Climate change impacts on biodiversity in Australia

Outcomes of a workshop sponsored by the Biological Diversity Advisory Committee, 1–2 October 2002

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Foreword

Climate change is happening—the extensive and critically accepted reports of the Intergovernmental Panel on Climate Change (IPCC) have removed any remaining doubt.

One particularly visible sight that brings climate change to the attention of the public is the series of large tracts of bleached coral on the Great Barrier Reef resulting from unusually warm summers. The Great Barrier Reef is an Australian icon, symbolic of the wealth of Australia's biological diversity. It is the nursery to fishing industries and is visited by thousands of tourists each year, bringing hundreds of millions of dollars into our community. While the high visibility of coral bleaching has made us aware of this impact of climate change we should be equally concerned about the many other, less obvious but perhaps equally damaging impacts of climate change on biological assets and ecosystem processes. Are there more subtle responses hidden in our Gondwanan rainforests and extensive rangelands that we are failing to see? Will these responses only become apparent when it is too late to act and we have already lost ecosystem services and biological assets forever?

Although the Earth has gone through episodes of climate change in the past, this is the first time such major changes can be attributed to human-induced causes. The Australian Terrestrial Biodiversity Assessment 2002 and State of Environment reports have shown that as a direct consequence of continuing human activities, many of our natural systems are already under severe stress. There is no doubt that we are facing real and serious threats to our biodiversity. Our modification of the landscape has reduced habitat. At the same time, introduced species and diseases threaten many species in the restricted and modified habitats that remain. These threats are likely to be even more damaging to native biodiversity under the influence of changing climates. We must respond with adequate and timely policy and management action. The Biological Diversity Advisory Committee (BDAC) is concerned that investment in ameliorating known threats and repairing current damage will be inadequate if climate change is not taken into consideration in future policies and management actions.

The BDAC has been established to advise the Minister on matters relating to the conservation and ecologically sustainable use of biodiversity. The Committee believes that these four questions are important for governments:

- What are the current and future impacts of climate change on biodiversity?
- What can we do to buffer these climatic impacts?
- Who needs to make the relevant policy and management decisions?
- What information is out there to help with these decisions?

To begin to answer these questions, we brought together climate change researchers, biodiversity researchers and policy makers, covering a wide range of expertise.

We recognise that, while much valuable work on biodiversity conservation is being undertaken, there are many research gaps in Australia. There is an enormous amount of information on biodiversity, but very little has been put into the context of climate change—the required linkages have not yet been made. It is up to policy makers to describe their information needs clearly to researchers, and to help direct research towards filling these needs.

The resulting workshop report has collated up-to-date information on the impacts climate change is having on a range of Australian ecosystems and how we might go about measuring these impacts. It provides a first and vitally important contribution demonstrating where we should be directing our attention, both in research and in policy. The report is a fine example of researchers, decision-makers and their institutions working together.

Acknowledgements

I would like to thank the Committee, and in particular Imogen Zethoven, for raising and pursuing this issue. Thanks to Mark Howden, Michael Dunlop (CSIRO) and Lesley Hughes (Macquarie University) for developing this proposal with BDAC and for their significant contribution to the report. I would like to particularly thank the editorial team, which included the above contributors as well as David Hilbert and Chris Chilcott. The team put in significant hours compiling the report. Environment Australia and the Australian Greenhouse Office have been supportive throughout. Environment Australia also provided funding for the workshop and publication of the report.

Thanks to the workshop participants for their enthusiastic involvement throughout the process. Their unpaid expert advice is acknowledged—it is a testament to the strength and breadth of the ecological sciences in Australia that such world-class experience can be brought together on this topic.

Prof Hugh Possingham [1]

Chair
Biological Diversity Advisory Committee

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Summary

The workshop

A workshop held in Canberra on 1–2 October 2002 brought together for the first time researchers and policymakers from all over Australia to assess the issue of climate change in relation to biodiversity in Australia: a growing policy concern.

The participants had expertise in the key ecosystems of concern: coral reefs, rainforests, alpine regions, rangelands, grasslands, arid zone, temperate forests, coastal marine systems, rivers, mammals and birds. Presentations were made about these key ecosystems, outlining existing trends in climate, as well as future climate change scenarios (Chapter 2), current understanding of the impacts of climate changes, and likely sensitivities to future impacts (Chapters 1 and 3). The workshop identified potential signs of climate change (Chapter 4), modelling approaches that could improve both predictions of impacts and assessments of possible adaptation strategies (Chapter 5), and possible policy responses (Chapter 6).

The workshop was part of an iterative process that will help meet the objectives of the Council of Australian Governments' Impacts and Adaptation Work Plan and an action plan under the *National Objectives and Targets for Biodiversity Conservation (2001–2005)*. These plans will identify potential impacts of climate change on Australia's biodiversity, and measures to address those impacts.

Climate changes

Human activities appear to be affecting the global climate (see Chapter 1). Global mean temperatures have risen approximately 0.7°C since the mid-1800s. Changes in rainfall patterns, sea-levels, and rates of glacial retreat are being seen and found to be consistent with expectations of 'greenhouse' climate change. The eight warmest years measured globally have occurred in the 1990s and 2000s. Last year (2002) was the second warmest on record. The 1990s was the warmest decade ever recorded with measuring instruments, and the last 100 years were the warmest of the millennium, according to instruments and other means of estimating temperature.

The above trends also apply in Australia. In 2002, Australia recorded its highest-ever average March–November daytime maximum temperature, with the temperature across Australia 1.6°C higher than the long-term average and 0.8°C higher than the previous record. Evaporation rates were also the highest recorded so far.

The most recent report of the Intergovernmental Panel on Climate Change (IPCC) concluded that there is now strong evidence for a human influence on global climate, and that these trends will continue for the foreseeable future because of continued emissions of fossil fuels and other greenhouse gases.

Current projections predict an increase in global average temperatures of between 1.5°C and 6°C by the end of the present century (Chapter 2). To place these changes in perspective, a 1°C rise in average temperature will make Melbourne's climate like that currently experienced at Wagga Wagga in southern New South Wales (NSW), and with a 4°C or 6°C rise, Melbourne's climate will resemble the climate at Moree in northern NSW or just north of Roma in Queensland. Intuitively, given the differences in ecosystems across this transect of around 1400 km, the workshop participants recognised that such changes are likely to have large implications for Australia's biodiversity.

The relatively modest warming experienced so far has *already* had measurable impacts on the distributions, physiology and life cycles of a range of plants and animals across the globe.

For example, the distributions of some species of birds, mammals and insects have apparently moved toward the poles or upwards in altitude, in response to shifting climatic zones. There is also increasing evidence of earlier flowering and fruiting in plants, and earlier reproduction in amphibians and birds, in response to warmer temperatures. Unfortunately, few studies have been made in Australia because of a lack of long-term recording and little support for such research to date.

Likely climate change impacts on ecosystems

The workshop presentations identified potential impacts to a range of key Australian ecosystems (Chapter 3).

