted above).

Table 2 - List of recommendations for climate change adaptation strategies for biodiversity management assembled from 112 scholarly articles
524 records were condensed into 113 recommendation categories and are ranked by frequency of times cited in different articles, expressed as a percentage. (Adapted from Heller and Zavaleta 2008)
1 (21% of articles)
Increase connectivity (design corridors, remove barriers for dispersal, locate reserves close to each other, reforestation
2 (17%)
Integrate climate change into planning exercises (reserve, pest outbreaks, harvest schedules, grazing limits, incentive programs)
3 (15%)
Mitigate other threats, i.e. invasive species, fragmentation, pollution
4 (13%)

Study response of species to climate change physiological, behavioral, demographic
Practice intensive management to secure populations
Translocate species
5 (12%)
Increase number of reserves
6 (11%)
Address scale problems; match modeling, management, and experimental spatial scales for improved predictive capacity
Improve inter-agency, regional coordination
7 (10%)
Increase and maintain basic monitoring programs
Practice adaptive management
Protect large areas, increase reserve size
8 (9%)
Create and manage buffer zones around reserves
9 (7%)
Create ecological reserve networks, large reserves connected by small reserves, stepping stones
Develop improved modeling and analysis capacity i.e. more effective software, integration with GIS, integrate greater complexity
Do integrated study of multiple global change drivers
Improve techniques for, and do more, restoration of wetlands, rivers, matrix
Increase interdisciplinary collaboration
Promote conservation policies that engage local users and promote healthy human communities
Protect full range of bioclimatic variation
Soften land-use practices in the matrix
10 (6%)
Adopt long-term and regional perspective in planning, modeling, and management
Re-asses conservation goals (i.e. move away from concepts of natural, embrace processes over patterns)
Study species dispersal across land-use boundaries, gene flow, migration rates, historic flux
Study species distributions, current and historic
11 (5%)
Broaden genetic and species diversity in restoration and forestry
Develop adaptation strategies now; early adaptation is encouraged
Do not implement CO_2 emission mitigation projects that negatively impact biodiversity
Manage for flexibility, use of portfolio of approaches, maintain options
Validate model results with empirical data
12 (4%)
Do regional impact assessments
Identify indicator species
Initiate long-term studies of species' responses to climate
Model species' ranges in the future
Protect refugia, current and predicted future
Study adaptive genetic variation
13 (3.6%)
Leadership by those with power; senior management, government agencies
Limit CO_2 emissions
Predict effects of directional climate change on ecosystems, communities, populations

Preserve genetic diversity in populations
Represent each species in more than one reserve
14 (3%)
Create culturally appropriate adaptation/management options
Create education programs for public about land-use practices and effects on and with climate
Develop best management practices for climate change scenarios
Institute flexible zoning around reserves
Increase investment in climate related research
Increase communication of knowledge about climate change impacts to policymakers and stakeholders
Initiate dialogue among stakeholders
Institute government reform (i.e. adaptive governance)
Locate reserves in areas of high heterogeneity, endemism
Maintain natural disturbance dynamics of ecosystems
Practice proactive management of habitat to mitigate warming
Secure boundaries of existing preserves
Start strategic zoning of land-use to minimize climate related impacts
Study and monitor ecotones and gradients
Study effectiveness of corridors
Use predictive models to make decisions on where to situate new reserves
15 (1.7%)
Anticipate surprises and threshold effects i.e. major extinctions or invasions
Design biological preserves for complex changes in time, not just directional change
Locate reserves at [southern] boundary of species' ranges
Manage the matrix
Practice proactive research on climate change
Protect many small reserves rather than single large
Provide education opportunities and summaries of primary literature for management staff to learn and network about climate change
Study and protect metapopulations
Study processes of change at multiple spatial and temporal scales
Use GIS to study species distributions and landscape patterns
16 (1%)
Action plans must be time-bound and measurable
Adjust park boundaries to capture 1 anticipated movement of critical habitats
Create institutional flexibility
Create linear reserves oriented longitudinally
Establish cross-national collaboration
Establish neo-native forests plant species where they were in the past, but are not found currently
Experiment with refugia
Focus protection on sensitive biomes
Focus on annual plants rather than perennials near climate boundaries
Increase wetland protection
Institutional capacity enhancement to address climate change
Institute reform to improve support for interdisciplinary, multi-institutional research
Locate reserves so major vegetation transitions are in core
Locate reserves at core of ranges
Manage for landscape asynchrony
Manage human-wildlife conflict as change occurs

Manage populations to reduce temporal fluctuations in population sizes
Develop guidelines for climate sensitive restoration and infrastructure development
Need to increase social acceptance of shared resilience goals
Promote personal action plans among employees to reduce emissions
Protect endangered species *ex situ*
Protect functional groups and keystone species
Protect mountains
Protect primary forests
Protect urban green space
Quantify environmental susceptibility versus adaptive capacity to inform conservation planning
Schedule dam releases to protect stream temperatures
Study changes in populations at rear of range rather than only range fronts
Study response of undisturbed areas to climate change
Study social agency and human decision making
Study time-series data on species dynamics
Substitute space for time to study the responses of species to climate change
Train more taxonomists
Use caution in predictive modeling because the responses of some species are not well predicted
Use simple decision rules for reserve planning
Use social networks for education about climate change
Use triage in short-term to prioritize action

6. Key messages and policy directions

From Steffen et al., A strategic assessment, 2009

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

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

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

REFORM OUR MANAGEMENT OF BIODIVERSITY

We need to adapt the way we manage biodiversity to meet existing and new threats – some existing policy and management tools remain effective, others need a major rethink, and new

approaches need to be developed in order to enhance the resilience of our ecosystems.