Coral reefs

The natural balance between reef-building (accretion) and reef-breakdown (dissolution) normally maintains and increases the bulk volume and complex architecture of coral reefs. But currently the balance is under threat on two fronts: coral is dying apparently because of more frequent and severe heat waves that stress and bleach it, and also there are detrimental changes in sea-water chemistry caused by increasing amounts of carbon dioxide (CO_2) in the atmosphere. Evidence suggests that with even mild warming (+2^{o}C), tropical near-shore communities will change from coral-dominance to algal-dominance. It is likely, given this evidence, that global warming will have major impacts on biodiversity and will affect the ecosystem services currently being supplied by coral reefs.

Near coastal marine systems

It is possible that plankton productivity could become significantly more variable in near coastal marine systems, and that change could have flow-on effects to system ecology and productivity.

Rangelands

There is likely to be a decrease in rangeland productivity, an increasing risk of degradation, increasing sensitivity to disturbance, a change in ecosystem function, and alteration to plant and animal community composition. In arid zones particularly, the effects of climate change may be hidden in the ‘noise’ caused by climate variability, management actions and other disturbances, at least in the next few decades.

Alpine regions

Large reductions in snow cover are likely to lead to declines in alpine flora and fauna as a result of changes to habitats, alterations in fire regimes and incursion of feral animals and weeds.

Temperate forests

As well as changes in vegetation composition in temperate forests, it is likely that changes in structure, productivity and foliage quality will have flow-on effects to other components of biodiversity. Additionally, likely increases in fire frequency and intensity will have also have impacts.

Tropical rainforests

The tropical forests of north Queensland are highly sensitive to the range of climate changes expected in the next two to three decades. Higher rainfall favours some rainforest types (lowland, for example) while reduced rainfall increases the area suitable for woodlands and forests dominated by *Eucalyptus*. Highland rainforest environments, the habitat for many of the region’s endemic vertebrates, may decrease in area by 50% even with only a 1^{o}C warming. A larger rise in average temperatures may result in the fragmentation and then disappearance of environments suitable for highland rainforest. For fauna, the evidence suggests that global warming will have severe effects on the long-term survival of many species. A 1°C increase in average temperatures is predicted to decrease the bio-climatic range of endemic species by about one-third (37%). A rise of 3.5^{o}C will reduce bioclimatic range to an average of 11% of current area, and will completely eliminate the current bioclimates occupied by 30 species of endemic vertebrates. Workshop presentations warned that there is a real possibility of at least 30 to 50 species becoming extinct this century and that most highland faunal species will disappear if average temperatures increase by 1–5°C.

Priorities for action

The workshop identified several areas for policy development and action (Chapter 6).

Understanding and managing for climate variability

As we have found with agriculture and other sectors, there are opportunities to manage the conservation estate effectively in spite of climate change. Climate information, together with an understanding of ecosystem dynamics, is increasingly being brought into management decisions (such as for fire management, culling permits, harvest licences, river flows, visitor numbers). The more we incorporate climate information into management tools now, the better we are likely to manage future climate change. Experience in other sectors such as agriculture shows that the most effective way to incorporate the information is through participatory research in which useful applications are developed in collaboration with on-ground managers, building their capacity for effective decision-making.

Immediate preservation of components of biodiversity that are sensitive to climate change

There is evidence suggesting that the rate of climate change will be faster than the rate at which most species can adapt, either by migration or by changing their behaviour, physiology or form. Hence, one short-term goal for management is to ensure the survival of species in spite of additional threats resulting from climate change. A first step is to identify threatening processes and threatened species or communities. If there are insufficient resources for managing problem situations, straightforward guidelines and priorities will be needed, which everyone can understand. The guidelines should set out the risks to biodiversity, how the risks are linked to resourcing, and the reasons for particular courses of action.

Some existing programs designed to manage threatening processes may also enhance species' adaptability or resilience to impacts from climate change, especially if implemented more vigorously. Examples include management programs for pest animals, disease and weeds, and activities that set out to reduce the risks of fire, or sediment and nutrient discharge to the Great Barrier Reef.

Where activities such as these are inadequate to reduce risks, new activities will be needed that explicitly target climate change. For example, we should assess the possibilities for translocating species, or identify the characteristics of sites that can act as 'refugia' (refuges) from climate change: perhaps specific sites, linked sites across regions, or more intensively managed areas.

For some species, the only practicable preservation options may be in aquaria, zoos and botanical gardens — although issues of genetic diversity, animal welfare and cost-effectiveness are likely to arise.

Facilitating long-term adaptation

Long-term adaptation may be achieved by species in environments where natural adaptation processes (such as migration, selection, change in structure) can take place because there is sufficient connectivity in the landscape and few other threatening processes. Two key components will be:

- appropriate management of both on- and off-reserve areas with high conservation value;
- a system of comprehensive, adequate and representative (CAR) reserves that takes the effects of climate change into consideration. The scale of potential climate change poses significant challenges in achieving the CAR goal.

However, there may be some conflict between these and other natural resource management goals. For example, well-connected landscapes (to facilitate natural adaptation) may also allow movement of, and give refuge to, pest animals and weeds, or provide avenues for fire (thereby threatening other species preservation goals). There may also be conflicts for revegetation teams that wish to use local provenances, because that objective may be at odds with proactive planting of 'future climatically appropriate' species or provenances to facilitate long-term adaptation.

Monitoring and research, setting current priorities and adjusting them as climate change occurs

There is very little information to guide priorities for managing for climate change. Focused research is needed, as well as predictions of future impacts, if an active adaptive management approach is to be adopted. Key elements in ecosystems of concern will need to be monitored.

- Some past approaches for predicting climate change impacts have been based simply on correlations between existing species distributions and climate variables (see Chapter 5). While these analyses can be useful as a first 'filter', they can be a problem if used and interpreted naïvely. We need better prediction techniques that can incorporate the effects of increased atmospheric CO_2 concentrations, and other environmental constraints such as soil characteristics, as well as management adaptations. Such systems have recently been tested using simple models of key ecological process (for example, establishment, growth, reproduction, death) in response to climate factors, CO_2, management and soils.
- Given the huge range of possible climate change across Australia (from 1 to 7^{o}C by 2070) monitoring will be very important, enabling progressive adaptation to climate changes as they occur. Monitoring activities should be undertaken for clearly defined purposes: either to make specific decisions or to learn about the system or species of concern.

Several types of indicator organisms can be used for monitoring. Of these, 'detectors' and 'sentinels' are most pertinent. Detectors are species occurring naturally in an area of interest that may show measurable responses to environmental change, such as changes in distribution or behaviour. Sentinels are sensitive organisms introduced into the environment as an early-warning device. These organisms may display changes in physiology, phenology and distribution and abundance. In Chapter 4 a set of possible indicators is outlined and a set of criteria for evaluating the appropriateness of these and/or other indicators is developed.

Understanding the balance between mitigation and impacts or adaptation

Ideally, decisions on climate change responses should be based on five elements:

- costs and/or benefits of mitigation,
- costs and/or benefits of adaptation (and costs of any residual impacts if adaptation is less than complete), and
- the interaction between these.

Workshop participants discussed the trade-offs between requirements for short-term responses (mitigation) and longer-term responses (adaptation). There is likely to be a 'see-saw' interaction between these, with large mitigation effort likely to reduce the need for, and cost of, future adaptation and vice versa. It is not possible at present to adequately inform policy-makers on any of the last three elements of the above dot points. Furthermore, such an analysis should deal with all sectors likely to be affected (including agriculture, forestry, transport, human health, tourism), of which biodiversity conservation is only one.

Information gaps

A large number of information gaps were identified at the workshop. Some of the key gaps were:

- documentation of impacts that are already occurring in response to existing climate trends;
- an understanding of the factors affecting the distribution and abundance of species, particularly those affecting the establishment and death phases of life-cycles, the likely migration rates, and the identification of migration barriers and refugia;
- analyses of the species, ecosystems and regions most vulnerable to climate changes, including those likely to be negatively affected by species advantaged by the changes (such as weeds and feral animals);
- a comprehensive assessment of adaptation options available, including the modifications needed to existing conservation planning

and practice, and the existing conservation estate;

- analyses of present and future social and economic costs of climate change impacts on biodiversity with or without adaptations;
- an understanding of the factors determining the resilience and adaptive capacity of ecosystems, including the roles of habitat extent, connectivity and quality, flow regimes, disturbances and management of mosaics;
- how to develop policy that is robust to the uncertainties and long response times of climate impacts and adaptations, including assessments of trade-offs between costs of mitigation and future costs of impacts and adaptation.

One of the recurring themes through this report is uncertainty. We are uncertain about

1) scenarios for emissions;
2) the implications of emissions for global and regional climate change;
3) the impacts of increased CO_2 concentrations and changed climate on ecosystems and their constituent species; and
4) the adaptation options available, and their associated effectiveness and cost.

One approach to deal with such pervasive uncertainty is to adopt a risk-management approach, which includes assessing the climate change impacts on biodiversity in relation to a suite of other pressures and factors (one of which is mitigation).

However, there is a range of barriers to adopting an integrated, risk-management approach. Adversarial institutional structures seem to be a key barrier; they stretch from the landscape level through to the peak political processes (for instance, approaches that foster either agriculture or conservation, but not ways to integrate the two). Lack of information is a barrier to understanding the nature of impacts of climate change or elevated CO_2 on ecosystems, and lack of information prevents full acknowledgement of the values of Australian ecosystems and species (even when abstracted down to only the ecosystem service components).

A first step

This workshop report should be seen as only an initial step in the iterative process needed to inform the Australian public and policymakers. It can be viewed as an input into further targeted assessment.

The workshop has identified the relatively poor and uncoordinated information base on the issue of climate change and its effects on biodiversity. Workshop participants agreed that in some respects, this area of work is at the stage of development that global climate science was some 15 years ago.

Chapter 1. Biodiversity and climate change: workshop aims and background

Lesley Hughes[1], Mark Howden[2] and Imogen Zethoven[3]

Human activities appear to be affecting the global climate. Global mean temperatures have risen approximately 0.7°C since the mid-1800s. Changes in rainfall patterns, sea-levels, and rates of glacial retreat are being seen and found to be consistent with expectations of 'greenhouse' climate change. The 1990s was the warmest decade ever recorded, and the last 100 years were the warmest of the millennium, according to various means of measuring or estimating temperature. Last year (2002) was the second warmest on record. The most recent report of the Intergovernmental Panel on Climate Change (IPCC 2001a,b) concluded that there is now strong evidence for a human influence on global climate and that these trends will continue for the foreseeable future because of continued emissions of fossil fuels and other greenhouse gases. The most up-to-date predictions indicate an increase in global average temperatures of 1.5–6°C by the end of the present century. To place these changes in perspective, a 1°C rise in average temperature will make Melbourne's climate like that currently experienced at Wagga Wagga in southern New South Wales (NSW), and with a 4°C or 6 °C rise Melbourne's climate will resemble the climates at Moree in northern NSW or just north of Roma in Queensland. Intuitively, it is hard to conceive that such changes will not have implications for Australia's biodiversity.

The IPCC Third Assessment Report (2001 a,b) concludes that Australia is significantly vulnerable to the changes in temperature and rainfall predicted over the next decades to 100 years. Natural resources and conservation are two of the key sectors identified as likely to be affected strongly. Climate change will add to the existing substantial pressures on these sectors.

Until recently, it was expected that the effects of climate change on species and communities would not be detectable for at least another couple of decades. However, over the last few years, evidence has accumulated which indicates that the relatively modest warming experienced so far has *already* had measurable impacts on the distributions, physiology, and life cycles of a range of plants and animals. For example, the distributions of some species of birds, mammals and insects have apparently moved toward the poles or upwards in altitude, in response to shifting climatic zones. There is also increasing evidence of earlier flowering and fruiting in plants, and earlier reproduction in amphibians and birds, in response to warmer temperatures. Consequently, there is growing recognition that these biological responses are very sensitive indicators of climate changes, as they integrate climate over long periods and often have thresholds over which abrupt changes occur.

The data collected so far on these changes have been almost exclusively from the Northern Hemisphere. The data have been made possible by the tradition of long-term monitoring of distribution, abundance and life-cycles of several groups of organisms by the International Phenological Gardens in Europe, the Butterfly Monitoring Scheme in Britain, and others. In the IPCC Third Assessment Report (IPCC 2001b), of the approximately 100 physical processes and 450 species analysed for such signals, there were no Australian studies.

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How will species respond to future climate change?

The effects of future climate change on species could be profound, as indicated by the earlier example of potential geographical shifts in climate zones within Australia. Species that are unable to tolerate changed conditions within their current range, or that cannot migrate fast enough to keep up with moving climate zones, face eventual extinction. The most vulnerable species will be those with long generation times, low mobility, highly specific host relationships, small or isolated ranges, and low genetic variation. Remnant populations within reserves and ecosystems such as alpine zones, coral reefs, polar regions and coastal wetlands are likely to be particularly vulnerable.

Considering that temperature and other climatic trends in Australia appear to be consistent with those happening globally, is there any evidence that the early impacts on species in the Northern Hemisphere are also occurring in Australia?

We cannot yet answer this important question with any degree of confidence, because few long-term data-sets exist in Australia. No co-ordinated monitoring of sensitive species has been undertaken, and analyses that demonstrate existing change have not yet taken place for those species for which we have the data. We urgently need to identify vulnerable plants, animals and ecosystems that are sensitive to climate change, in order to inform policy-makers about climate change in relation to conservation management. The need for work on this issue was the first research priority listed in the IPCC Third Assessment report chapter on Australasia (page 629, IPCC 2001b). The work could eventually tie into the development of effective indicators of climate change. Ideally, such indicators would already have some historical data available to serve as a baseline against which future change can be compared. Ongoing monitoring of these indicators would allow us to 'calibrate' the rate of ecological change against climate trends, so we could implement adaptive management procedures. They would be intended to supplement, not replace, the monitoring of climate itself.

Aims of the workshop

In response to the above issues, the Biological Diversity Advisory Committee supported a workshop held on 1–2 October 2002 in Canberra. The aims of the workshop were to:

- assess whether there is evidence for existing impacts from the climate change that has already occurred;
- compile knowledge about climate sensitivities (and thresholds if they exist) of species and communities;
- identify key characteristics of species, communities and ecosystems that will result in them being highly sensitive to climate changes;
- start to assess the state of data-sets that could be useful for analyses of climate impacts;
- assess the analysis and modelling approaches that could be used to identify past and future impacts of climate change.