As we are rapidly moving into an unprecedented state for our biodiversity and ecosystems, there is a need to transform our policy and management approaches to deal with this enormous challenge. Climate change presents a 'double whammy' – affecting species, ecosystems and ecosystem processes directly, as well as exacerbating the impacts of other stressors. Many effective management approaches already exist; the challenge is to accelerate, reorient and refine them to deal with climate change as a new and interacting complex stressor. The National Reserve System, the pillar of current biodiversity conservation efforts, needs to be enhanced substantially and integrated with more effective off-reserve conservation. Acceleration of actions to control and reduce existing stressors on Australian ecosystems and species is essential to increase resilience. However, there is a limit to how far enhancing resilience will be effective. Novel ecosystems will emerge and a wide range of unforeseen and surprising phenomena and interactions will appear. A more robust, long-term approach is to facilitate the self-adaptation of ecosystems across multiple pathways of adaptation that spread risk across alternative possible climatic and socio-economic futures. Active adaptive management – backed by research, monitoring, and evaluation – can be an effective tool to support self-adaptation of ecosystems. An especially promising approach is to develop integrated regional biodiversity response strategies, tailored for regional differences in environments, climate change impacts and socio-economic trends.

STRENGTHEN THE NATIONAL COMMITMENT TO CONSERVE AUSTRALIA'S BIODIVERSITY

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

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

INVEST IN OUR LIFE SUPPORT SYSTEM

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

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

BUILD INNOVATIVE AND FLEXIBLE GOVERNANCE SYSTEMS

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

While primary responsibility for biodiversity conservation resides with each state and territory, over the past two decades many biodiversity conservation policies and approaches have been developed nationally through Commonwealth–state processes. There has also been a recent trend towards devolution of the delivery of natural resource management programs to the level of regional catchment management authorities and local Landcare groups. Dealing with the climate change threat will place further demands on our governance system, with a need to move towards strengthening and reforming governance at the regional level, and towards more flexibility and coherence nationally. Building on the strengths of current arrangements, a next step is to explore the potential for innovation based on the principles of:

I. strengthening national leadership to underpin the reform agenda required;
II. devolving responsibilities and resources to the most local, competent level, and building capacity at that level;
III. facilitating a mix of interacting regional governance arrangements sensitive to local conditions; and
IV. facilitating new partnerships with other groups and organisations, for example, with Indigenous and business entities.

In addition, improved policy integration across climate change, environment protection and commercial natural resource use is required nationally, including across jurisdictional boundaries.

MEET THE MITIGATION CHALLENGE

Australia's biodiversity has only so much capacity to adapt to climate change, and we are

approaching that limit. Therefore, strong emissions mitigation action globally and in Australia is vital – but this must be carried out in ways that deliver both adaptation and mitigation benefits.

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

7. REFERENCES

Alford, R. A., Bradfield, K. S. and Richards, S. J., **Ecology - Global warming and amphibian losses**, Nature, 447, E3-E4, 2007

Alo, C. A. and Wang, G. L., **Potential future changes of the terrestrial ecosystem based on climate projections by eight general circulation models**, Journal of Geophysical Research-Biogeosciences, 113, G01004, 2008

Badgley, C., Barry, J. C., Morgan, M. E., Nelson, S. V., Behrensmeyer, A. K., Cerling, T. E. and Pilbeam, D., **Ecological changes in Miocene mammalian record show impact of prolonged climatic forcing**, Proceedings of the National Academy of Sciences of the United States of America, 105, 12145-12149, 2008

Beaumont, L.J., McAllan, I.A.W. and Hughes, L., **A matter of timing: changes in the first date of arrival and last date of departure of Australian migratory birds**, *Global Change Biology*, 12, 1339-1354, 2006

Beckage, B., Osborne, B., Gavin, G. G., Pucko, C., Siccama, T. and Perkins, T., **A rapid upward shift of a forest ecotone during 40 years of warming in the Green Mountains of Vermont**, PNAS, 105, 4197-4202, 2008

Bertin, R. I., **Plant phenology and distribution in relation to recent climate change**, Journal of the Torrey Botanical Society, 135, 126-146, 2008

Bloor, J. M. G., Barthes, L. and Leadley, P. W., **Effects of elevated CO2 and N on tree-grass interactions: an experimental test using *Fraxinus excelsior* and *Dactylis glomerata***, Functional Ecology, 22, 537-546, 2008

Both, C., Bouwhuis, S., Lessells, C. M. and Visser, M. E., **Climate change and population declines in a long-distance migratory bird**, Nature, 441, 81-83, 2006

Botkin, D. B., Saxe, H., Araújo, M. B., Betts, R., Bradshaw, R. H. W., Cedhagen, T., Chesson, P., Dawson, T. P., Etterson, J. R., Faith, D. P., Ferrier, S., Guisan, A., Hansen, A. S., Hilbert, D. W., Loehle, C., Margules, C., New, M., Sobel, M. J. and Stockwell, D. R. B., **Forecasting the effects of global warming on biodiversity**, Bioscience, 57, 227-236, 2007

Bradley, K. L. and Pregitzer, K. S., **Ecosystem assembly and terrestrial carbon balance under elevated CO_2**, Trends in Ecology and Evolution, 22, 538-547, 2007

Brooker, R. W., Travis, J. M. J., Clark, E. J. and Dytham, C., **Modelling species' range shifts in a changing climate: The impacts of biotic interactions, dispersal distance and the rate of climatic change**, Journal of Theoretical Biology, 245, 59-65, 2007

Brown, S., **Conservation ecology of the endangered Mallee Emu-wren**, Presentation given at Deakin University, 5th February 2010

Buisson, L., Thuiller, W., Leks, S., Lim, P. and Grenouillet, G., **Climate change hastens the turnover of stream fish assemblages**, Global Change Biology, 14, 2232-2248, 2008

Bull, C.M. and Burzacott, D., **Changes in climate and in the timing of pairing of the Australian lizard, *Tiliqua rugosa***, *J. Zool. London*, 256, 383-387, 2002

Bunker, D. E., DeClerck, F., Bradford, J. C., Colwell, R. K., Perfecto, I., Phillips, O. L., Sankaran, M. and Naeem, S., **Species loss and above ground carbon storage in a tropical forest**, Science, 310, 1029-1031, 2005

Campbell, A., Kapos, V., Scharlemann, J. P. W., Bubb, P., Chenery, A., Coad, L., Dickson, B., Doswald, N., Khan, M. S. I., Kershaw, F. and Rashid, M. (2009). **Review of the Literature on the Links between Biodiversity and Climate Change: Impacts, Adaptation and Mitigation**. Secretariat of the Convention on Biological Diversity, Montreal. Technical Series No. 42 available at https://www.cbd.int/ts/