The workshop was part of an iterative process that is helping meet the objectives of the Council of Australian Governments' Impacts and Adaptation Work Plan and an action plan under the *National Objectives and Targets for Biodiversity Conservation (2001–2005)* (Environment Australia 2001). These plans will identify the potential impacts of climate change on Australia's biodiversity, and initiate measures to address the impacts. Hence, the workshop also addressed the policy-making environment and developed suggestions for attention in the policy-making processes.

Chapter 2. Climate trends and climate change scenarios

Mark Howden[1]

Are changes happening now?

The IPCC Third Assessment Report (2001b) documents trends in a large number of aspects of climate and related factors. Primary amongst these is the continued increase in the concentration of atmospheric carbon dioxide (CO_2). Levels have increased from 280 ppm, during the pre-industrial era, to 371 ppm today. Post-1800s CO_2 concentrations grew almost exponentially (Figure 2.1), with the concentrations of other greenhouse gases such as methane and nitrous oxide showing similar growth curves.

The increase in greenhouse gas concentrations has contributed to the increases in temperature experienced over the past 50 years, although there are other factors contributing to temperature rise, such as volcanic eruptions, variations in solar output and changes in aerosol concentrations. The measurements of increased surface temperature come from thermometers, tree ring data, ocean temperature soundings, coral data, borehole temperatures and satellite measurements of tropospheric temperature. Factors such as the influence of 'urban-heat islands' have been removed from the signals. Previous apparent conflicts between the satellite data and surface temperature records have been reconciled, by re-analysis which has allowed for orbital decays (Wentz and Schabel 1998), as well as by calibration factors on successive satellites (Prabhakara et al. 1998), and by separation of the temperature signals into those arising from the lower atmosphere (troposphere) and those arising from the upper atmosphere (stratosphere). The satellite tropospheric temperature record is now consistent with the surface record (IPCC 2001a).

Consistent with global trends, Australia's continental average temperature increased 0.7ºC from 1910 to 1999 as measured by high-quality surface temperature records (Plummer et al. 1995, Torok and Nicholls 1996), with most of the increase recorded since 1950. These results are supported by data from dendrochronological (tree ring) studies (Cook et al. 1991). The year 1998 was Australia's warmest year on record, and the 1990s the warmest decade (Skirving et al. 2002). Annual minimum temperatures have increased by 0.85ºC per century and maximum temperatures by 0.39ºC per century (Wright et al. 1996). These increases have not been spatially or temporally uniform, with minimum temperatures increasing more in the north-east part of the continent and greater increases occurring in autumn, particularly in May (McKeon and Howden 1993, McKeon et al. 1998). Part of this autumn warming in the north-east may be related to recorded increases in sea-surface temperatures in the Coral Sea (Salinger et al. 1996, Zheng et al. 1997). Upper ocean temperatures have also been increasing globally. Changes from 1955 to 1996 were consistent with the increase in net radiative forcing arising from increased concentrations of both greenhouse gases and aerosols (White et al. 1998), although long-term natural variability may also be influencing temperatures (Latif et al. 1997).

The increased minimum temperatures recorded in Australia may be partly related to a 5% increase in cloud cover since 1910 (Jones 1991). This trend is similar to that recorded globally (McGuffie and Henderson-Sellers 1994). The change in cloudiness appears to have resulted

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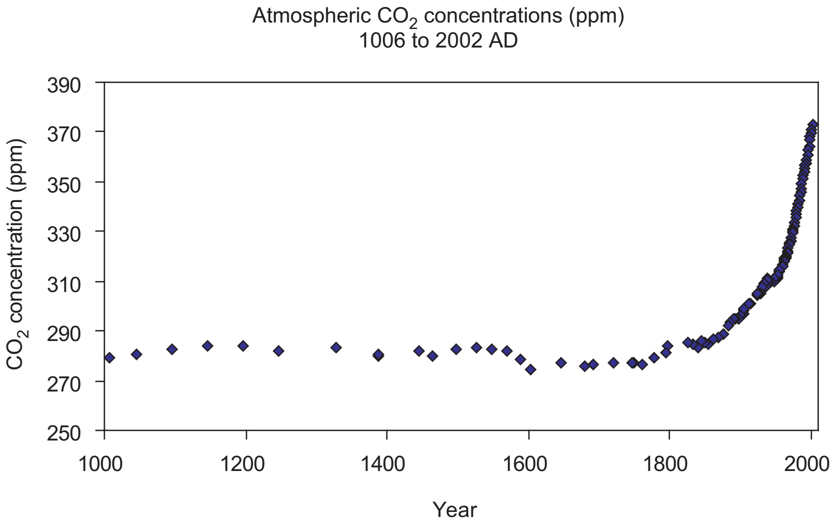

Figure 2.1. Atmospheric CO_2 levels derived from measurements in ice cores (Etheridge and Wookey 1989, Etheridge et al. 1996, 1998, Morgan et al. 1997) and direct measurement from Mauna Loa (Keeling and Whorf 2002)

in significant decreases in solar radiation in both coastal and inland Queensland, in autumn and winter, and increases in vapour pressure in May (McKeon et al. 1998).

The trend to warmer temperatures appears to have already reduced frost frequency and duration (Stone et al. 1996) resulting in an increase in Australian wheat yields (Nicholls 1997) and the frequency of heat stress in livestock (Howden and Turnpenny 1997). Higher temperatures have also reduced snow cover (Green and Pickering 2002).

Global and regional air temperature increases are closely linked to reductions in global glacial mass (Dyurgerov and Meier 1997b, Haeberli and Beniston 1998), although in some regions increased precipitation has increased glacial mass (Dowdeswell et al. 1997). Increased air temperatures during the period 1961–1990 have been associated with a marked reduction in global glacial mass, which has contributed an average of 0.25 mm/year to sea-level rise (14 to 18% of the 100-year average sea-level rise). The rate of glacial shrinkage has increased significantly since the mid-1980s (Dyurgerov and Meier 1997a,b) with European glaciers losing 10–20% of their mass in this period (Haerberli and Beniston 1998). Glaciers in New Zealand are also showing substantial retreat (de Freitas 1988), whilst in the Antarctic there have been changes in ice flow rates (Bindschadler and Vornberger 1998) and retreats and break-up of large ice-shelves which are close to the climatic limit (Doake and Vaughan 1991, Skvarca 1993, Vaughan and Lachlan-Cope 1996). These changes in ice shelf area and dynamics have been linked (Doake and Vaughan 1991) to the significant warming that has occurred at the edge of Antarctica and in the surrounding ocean (Jones 1995). There has also been a marked decline in the extent of antarctic sea ice, with a southerly migration (2.8 degrees of latitude) of the summer sea ice boundary between the mid-1950s and the 1970s. There is some suggestion that this has already affected antarctic marine productivity (de la Mare 1997). Increasing sea-surface temperatures are also implicated in a general increase in wave energy and wave heights (Grevemeyer et al. 2000).

As well as temperature changes, there have been consistent trends in precipitation over many regions of the world, with some increasing and some decreasing. There have also been trends towards increased intensity of precipitation (IPCC 2001a).

These trends are also present in Australia, with studies documenting an increase in both heavy rain events and average rainfall over large areas of Australia from 1910 to 1990 (Suppiah and Hennessy 1996, 1997, Lavery et al. 1997). The largest increases were along the east coast, particularly in NSW, but decreases occurred in the south-west of Western Australia and inland Queensland over this period. In the summer half-year, the all-Australian average rainfall (based on area-weighted station data) increased by 14%, heavy rainfall increased by 10–20%, and the number of dry days decreased by 4% (Suppiah and Hennessy 1996, 1997). In the winter half-year, the changes were about half these figures. The trends in heavy rain events are partially but not totally explained by ENSO (El Niño Southern Oscillation) fluctuations over recent decades (Suppiah and Hennessy 1996, 1997). The changes in rainfall are also reflected in the number of wet days. There are up to 20% more wet days now in parts of NSW and the Northern Territory, but fewer by about 10% in Western Australia (WA) (Hennessy et al. 1999). However, a significant part of the trends (both positive and negative) consists of an almost step-wise change around the mid-1970s. A similar 'state-change' in climate and oceanic systems occurred almost globally at this time.

The possible relationship between ENSO and rainfall amount has altered since the 1970s, with higher rainfalls for any value of the SOI (Southern Oscillation Index) than would have previously been expected (Nicholls et al. 1996). Furthermore, it appears that the ENSO system itself is changing (Nicholls et al. 1997) with an apparent functional change in the mid-1970s (Graham 1994) to increased frequency of El Niño events and fewer La Niña events. These have been assessed in the context of the historical record as being very unusual and unlikely to be accounted for solely by natural variability (Trenberth and Hoar 1996, 1997). Others, such as Mantua et al. (1997) and Allan and D'Arrigo (1998), have a conflicting view that the recent persistent El Niño events could be part of long-term natural variability. Ongoing research on decadal climatic fluctuations (Power et al. 1999) should eventually allow us to more effectively differentiate any climate change signal from other, natural influences.

Tropical cyclones contribute a large part of the summer rainfall in many tropical areas, but the number of tropical cyclones observed in the Australian region has declined since the start of reliable satellite observation (1969–1970), reflecting the increased incidence of El Niño events (Nicholls et al. 1998).

Sea-level

Global sea-level has risen by 10–25 cm over the past 100 years (Peltier and Tushingham 1989, Barnett 1988 cited in Quayle and Karl 1996) with trends of 1.7 to 2.7 mm/year for Australia and New Zealand (Salinger et al. 1996), similar to the global estimated rate of 1.8 mm/year (Douglas 1991). However, more recent analyses suggest that Australian sea-level rises, and those of the Southern Hemisphere in general, are less than the global average (Mitchell et al. 2000). This rise in sea-level is a combination of thermal expansion due to observed temperature increases of the oceans (Church et al. 1991), glacial melting (Dyurgerov and Meier 1997a,b), groundwater extraction (Sahagian et al. 1994) and an uncertain component from changes in the Antarctic and Greenland ice caps (Zuo and Oerlemans 1997). Preliminary analyses of data from new satellite-based sensors indicate sea-level rises of about 4 mm/year in the last few years, perhaps linked to ENSO behaviour (Nerem 1995).

UV-B

The short wavelength portion of the ultraviolet range (UV-B; 290–320 nm) is damaging to both plants and animals (Rozema et al. 1997) and is strongly absorbed by ozone. Emission of chlorinated fluorocarbons and similar compounds has led to reductions in stratospheric ozone levels particularly around the poles in winter (Farman et al. 1985, Rex et al. 1997). One result has been an increased intensity of UV-B radiation at the Earth's surface, with the Antarctic 'ozone hole' being of record size in the year 2000 (Watkins 2001). The increases in UV-B have been significant at latitudes greater than 35ºS, and range from about 7% per decade for Tasmanian latitudes to 3% per decade for latitudes in northern Australia (Herman et al. 1996). Similar trends of increasing UV-B are found in data from New Zealand (Basher et al. 1994) and other regions (Blumthaler and Ambach 1990). In polluted areas, aerosols and high concentrations of tropospheric ozone tend to absorb UV-B radiation and reduce its intensity at the ground surface (Bruhl and Crutzen 1989).

Shindell et al. (1998) suggest a link between the observed increasing concentrations of greenhouse gases and the decreases in polar stratospheric ozone. The mechanism they explored through global climate models is that higher concentrations of greenhouse gases increase the stability of the stratosphere and the polar vortices, resulting in a significantly colder lower stratosphere and thus greater ozone loss. Further research is required to explore the relationships between these two trends (Salawitch 1998).

Climate change scenarios

The IPCC has released a report describing scenarios for greenhouse gas emissions (IPCC 2000). The scenarios are based on internally-consistent and plausible projections of future population, economic growth, energy technology and political situations. They span a range of possibilities, from rapid growth in total energy use to smaller increases in emissions early on, which plateau then fall later in the century (Figure 2.2). In all cases, however, CO_2 concentrations in the atmosphere are likely to increase over the next 100 years, and hence some level of climate change seems inevitable. A further point to note is the broad span of possible outcomes—this inherently expands the uncertainty in any climate-change scenario. Even the most conservative of the scenarios in Figure 2.2b will result in concentrations far exceeding any experienced over the past 420 000 years and possibly the past 20 million years. Implicitly, this means that nothing in our experience as a species provides a precedent for this sort of change (*Homo sapiens sapiens* having been in existence for 90 000 to 130 000 years). This increase in CO_2 concentrations is the most certain of potential changes (that is, it is the primary cause of the climate changes). Increased CO_2 concentrations will have significant direct impacts because they increase the photosynthetic rate and water use efficiency of plants. The outcome tends to be increased biomass but decreased nitrogen content in plants—with a variety of flow-on effects on herbivores. Another consequence can be a change in competitive interactions, and altered species composition within communities.

CSIRO has recently updated their climate change projections for Australia (http://www.dar.csiro.au/publications/projections2001.pdf) and their likely impacts (http://www.marine.csiro.au/iawg/impacts2001.pdf). These projections indicate that by 2030, annual average temperatures will be 0.4–2.0ºC higher than present. By 2070, annual average temperatures may increase by 1.0–6.0ºC (Figure 2.3).

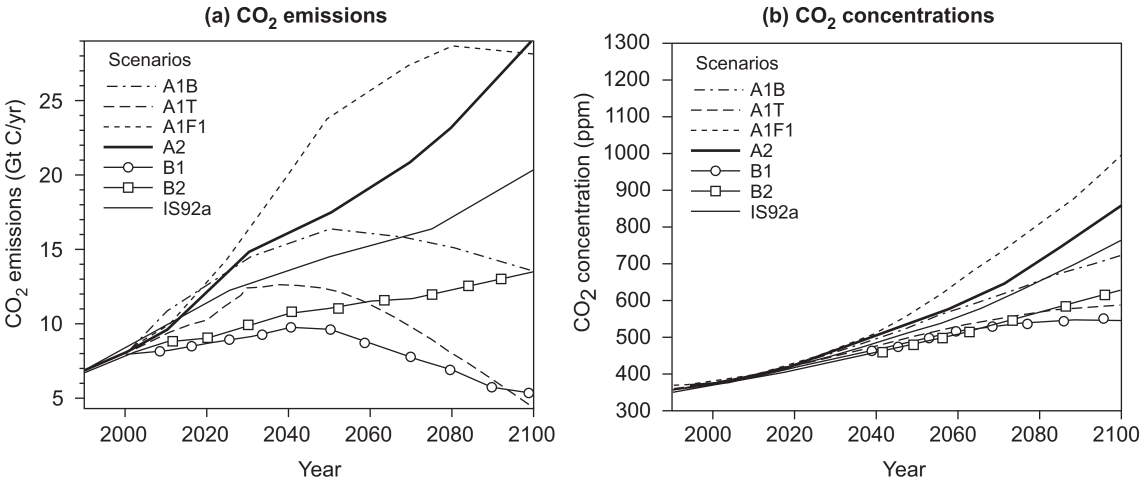

Figure 2.2. Scenarios of a) CO_2 emissions and b) atmospheric CO_2 concentrations over the 21st century (IPCC 2000)