Canadell, J. G., C. Le Que´re´, M. R. Raupach, C. B. Field, E. T. Buitenhuis, P. Ciais, T. J. Conway, N. P. Gillett, R. A. Houghton and G. Marland, **Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks**, Proceedings of the National Academy of Sciences of the USA, 104, 2007

Carroll, C., **Interacting effects of climate change, landscape conversion, and harvest on carnivore populations at the range margin: Marten and lynx in the northern Appalachians**, Conservation Biology, 21, 1092-1104, 2007

Chambers, L.E., **Migration dates at Eyre Bird Observatory: Links with climate change?** *Climate Research* 29, 157-165, 2005

Chambers, L.E., **Trends in avian migration timing in south Western Australia and their relationship to climate**, *Emu* 108, 1-14, 2008

Chambers, L. E., Quin, B. R., Menkhorst, P., Franklin, D. C. and Smales, I., **The effects of climate on breeding in the Helmeted Honeyeater**, Emu, 108, 15-22, 2008

Chambers, L.E., **Evidence of climate related shifts in Australian phenology,** 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009

Chapin, F. S., Randerson, J. T., McGuire, A. D., Foley, J. A. and Field, C. B., **Changing feedbacks in the climate-biosphere system**, Frontiers in Ecology and the Environment, 6, 313-320, 2008

Clarke JM, Whetton PH, Hennessy KJ (in press) Providing Application-specific Climate Projections Datasets: CSIRO's Climate Futures Framework. In 'MODSIM Conference'. 12-16 December Perth, Western Australia.

Cleland, E. E., Chiariello, N. R., Loarie, S. R., Mooney, H. A. and Field, C. B., **Diverse responses of phenology to global changes in a grassland ecosystem**, Proceedings of the National Academy of Sciences of the United States of America, 103, 13740-13744, 2006

Cleland, E. E., Chuine, I., Menzel, A., Mooney, H. A. and Schwartz, M. D., **Shifting plant phenology in response to global change**, Trends in Ecology and Evolution, 22, 357-365, 2007

Colwell, R. K., Brehm, G., Cardelus, C. L., Gilman, A. C. and Longino, J. T., **Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics**, Science, 322, 258-261, 2008

Cooke, D., **City branches out to replace drought-hit trees**, The Age 11 May, 2010

CSIRO Climate Futures for Eastern Melbourne, Data provided for the Eastern Alliance for Greenhouse Action, July 2010

Cubasch, U., G. A. Meehl, G. F. Boer, R. J. Stouffer, M. R. Dix, A. Noda, C. A. Senior, S. C. B. Raper and K. S. Yap, 2001: Projections of Future Climate Change. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Currano, E. D., Wilf, P., Wing, S. L., Labandeira, C. C., Lovelock, E. C. and Royer, D. L., **Sharply increased insect herbivory during the Paleocene- Eocene Thermal Maximum**, Proceedings of the National Academy of Sciences, 105, 1960-1964, 2008

Daufresne, M. and Boet, P., **Climate change impacts on structure and diversity of fish communities in rivers**, Global Change Biology, 13, 2467-2478, 2007

De Boeck, H. J., Lemmens, C. M. H. M., Zavalloni, C., Gielen, B., Malchair, S., Carnol, M., Merckx, R., Van den Berge, J., Ceulemans, R. and Nijs, I., **Biomass production in experimental grasslands of different species richness during three years of climate warming**, Biogeosciences, 5, 585-594, 2008

Del Barrio, G., Harrison, P. A., Berry, P. M., Butt, N., Sanjuan, M. E., Pearson, R. G. and Dawson, T. P., **Integrating multiple modelling approaches to predict the potential impacts of climate change on species' distributions in contrasting regions: comparisons and implications for policy**, Environmental Science and Policy, 9, 129-147, 2006

DeLucia, E. H., Casteel, C. L., Nabity, P. D. and O'Neill, B. F., **Insects take a bigger bite out of plants in a warmer, higher carbon dioxide world**, Proceedings of the National Academy of Sciences of the United States of America, 105, 1781-1782, 2008

Deutsch, C. A., Tewksbury, J. J., Huey, R. B., Sheldon, K. S., Ghalambor, C. K., Haak, D. C. and Martin, P. R., **Impacts of climate warming on terrestrial ectotherms across latitude**, Proceedings of the National Academy of Sciences of the United States of America, 105, 6668-6672, 2008

Dolenec, Z., **Spring temperatures in relation to laying dates and clutch size of the blue tit (*Parus caeruleus*) in Croatia**, Wilson Journal of Ornithology, 119, 299-301, 2007

Duckworth, R. A., **Adaptive dispersal strategies and the dynamics of range expansion**, American Naturalist, 172, S4-S17, 2008

Edwards, M. and Richardson, A. J**., Impact of climate change on marine pelagic phenology and trophic mismatch**, Nature, 430, 881-883, 2004

EEA, JRC and WHO, **Impacts of Europe's changing climate - 2008 indicator-based assessment**, European Environment Agency, Copenhagen, 2008

Ehlers, A., Worm, B. and Reusch, T. B. H**., Importance of genetic diversity in eelgrass (*Zostera marina*) for its resilience to global warming**, Marine Ecology-Progress Series, 355, 1-7, 2008

February, E. C., West, A. G. and Newton, R. J., **The relationship between rainfall, water source and growth for an endangered tree**, Austral Ecology, 32, 397-402, 2007

Fisher, M. C., **Potential interactions between amphibian immunity, infectious disease and climate change**, Animal Conservation, 10, 420-421, 2007

Foden, W., Mace, G., Vié, J.-C., Angulo, A., Butchart, S., DeVantier, L., Dublin, H., Gutsche, A., Stuart, A. and Turak, E., **Species susceptibility to climate change impacts**, The 2008 Review of The IUCN Red List of Threatened Species (eds Vié, J.-C., Hilton-Taylor, C. and Stuart, S.N.), IUCN, Gland, Switzerland, 2008

Foden, W., Jamie Carr, Renuka Badhe, Chun Yuen Wong and Sarah Brooke, **Species and climate change: more than Just the polar Bear**, IUCN 2009

Foden, W., Midgley, G. F., Hughes, G., Bond, W. J., Thuiller, W., Hoffman, M. T., Kaleme, P., Underhill, L. G., Rebelo, A. and Hannah, L., **A changing climate is eroding the geographical range of the Namib Desert tree Aloe through population declines and dispersal lags**, Diversity and Distributions, 13, 645-653, 2007

Franco, A. M. A., Hill, J. K., Kitschke, C., Collingham, Y. C., Roy, D. B., Fox, R., Huntley, B. and Thomas, C. D., **Impacts of climate warming and habitat loss on extinctions at species' low-latitude range boundaries**, Global Change Biology, 12, 1545-1553, 2006

Fujimoto, S., **Estimating the impact of thermal change on broad-leaved tree leaf phenology in the warm temperate zone**, Japanese Journal of Conservation Ecology, 13, 75-87, 2008

Garnaut Climate Change Review, 2008: Garnaut Climate Change Review Interim Report. A report prepared for the Commonwealth, State and Territory Governments of Australia, 63pp, http://www.garnautreview.org.au/domino/Web_Notes/Garnaut/garnautweb.nsf.

Gaston, A. J., Gilchrist, H. G. and Hipfner, J. M., **Climate change, ice conditions and reproduction in an Arctic nesting marine bird: Brunnich's guillemot (Uria lomvia L.)**, Journal of Animal Ecology, 74, 832-841, 2005

Gibbs, H., **Climatic variation and breeding in the Australian Magpie (*Gymnorhina tibicen*): a case study using existing data**, *Emu* 107, 284-293, 2007

Gleadow, R., **Food Security in a warming World**, Australasian Science, Jan/Feb 2010

Gordo, O. and Sanz, J. J., **Phenology and climate change: a long-term study in a Mediterranean locality**, Oecologia, 146, 484-495, 2005

Gough, C. M., Vogel, C. S., Schmid, H. P. and Curtis, P. S., **Controls on annual forest carbon storage: Lessons from the past and predictions for the future**, Bioscience, 58, 609-622, 2008

Green, K. and Pickering, C.M., **A potential scenario for mammal and bird diversity in the Snowy Mountains of Australia in relation to climate change**, In *Global Mountain Biodiversity: Changes and Threats* (Eds C Korner and E Sphen) pp. 241-249 (Springer-Verlag, Berlin), 2002

Green, R. E., Collingham, Y. C., Willis, S. G., Gregory, R. D., Smith, K. W. and Huntley, B., **Performance of climate envelope models in retrodicting recent changes in bird population size from observed climatic change**, Biology Letters, 4, 599-602, 2008

Haines, A., Kovats, R. S., Campbell-Lendrum, D. and Corvalan, C., **Climate change and human health: Impacts, vulnerability and public health**, Public Health, 120, 585-596, 2006

Heller, N.E., Erika S. Zavaleta, **Biodiversity management in the face of climate change: A review of 22 years of recommendations,** Biological Conservation 142 14–32, 2008

Hellmann, J. J., Byers, J. E., Bierwagen, B. G. and Dukes, J. S., **Five potential consequences of climate change for invasive species**, Conservation Biology, 22, 534-543, 2008

Hennessy, K. J., C. Lucas, N. Nicholls, J. M. Bathols, R. Suppiah and J. H. Ricketts, **Climate Change Impacts on Fire-Weather in South-East Australia**, A report prepared by the Bushfire CRC, Australian Bureau of Meteorology and CSIRO Marine and Atmospheric Research for the New South Wales Government, Victorian Government, Tasmanian Government and Australian Government, 2006

Hickling, R., Roy, D. B., Hill, J. K., Fox, R. and Thomas, C. D., **The distributions of a wide range of taxonomic groups are expanding polewards**, Global Change Biology, 12, 450-455, 2006

Higgins, P. A. T., **Biodiversity loss under existing land use and climate change: an illustration using northern South America**, Global Ecology and Biogeography, 16, 197-204, 2007

Hitch, A. T. and Leberg, P. L., **Breeding distributions of north American bird species moving north as a result of climate change**, Conservation Biology, 21, 534-539, 2007

Hobbs, R. J., Yates, S. and Mooney, H. A., **Long- term data reveal complex dynamics in grassland in relation to climate and disturbance**, Ecological Monographs, 77, 545-568, 2007

Hovenden, M. J., Wills, K. E., Schoor, J. K. V., Williams, A. L. and Newton, P. C. D., **Flowering phenology in a species-rich temperate grassland is sensitive to warming but not elevated CO_2**, New Phytologist, 178, 815-822, 2008

Hudson, I.L., Susan W Kim and Marie R Keatley, **Climatic influences on the flowering**

phenology of four Eucalypts: a GAMLSS approach, 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009

Hughes, Lesley, Cawsey, E.M. and Westoby, Mark, **Climatic range sizes of *Eucalyptus* species in relation to future climate change**, Global Ecology and Biogeography Letters, 1996

Hume, I., **Koalas under threat**, The University of Sydney News, 9 May 2008

Huntley, B., **Climatic change and the conservation of European biodiversity: Towards the development of adaptation strategies**, Bern Convention Standing Committee on Climate Change, Council of Europe, Strasbourg, 2007

Huntley, B., Green, R. E., Collingham, Y. C. and Willis, S. G., **A Climatic Atlas of European Breeding Birds**, Lynx Editions, 2008a

Ims, R.A. and Fuglei, E., **Trophic interaction cycles in tundra ecosystems and the impact of climate change**, Bioscience, 55, 311-322, 2005

IPCC, 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jetz, W., Wilcove, D. S. and Dobson, A. P., **Projected impacts of climate and land-use change on the global diversity of birds**, Plos Biology, 5, 1211-1219, 2007