Projections for rainfall vary much more, both spatially and seasonally (Figure 2.4). In general, the projections indicate substantial reductions in autumn, winter and spring rainfall (the main rainfall seasons) for much of southern Australia and particularly the south-west of Western Australia. In the north of Australia, increases in summer rainfall—the main rainfall season—are suggested in some regions. In most areas, an increase in rainfall intensity is indicated—even in projections where mean rainfall decreases. The projections also suggest increases in evaporation, provided that the increases in temperature remain roughly equivalent between day and night. If minimum temperatures continue to increase faster than maximum temperatures, then the results in terms of evaporative demand are likely to be equivocal.

Overall, the scenarios emphasise a more variable and unpredictable climate in Australia, with increased incidence of extreme events such as fires, floods, droughts and tropical storms. River flows in particular are likely to be significantly affected, with a rule of thumb being that in humid regions there is a doubling of reduction in river flow for a given reduction in rainfall (that is, a 10% decrease in rainfall would translate to a 20% decrease in river flows). In drier zones the multiplier is greater than two.

Climate is a key determinant of the location, structure and function of natural ecosystems. We see this every day in the landscapes in which we live: for example, there are progressive changes in vegetation up a mountainside; and forest types are related to rainfall. There are also many examples showing that climate change, on geological timescales, has affected the distribution of flora and fauna and the survival and ranges of whole ecosystems. These observations lead us to predict that the climate changes projected above will have profound impacts on natural ecosystems and their component species.

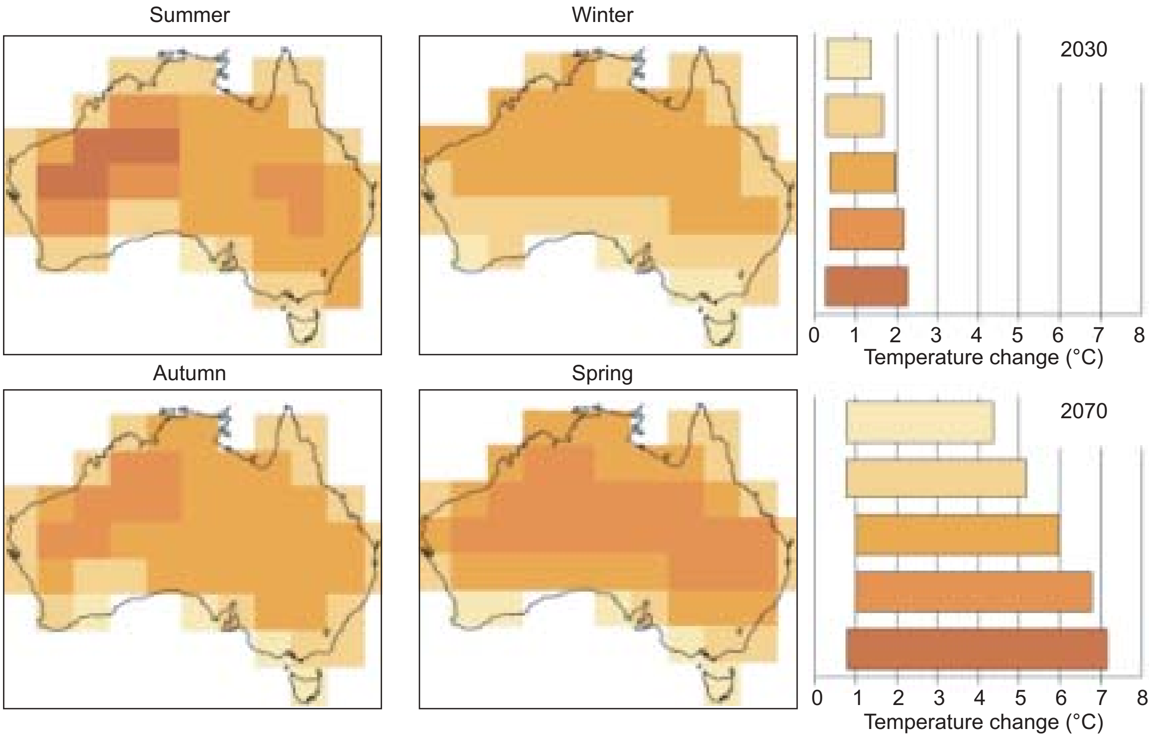

Figure 2.3. Possible average seasonal warming ranges (°C) for years 2030 and 2070 relative to 1990 (CSIRO 2001)

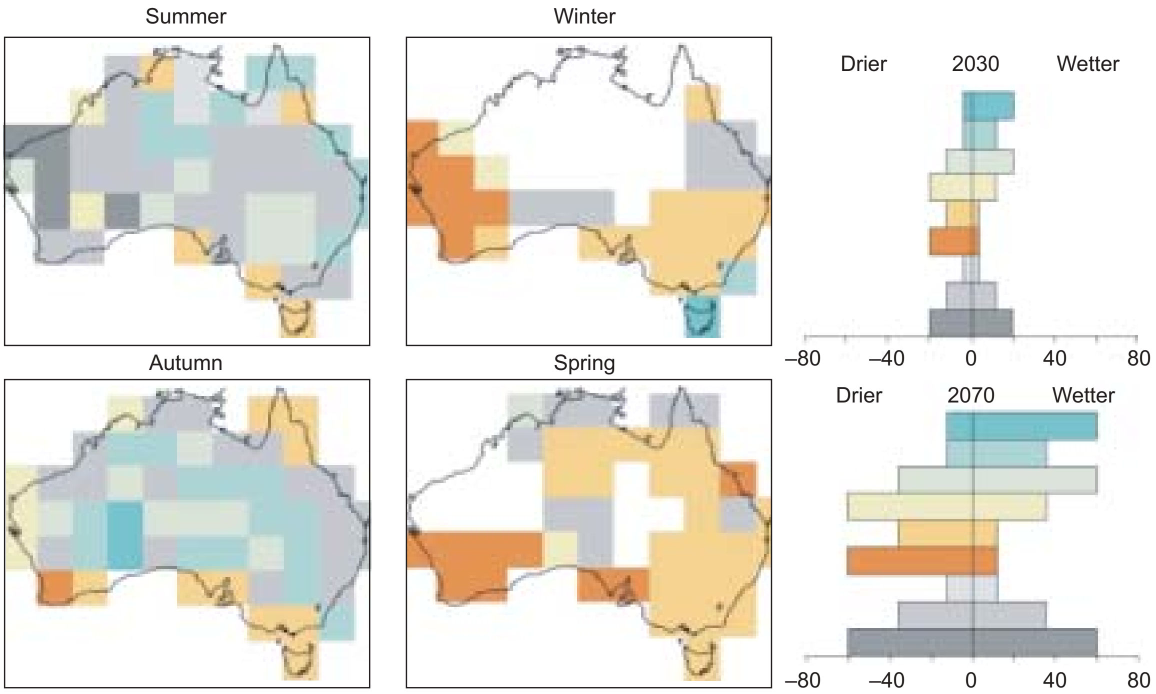

Figure 2.4. Possible ranges of average seasonal rainfall change (%) for around 2030 and 2070 relative to 1990 (CSIRO 2001)