Kammann, C., Müller, C., Grünhage, L. and Hans-Jürgen, J., **Elevated CO_2 stimulates N_2O emissions in permanent grassland**, Soil Biology and Biochemistry, 40, 2194-2205, 2008

Kearney, Michael R., Natalie J. Briscoe, David J. Karoly, Warren P. Porter, Melanie Norgate and Paul Sunnucks, **Early emergence in a butterfly causally linked to anthropogenic warming,** *Biology Letters, Royal Society,* published online 17 March 2010

Kearny, M., Philips, B. L, Tracy, C. R., Christian, K. A., Betts, G. and Porter, W. P., **Modelling species distributions without using species distributions: the cane toad in Australia under current and future climates**, Ecography, 31, 423-434, 2008

Keatley, M.R., Fletcher, T.D., Hudson, I.L. and Ades, P.K., **Phenological studies in Australia: potential application in historical and future climate analysis**, *Int. J. Climatol.* 22, 1769-1780, 2002

Keatley, M.R., Fletcher, T.D., Hudson, I.L. and Ades, P.K., **Shifts in the date of flowering commencement in some Australian plants**, *16th Biometeorology and Aerobiology Conference*. Vancouver, Canada, 2004

Keatley, M.R. and Hudson, I.L., **Shift in flowering dates of Australian plants related to climate: 1983- 2006**, In *MODSIM 2007 International Congress on Modelling and Simulation*, New Zealand (Eds L Oxley and D Kulasiri) pp. 504-510, 2007

Keith, D. A., Akçakaya, H. R., Thuiller, W., Midgley, G., Pearson, R. G., Phillips, S. J., Regan, H. M., Araújo, M.B. and Rebelo, A. G., **Predicting extinction risks under climate change: coupling stochasitic population models with dynamic bioclimatic habitat models**, Biology Letters, 4, 560-563, 2008

Kelly, A. E. and Goulden, M. L., **Rapid shifts in plant distribution with recent climate change**, Proceedings of the National Academy of Sciences of the United States of America, 105, 11823-11826, 2008

Knapp, A. K., Beier, C., Briske, D. D., Classen, A., Luo, Y., Reichstein, M., Smith, M. D., Smith, S. D., Bell, J. E., Fay, P. A., Heisler, J. L., Leavitt, S. W., Sherry, R., Smith, B. and Weng, E., **Consequences of More Extreme Precipitation Regimes for Terrestrial Ecosystems**, Bioscience, 58, 811-821, 2008

Kozlov, M. V., **Losses of birch foliage due to insect herbivory along geographical gradients in Europe: a climate-driven pattern?** Climatic Change, 87, 107-117, 2008

Kullman, L., **Tree line population monitoring of *Pinus sylvestris* in the Swedish Scandes, 1973-2005: implications for tree line theory and climate change ecology**, Journal of Ecology, 95, 41-52, 2007

Kurz, W. A., Dymond, C. C., Stinson, G., Rampley, G. J., Neilson, E. T., Carroll, A. L., Ebata, T. and Safranyik, L., **Mountain pine beetle and forest carbon feedback to climate change**, Nature, 452, 987-990, 2008a

Lapenis, A, Shvidenko, A, Shepaschenko, D, Nilsson, S. and Aiyyer, A., **Acclimation of Russian forests to recent changes in climate**, Global Change Biology, 11, 2090–102, 2005

Laurance, W. F., **Global warming and amphibian extinctions in eastern Australia**, Austral Ecology, 33, 1-9, 2008

Lemoine, N., Schaefer, H. C. and Böhning-Gaese, K., **Species richness of migratory birds is influenced by global climate change**, Global Ecology and Biogeography, 16, 55-64, 2007

Lenoir, J., Gegout, J. C., Marquet, P. A., de Ruffray, P. and Brisse, H., **A significant upward shift in plant species optimum elevation during the 20th century**, Science, 320, 1768-1771, 2008

Levinsky, I., Skov, F., Svenning, J. C. and Rahbek, C., **Potential impacts of climate change on the distributions and diversity patterns of European mammals**, Biodiversity and Conservation, 16, 3803-3816, 2007

Liow, L. H. and Stenseth, N. C., **The rise and fall of species: implications for macroevolutionary and macroecological studies**, Proceedings of the Royal Society B Biological Sciences, 247, 2745-2752, 2007

Loarie, S.R. , P.H. Duffy, H. Hamilton, G.P. Asner, C.B. Field, D.D. Ackerly, **The velocity of climate change,** Nature 462:1052-1055, 2009

Lucas, C., K. J. Hennessy, G. Mills and J. M. Bathols, **Bushfire Weather in Southeast Australia: Recent Trends and Projected Climate Change Impacts**, A report prepared by the Bushfire CRC, Australian Bureau of Meteorology and CSIRO Marine and Atmospheric Research for The Climate Institute of Australia, 80 pp, 2007

Luyssaert, S., Schulze, E. D., Borner, A., Knohl, A., Hessenmoller, D., Law, B. E., Ciais, P. and Grace, J., **Old-growth forests as global carbon sinks**, Nature, 455, 213-215, 2008

Magnusdottir, R., Wilson, B. A. and Hersteinsson, P., **Dispersal and the influence of rainfall on a population of the carnivorous marsupial swamp antechinus (*Antechinus minimus maritimus*)**, Wildlife Research, 35, 446-454, 2008

Malhi, Y., Roberts, J. T., Betts, R. A., Killeen, T. J., Li, W. H. and Nobre, C. A., **Climate change, deforestation, and the fate of the Amazon**, Science, 319, 169-172, 2008

Manning MR, Edmonds J, Emori S*, et al.* (2010) Misrepresentation of the IPCC CO2 emission scenarios. *Nature Geoscience,* **3**, 376. http://dx.doi.org/10.1038/ngeo880

Massot, M., Clobert, J. and Ferriere, R., **Climate warming, dispersal inhibition and extinction risk**, Global Change Biology, 14, 461-469, 2008

McMenamin, S. K., Hadly, E. A. and Wright, C. K., **Climatic change and wetland desiccation cause amphibian decline in Yellowstone National Park**, Proceedings of the National Academy of Sciences, 105, 16988-16993, 2008

McRae, B. R., Schumaker, N. H., McKane, R. B., Busing, R.T., Solomon, A. M. and Burdick, C. A., **A multi-model framework for simulating wildlife population response to land-use and climate change**, Ecological Modelling, 219, 77-91, 2008

Memmott, J., Craze, P. G., Waser, N. M., and Price, M. V., **Global warming and the disruption of plant-pollinator interactions**, Ecology Letters, 10, 710-717, 2007

Menendez, R., Megias, A. G., Hill, J. K., Braschler, B., Willis, S. G., Collingham, Y., Fox, R., Roy, D. B. and Thomas, C. D., **Species richness changes lag behind climate change**, Proceedings of the Royal Society B: Biological Sciences, 273, 1465-1470, 2006

Menzel, A., Sparks, T. H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kubler, K., Bissolli, P., Braslavska, O., Briede, A., Chmielewski, F. M., Crepinsek, Z., Curnel, Y., Dahl, A., Defila, C., Donnelly, A., Filella, Y., Jatcza, K., Mage, F., Mestre, A., Nordli, O., Penuelas, J., Pirinen, P., Remisova, V., Scheifinger, H., Striz, M., Susnik, A., Van Vliet, A. J. H., Wielgolaski, F. E., Zach, S. and Zust, A., **European phenological response to climate change matches the warming pattern**, Global Change Biology, 12, 1969-1976, 2006

Metzger, M. J., Bunce, R. G. H., Leemans, R. and Viner, D., **Projected environmental shifts under climate change: European trends and regional impacts**, Environmental Conservation, 35, 64-75, 2008

Mitikka, V., Heikkinen, R., Luoto, M., Araùjo, M., Saarinen, K., Pyry, J. and Fronzek, S**.,** **Predicting range expansion of the map butterfly in Northern Europe using bioclimatic models**, Biodiversity and Conservation, 17, 623-641, 2008

Møller, A. P., Flensted-Jensen, E., Mardal, W., **Dispersal and climate change: a case study of the Arctic tern (*Sterna paradisaea)***, Global Change Biology, 12, 2005-2013, 2006

Morales, P., Hickler, T., Rowell, D. P., Smith, B. and Sykes, T., **Changes in European ecosystem productivity and carbon balance driven by regional climate model output**, Global Change Biology, 13, 108-122, 2007

Morgan, J. A., Milchunas, D. G., Lecain, D. R., West, M. and Mosier, A. R., **Carbon dioxide enrichment alters plant community structure and accelerates shrub growth in the shortgrass steppe**, Proceedings of the National Academy of Sciences of the United States of America, 104, 14724-14729, 2007

Moritz, C., Patton, J. L., Conroy, C. J., Parra, J. L., White, G. C. and Beissinger, S. R., **Impact of a Century of Climate Change on Small-Mammal Communities in Yosemite National Park, USA**, Science, 322, 261-264, 2008

Mpelasoka, F., K. J. Hennessy, R. N. Jones and B. Bates, **Comparison of suitable drought indices for climate change impacts assessment over Australia towards resource management**, International Journal of Climatology, 2007

Muths, E., Pilliod, D. S. and Livo, L. J., **Distribution and environmental limitations of an amphibian pathogen in the Rocky Mountains, USA**, Biological Conservation, 141, 1484-1492, 2008

Nakićenović N, Swart R (2000) *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge.

Nitschke, C.R. and Hickey, G.M., **Assessing the vulnerability of Victoria's Central Highland forests to climate change**, Technical Report. Peer reviewed and unpublished. 2007

Nitschke, C. and Innes, J., **Interactions between fire, climate change and forest biodiversity**, CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 2006

Norment, C.J. and Green, K., **Breeding ecology of Richard's Pipit (*Anthus novaeseelandiae*) in the Snowy Mountains**, *Emu* 104, 327-336, 2004

Notaro, M., Vavrus, S. and Liu, Z. Y., **Global vegetation and climate change due to future increases in CO2 as projected by a fully coupled model with dynamic vegetation**, Journal of Climate, 20, 70-90, 2007

Nakićenović, N., and R. Swart (eds.), **Special Report on Emissions Scenarios**, A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 599 pp., 2000

Nunes, J. P., Seixas, J. and Pacheco, N. R., **Vulnerability of water resources, vegetation productivity and soil erosion to climate change in Mediterranean watersheds**, Hydrological Processes, 22, 3115-3134, 2008

Öhlemüller, R., Anderson, B. J., Araújo, M. B., Butchart, S. H. M., Kudrna, O., Ridgely, R. S. and Thomas, C. D., **The coincidence of climatic and species rarity: high risk to small-range species from climate change**, Biology Letters, 4, 568-572, 2008

Parmesan C and Yohe G, **A globally coherent fingerprint of climate change impacts across natural systems**, *Nature* **421**: 37–42, 2003

Parmesan, C., **Ecological and evolutionary responses to recent climate change**, Annual Review of Ecology Evolution and Systematics, 37, 637-669, 2006

Parmesan, C., **Influences of species, latitudes and methodologies on estimates of phenological response to global warming**, Global Change Biology 13, 1860-1872, 2007

Peh, K. S. H., **Potential effects of climate change on elevational distributions of tropical birds in Southeast Asia**, Condor, 109, 437-441, 2007

Pompe, S., Hanspach, J., Badeck, F., Klotz, S., Thuiller, W. and Kuhn, I., **Climate and land use change impacts on plant distributions in Germany**, Biology Letters, 4, 564-567, 2008

Post, E., Peterson, R. O., Stenseth, N. C. and McLaren, B. E., **Ecosystem consequences of wolf behavioral response to climate**, Nature, 401, 905–907, 1999

Pounds, J. A., Bustamante, M. R., Coloma, L. A., Consuegra, J. A., Fogden, M. P. L., Foster, P. N., La Marca, E., Masters, K. L., Merino-Viteri, A., Puschendorf, R., Ron, S. R., Sanchez-Azofeifa, G. A., Still, C. J. and Young, B. E., **Widespread amphibian extinctions from epidemic disease driven by global warming,** Nature, 439, 161-167, 2006