Gidyea (*Acacia georginae*) in Central Australia. Climate changes are expected to have profound impacts on natural ecosystems and their component species. (Photo: Peter Canty, courtesy of CSIRO Sustainable Ecosystems)

Chapter 3. Summaries of workshop presentations

3.1 Recent impacts of climate change on species and ecosystems

Lesley Hughes[1]

Increasing greenhouse gas concentrations are expected to have significant impacts on the world's climate on a timescale of decades to centuries. There is accumulating evidence from long-term studies that the climate trends of the past few decades are anomalous, and that these trends are already affecting the physiology, geographic distributions and phenology (life-cycles) of species. Predictions about the ways in which species respond to climate change can be broadly summarised into the following categories:

Effects on physiology: Changes in atmospheric CO_2 concentration, temperature or precipitation will directly affect rates of metabolism and development in many animals, and processes such as photosynthesis, respiration, growth and tissue composition in plants.

Effects on distributions: A 3°C change in mean annual temperature corresponds to a shift in isotherms of approximately 300–400 km in latitude (in the temperate zone) or 500 m in altitude. Species' geographic ranges are therefore expected to move upwards in altitude or towards the poles in response to shifting climate zones, in those species capable of moving range relatively rapidly.

Effects on phenology: Life cycle events triggered by environmental cues such as degree-days may be altered, and the result may break the coupling of life-cycle interactions between species.

Changes in the physiology, phenology and distributions of individual species will alter their competitive relationships and other interactions with other species. This will lead to changes in the local abundance of species and to changes in the composition of communities. Inevitably, at least some species will become extinct, either as a direct result of physiological stress, or via interactions with other species.

Recent analyses of long-term datasets show that some species are already responding to the anomalous atmosphere and climate of the 20th century (Hughes 2000, McCarty 2001, Walther et al. 2002, Parmesan and Yohe 2003, Root et al. 2003). Here are some examples.

(i) Changes in plant physiology, productivity and growth

- Tree-ring records in both the Northern and Southern Hemispheres show clear, century-scale increases in the amount of wood laid down each year. It is possible that the increase has been caused by higher temperatures and/or CO_2 supply and nitrogen deposition.
- Since the early 1960s, the difference between annual maximum and annual minimum concentrations of atmospheric CO_2 has increased by 20% in Hawaii and by 40% in the Arctic. A likely explanation for this trend is that more CO_2 is being absorbed by land plants during the growing season.
- Basal areas of trees and lianas (climbers) have been increasing in the Amazon, with lianas increasing their dominance faster.

(ii) Changes in phenology (life-cycle timing)

- Data from the International Phenological Garden (1959–1993) show that spring events now happen 6 days earlier and autumn events

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happen 4.8 days later, with the result that the growing season is now 10.8 days longer than in the late 1950s–early 1960s.

- Monitoring of life cycles at Cardedeu, Spain, since 1952 finds that leaves now unfold 16 days earlier and fall 13 days later, plants fruit 9 days earlier, butterflies emerge 11 days earlier and spring migratory birds arrive 15 days later.
- Twenty of 65 British bird species surveyed from 1971 to 1995 show statistically significant tendencies to lay eggs earlier (about 9 days earlier on average). Only one species lays significantly later. Parallel trends of earlier reproduction have been reported for several British amphibians (during 1978–1994), with every 1^{o}C increase in maximum temperatures corresponding to an advance in spawning date by 9–10 days.
- Phenological mismatches have started to affect predator–prey and plant–herbivore relationships, such as the interactions between the oak, the winter moth and the great tit in Europe.

(iii) Changes in species distribution and abundance

- Ten of the 16 new heat-loving (thermophilic) plankton species that established in the North Sea during the 20th century have been recorded for the first time in the 1990s.
- On many mountain ranges in western North America, the treeline has moved upwards since 1890, reaching maximum extent between 1920 and 1950. By 1992–1993, there was greater plant-species-richness (number of plant species) than is noted in historical records, at almost three-quarters (70%) of the sites inspected on 30 peaks in the European Alps, possibly as a result of upward colonisation.
- Both species of antarctic vascular plants have dramatically increased in numbers at many locations in maritime Antarctica as a result of better seed germination and seedling establishment.
- Surveys of 35 non-migratory European butterflies find that the ranges of 22 species (63%) have shifted northwards by 35–240 km during the 20th century. Only two species (3%) have shifted south. For two-thirds of the species, the northern boundaries moved north while the southern boundaries remained stable, so their geographic ranges effectively expanded. Northward shifts of the ranges of European birds have also been recorded.
- Malaria and dengue fever have been recently reported at increasingly higher altitudes in Papua New Guinea, South America, Asia and Africa.
- Warming of the California Current (during 1951–1993) has been associated with significant declines in populations of zooplankton, macroalgae, reef fish and predatory seabirds.
- Increasing sea-surface temperatures have been associated with a lifting cloud base in Costa Rican cloud forests and a decline in precipitation. The changes have been accompanied by upward colonisation of lowland birds and sharp declines in amphibian and lizard populations.

Trends and impacts in Australia

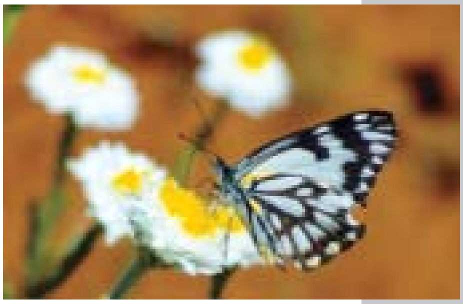
Climate trends in Australia have been consistent with global patterns, but few biological impacts have been recorded, largely because we lack long-term datasets and active monitoring programs. Nonetheless, there is evidence of change (see Hughes, in press), such as:

- thickening of vegetation in eucalypt woodlands as a result of CO_2 supply (in addition to the impacts of grazing and altered fire regimes);
- increased establishment of snow gums in sub-alpine meadows;
- intrusion of mangroves into swamps that were formerly freshwater, especially in the Northern Territory;
- higher wheat yields associated with less frequent frosts;
- rainforests invading eucalypt woodlands;
- behavioural changes in the sleepy lizard (*Tiliqua rugosa*) and changes in the position

of the parapatric boundary between lizard ticks;

- new seabird colonies to the south of their historical range;
- more frequent and intense coral bleaching as a result of increasing sea surface temperatures.

Future monitoring of carefully selected species and communities in Australia will be vital if we are to understand the impacts of global change. A national monitoring scheme such as that developed in the United Kingdom by the Department of Environment and Transport (DETR) would be highly desirable (see page 60).