Prentice, I. C., Bondeau, A., Cramer, W., Harrison, S. P., Hickler, T., Lucht, W., Sitch, S., Smith, B. and Sykes, M. T. **Dynamic Global Vegetation Modeling: Quantifying Terrestrial Ecosystem Responses to Large-Scale Environmental Change**, In Terrestrial Ecosystems in a Changing World, Springer, Berlin, 2007

Purse, B. V., Mellor, P. S., Rogers, D. J., Samuel, A. R., Mertens, P. P. C. and Baylis, M., **Climate change and the recent emergence of bluetongue in Europe**, Nature Reviews Microbiology, 3, 171-181, 2005

Rahel, F. J., Bierwagen, B. and Taniguchi, Y., **Managing aquatic species of conservation concern in the face of climate change and invasive species**, Conservation Biology, 22, 551-561, 2008

Rahel, F. J. and Olden, J. D., **Assessing the effects of climate change on aquatic invasive species,** Conservation Biology, 22, 521-533, 2008

Rahmstorf, S., A. Cazenave, J. A. Church, J. E. Hansen, R. F. Keeling, D. E. Parker and R. C. J. Somerville, 2007: Recent climate observations compared to projections. Science, 316, 709-710.

Raupach, M. R., G. Marland, P. Ciais, C. Le Que´re´, J. G. Canadell, G. Klepper and C. B. Field, 2007: Global and regional drivers of accelerating CO2 emissions. Proceedings of the National Academy of Sciences of the USA, 104, 10288–10293.

Raxworthy, C. J., Pearson, R. G., Rabibsoa, N., Rakotondrazafy, A. M., Ramanamanjato, J.-B., Raselimanana, A. P., Wu, S., Nussbaum, R.A. and Stone, D., **Extinction vulnerability of tropical montane endemism from warming and upslope displacement: a preliminary appraisal for the highest massif in Madagascar**, Global Change Biology, 14, 1-18, 2008

Reading, C.J., L. M. Luiselli, G. C. Akani, X. Bonnet, G. Amori, J. M. Ballouard, E. Filippi, G. Naulleau, D. Pearson and L. Rugiero, **Are snake populations in widespread decline?**, Biology Letters, The Royal Society, 2010

Reisinger A (2010) Climate Change 101 - An Educational Resource. http://ips.ac.nz/events/downloads/2009/Copenhagen%202/Climate%20Change%20101%20ver4.pdf

Ritchie, Euan G. and Bolitho, Elizabeth E., **Australia's Savanna Herbivores: Bioclimatic Distributions and an Assessment of the Potential Impact of Regional Climate Change**, *Physiological and Biochemical Zoology* 81(6), The University of Chicago, 2008

Roderfeld, H., Blyth, E., Dankers, R., Huse, G., Slagstad, D., Ellingsen, I., Wolf, A. and Lange, M. A., **Potential impact of climate change on ecosystems of the Barents Sea Region**, Climatic Change, 87, 283-303, 2008

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C and Pounds JA ,
Fingerprints of global warming on wild animals and plants. *Nature* **421**: 57–60, 2003

Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q. G., Casassa, G., Menzel, A., Root, T. L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C. Z., Rawlins, S. and Imeson, A., **Attributing physical and biological impacts to anthropogenic climate change**, Nature, 453, 353-357, 2008

Ruiz, D., Moreno, H. A., Gutierrez, M. E. and Zapata, P. A., **Changing climate and endangered high mountain ecosystems in Colombia**, Science of the Total Environment, 398, 122-132, 2008

Sayer, E. J., Powers, J. S. and Tanner, E. V. J., **Increased litterfall in tropical forests boosts the transfer of soil CO2 to the atmosphere,** Plos One, 2, e1299, 2007

Schliebe, S., Rode, K. D., Gleason, J. S., Wilder, J., Proffitt, K., Evans, T. J. and Miller, S., **Effects of sea ice extent and food availability on spatial and temporal distribution of polar bears during the fall open-water period in the Southern Beaufort Sea**, Polar Biology, 31, 999-1010, 2008

Schmitz, O. J., Post, E., Burns, C. E. and Johnstone, K. M., **Ecosystem responses to climate change: Moving beyond color mapping**, BioScience, 53, 1199–1205, 2003

Schweiger, O., Settele, J., Kudrna, O., Klotz, S. and Kuhn, I., **Climate change can cause spatial mismatch of trophically interacting species**, Ecology, 89, 3472-3579, 2008

Sekercioglu, C. H., Schneider, S. H., Fay, J. P. and Loarie, S. R., **Climate change, elevational range shifts, and bird extinctions**, Conservation Biology, 22, 140-150, 2008

Shoo, L. P., Williams, S. E. and Hero, J. M., **Climate warming and the rainforest birds of the Australian Wet Tropics: Using abundance data as a sensitive predictor of change in total population size**, Biological Conservation, 125, 335-343, 2005

Shuttle, K. B., Thomsen, M. A. and Power, M. E., **Species interactions reverse grassland responses to changing climate**, Science, 315, 640-642, 2007

Sinervo, Barry, Fausto Méndez-de-la-Cruz, Donald B. Miles, Benoit Heulin, Elizabeth Bastiaans, Maricela Villagrán-Santa Cruz, Rafael Lara-Resendiz, Norberto Martínez-Méndez, Martha Lucía Calderón-Espinosa, Rubi Nelsi Meza-Lázaro, Héctor Gadsden, Luciano Javier Avila, Mariana Morando, Ignacio J. De la Riva, Pedro Victoriano Sepulveda, Carlos Frederico Duarte Rocha, Nora Ibargüengoytía, César Aguilar Puntriano, Manuel Massot, Virginie Lepetz, Tuula A. Oksanen, David G. Chapple, Aaron M. Bauer, William R. Branch, Jean Clobert, Jack W. Sites, Jr., **Erosion of Lizard Diversity by Climate Change and Altered Thermal Niches,** Science: Vol. 328. no. 5980, pp. 894 – 899, 14 May 2010

Sodhi, N. S., Bickford, D., Diesmos, A. C., Lee, T. M., Koh, L. P., Brook, B. W., Sekercioglu, C. H. and Bradshaw, C. J., **Measuring the meltdown: drivers of global amphibian extinction and decline**, Plos One, 3, e1636, 2008

Sommer, Jan Henning, Holger Kreft, Gerold Kier, Walter Jetz, Jens Mutke and Wilhelm Barthlott, **Projected impacts of climate change on regional capacities for global plant species richness,** *Proc. R. Soc. B* published online 24 March 2010

Sorte, F. and Thompson, F., **Poleward shifts in winter ranges of North American birds**, Ecology, 88, 1803-1812, 2007

Steffen, Will, Andrew Burbidge, Lesley Hughes, Roger Kitching, David Lindenmayer, Warren Musgrave, Mark Stafford Smith and Patricia Werner, **A strategic assessment of the vulnerability of Australia's biodiversity to climate change**, Department of Climate Change, Commonwealth of Australia 2009

Thibault, K. M. and Brown, J. H., **Impact of an extreme climatic event on community assembly**, Proceedings of the National Academy of Sciences of the United States of America, 105, 3410-3415, 2008

Thomas, C. D., Bodsworth, E. J., Wilson, J. D., Simmons, A. D., Davies, Z. G., Musche, M. and Conradt, L., **Ecological and evolutionary processes at expanding range margins**, Nature, 411, 577-581, 2001

Thomas, C. D., Öhlemüller, R., Anderson, B., Hickler, T., Miller, P. A., Sykes, M. T. and Williams,J.W., **Exporting the ecological effects of climate change - Developed and developing**

countries will suffer the consequences of climate change, but differ in both their responsibility and how badly it will affect their ecosystems, Embo Reports, 9, S28-S33, 2008

Thuiller, W., Albert, C., Araujo, M. B., Berry, P. M., Cabeza, M., Guisan, A., Hickler, T., Midgely, G. F., Paterson, J., Schurr, F. M., Sykes, M. T. and Zimmermann, N.E., **Predicting global change impacts on plant species' distributions: Future challenges**, Perspectives in Plant Ecology Evolution and Systematics, 9, 137-152, 2008

Trivedi, M. R., Morecroft, M. D., Berry, P. M. and Dawson, T. P., **Potential effects of climate change on plant communities in three montane nature reserves in Scotland, UK**, Biological Conservation, 141, 1665-1675, 2008b

Tylianakis, J. M., Didham, R. K., Bascompte, J. and Wardle, D. A., **Global change and species interactions in terrestrial ecosystems**, Ecology Letters, 11, 1351-1363, 2008

van der Wal, R., Truscott, A. M., Pearce, I. S. K., Cole, L., Harris, M. P. and Wanless, S., **Multiple anthropogenic changes cause biodiversity loss through plant invasion**, Global Change Biology, 14, 1428-1436, 2008

Van Vliet, A. J. H., **Monitoring, analysing, forecasting and communicating phenological changes**, PhD Thesis, University of Wageningen, 2008

van Vuuren, D. P., Sala, O. E. and Pereira, H. M., **The future of vascular plant diversity under four global scenarios**, Ecology and Society, 11, 25, 2006

Victorian Government Department of Sustainability and Environment Melbourne, **Securing Our Natural Future, A white paper for land and biodiversity at a time of climate change**, November 2009

Victorian Government Department of Sustainability and Environment Melbourne, **Biodiversity is Everybody's Business, Victoria's Biodiversity Stategy 2010 – 2015 (Consultation Draft**), May 2010

Walther, G. R., Beißner, S. and Burga, C. A., **Trends in the upward shift of alpine plants**, Journal of Vegetation Science, 16, 541-548, 2005

Wang, G. X., Li, Y. S., Wang, Y. B. and Wu, Q. B., **Effects of permafrost thawing on vegetation and soil carbon pool losses on the Qinghai-Tibet Plateau, China**, Geoderma, 143, 143-152, 2008

Watterson, I. G., **Calculation of probability density functions for temperature and precipitation change under global warming** Journal of Geophysical Research (in press) 2008

Welbergen, J. A., Klose, S. M., Markus, N. and Eby, P., **Climate change and the effects of temperature extremes on Australian flying-foxes**, Proceedings of the Royal Society, Biological Sciences, 275, 419-425, 2008

Williams, S. E. and Middleton, J., **Climatic seasonality, resource bottlenecks, and abundance of rainforest birds: implications for global climate change**, Diversity and Distributions, 14, 69-77, 2008

Willis, K. J., Araujo, M. B., Bennett, K. D., Figueroa- Rangel, B., Froyd, C. A. and Myers, N., **How can a knowledge of the past help to conserve the future? Biodiversity conservation and the relevance of long-term ecological studies**, Philosophical Transactions of the Royal Society B-Biological Sciences, 362, 175-186, 2007

Wilson, R. J., Gutierrez, D., Gutierrez, J., Martinez, D., Agudo, R. and Monserrat,V. J., **Changes to the elevational limits and extent of species ranges associated with climate change**, Ecology Letters, 8, 1138-1146, 2005

Wilson, R. J., Gutierrez, D., Gutierrez, J. and Monserrat,V. J., **An elevational shift in butterfly species richness and composition accompanying recent climate change**, Global Change Biology, 13, 1873-1887, 2007

Wolf, A., Callaghan, T. V. and Larson, K., **Future changes in vegetation and ecosystem function of the Barents Region**, Climatic Change, 87, 51-73, 2008a

Wolf, A., Kozlov, M. V. and Callaghan, T. V., **Impact of non-outbreak insect damage on vegetation in northern Europe will be greater than expected during a changing climate**, Climatic Change, 87, 91-106, 2008b

Xenopoulos, M. A. and Lodge, D. M., **Going with the flow: Using species-discharge relationships to forecast losses in fish biodiversity,** Ecology, 87, 1907- 1914, 2006

Xenopoulos, M. A., Lodge, D. M., Alcamo, J., Märker, M., Schulze, K. and van Vuuren, D., **Scenarios of freshwater fish extinctions from climate change and water withdrawal**, Global Change Biology, 11, 1557- 1564, 2005