Wanderer butterfly on a poached egg daisy. The geographic ranges of Australian butterflies may be affected by climate change. (Photo: CSIRO Sustainable Ecosystems)

Bleached corals near Great Keppel Island on the Great Barrier Reef in early 2002. Large sectors of associated reefs bleached due to unusually warm sea temperatures. Some corals, like the one shown in the foreground can turn pink or blue due to the stimulation of host pigments. These pigments appear to be involved in the stress responses of corals. (Photo: O. Hoegh-Guldberg)

Massive bleaching occurred on the Great Barrier Reef during early 2002 due to unusually warm sea temperatures. Inshore sites like the Keppel Islands near Rockhampton experienced almost 100% bleaching. More than 50% of the Great Barrier Reef was damaged by bleaching in 2002. (Photo: O. Hoegh-Guldberg)

3.2 Coral reefs, thermal limits and climate change

Ove Hoegh-Guldberg[1]

Coral reefs are the most spectacular and diverse marine ecosystems on the planet, and provide major resources for at least 100 million people worldwide. At the heart of these highly productive ecosystems are Scleractinian corals that build the framework of coral reefs and provide a large portion of the primary productivity associated with reefs. Despite their importance, coral reefs are highly threatened by human activities (water quality, over-fishing); it is expected that at least 30% of today's coral reefs will be destroyed by 2050 (Wilkinson and Buddemeier 1994). Climate change has recently been added to these concerns, and it is now considered to be the primary threat to coral reefs over the next 50–100 years. This paper reviews the evidence for the impact of climate change on coral reefs such as Australia's Great Barrier Reef, and explores projections for the future if current rates of warming continue.

Corals are a mutualistic symbiosis between Scleractinian corals and single-celled dinoflagellate algae belonging to a number of species from the genus *Symbiodinium*. These algae give Scleractinian corals an overall brown colour. *Symbiodinium* photosynthesises while in the tissues of the coral host, providing most of the coral's energy requirements. The high rates of calcification that are a key feature of coral reefs are directly due to the abundant photosynthetic energy provided by *Symbiodinium* (Trench 1979).

Concern for biodiversity in the face of increased coral bleaching and mortality has increased as studies show the disappearance of coral-dependent organisms like the beautiful Orange-spotted Filefish, *Oxymonacanthus longirostris*. (Photo: O. Hoegh-Guldberg)

Several conditions can lead to failure of the symbiosis between corals and *Symbiodinium*, and as a result the corals turn from brown to white—an occurrence referred to as 'coral bleaching'. Coral bleaching is a response to environmental stress, and can be triggered by a range of stressful conditions including abrupt changes to salinity, light and temperature (Hoegh-Guldberg 1999). While it may occur at a local scale (affecting perhaps 100 m^2 on a coral reef), episodes of 'mass' coral bleaching have begun to affect thousands of square kilometres of coral reefs. These events appear to be increasing in severity and frequency, and are unknown in the scientific literature prior to 1979. Coral bleaching events have great significance for Australia, which harbours over a quarter of the world's coral reefs within its waters and some of the most spectacular examples of coral reef biodiversity (for instance, in the Great Barrier Reef and on the North West Shelf). Two recent mass bleaching events (in 1998 and 2002)

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affected over 50% of all coral reefs within the Great Barrier Reef Marine Park.

Mass coral bleaching events are caused by increased water temperature, which results from disturbances to the pattern of water movement and the development of hot and still conditions. Satellite mapping of sea-surface temperatures has revealed that temperatures as little as 0.8°C above the long-term summer maxima will lead to mass bleaching. In these cases, coral reefs may recover. If sea temperatures climb to as much as 2–3°C above long-term summer maxima, or sea temperatures remain higher for longer, corals may not recover from bleaching. In cases, mass mortality events have occurred. In the extremely warm conditions of the 1998 El Niño Southern Oscillation (ENSO) event, it is estimated that 16% of the world's coral reefs died. In some areas, such as the Western Indian Ocean, as much as 48% of living coral cover was removed (GCRMN 2000).

Current trends in sea temperature have scientists and managers concerned about how the frequency and severity of coral bleaching will change. Tropical sea temperatures are now approximately 0.6°C higher than they were at the beginning of the last century (Lough 2000). How conditions for coral reefs will change has been modelled using the output of general circulation models from three of the world's major climate centres. These analyses all tell the same story. The thermal limits currently seen on coral reefs will be exceeded on an annual basis by 2030–2050, even under best-case climate projections (Hoegh-Guldberg 1999). Perhaps of greatest concern is that levels of thermal stress are set to rise to more than 4–6 times the levels of stress known to have caused major mortality events in the past (Hoegh-Guldberg 2001). These conditions suggest that Scleractinian corals are likely to become remnant organisms on reefs that are currently dominated by these important organisms today.

How will reef systems like Australia's Great Barrier Reef respond to increased rates of coral mortality? Several people have suggested that corals and their symbionts will adapt despite the rapid changes to environmental conditions around them. There is some concern about these simplistic scenarios. Corals are slow-growing asexual organisms that are unlikely to respond fast enough relative to rates of climate change—reasoning supported by recent increases in the impact of mass bleaching events. Spatial (cellular automaton) models built using parameters measured from coral populations on the central Great Barrier Reef show that even relatively mild changes to the mortality of coral populations, such as those that occurred during the 1998 mass bleaching event on the Great Barrier Reef, lead to rapid declines in coral cover. Even with the assumption that ocean warming continues at the rate of 0.1°C per decade, with warm anomalies occurring every 10 years (note: they currently are occurring every 3–4 years) coral cover declines steadily to less than 15% after 100 years (Johnson et al. 2002).

Attempts to project the future of coral reefs under climate change are based on the key assumption that the thermal tolerance of reefs does not change over the short periods involved. Analysis of the thermal tolerance of corals and their symbionts reveals that tolerance varies with latitude. This clear evidence of genetic adaptation to sea temperature has been taken as a sign that populations of corals will therefore evolve in response to climate change. Proponents of this idea neglect to consider three major issues. First, corals have evolved to tolerate different sea temperatures but over relatively long periods (probably hundreds and thousands of years but not years or decades). Second, current rates of increase in sea temperature are very high—they are increasing almost monotonically. Third, the observation of increasingly frequent and severe bleaching events over the past 20 years contrasts with the situation expected if coral reefs were rapidly evolving tolerance to thermal stress.

Other workers have suggested that re-mixing of of the host and symbiont within symbiosis may produce additional mechanisms for rapid evolutionary change. The Adaptive Bleaching Hypothesis (Buddemeier and Fautin 1993), for example, suggests that corals may bleach to take on other strains of dinoflagellate symbionts (with higher thermal tolerances). While a tantalising possibility, the Adaptive Bleaching Hypothesis remains unproven. Creation of new symbiotic combination is likely to be a complex co-evolutionary step that is unlikely to occur at ecological time scales. The ratio of the components in multi-strain symbioses may be able to change, but that is not the same as a symbiosis that involves a new partnership. Again, the fact that coral populations are showing signs of increasing death over the last two decades suggests that bleaching does not lead to increased tolerance in coral populations.

Given these scenarios, we are left trying to project what coral reefs will look like as coral cover is reduced. Impacts on overall biodiversity will depend on the type of organism being considered. For example, in fish populations studied after mass bleaching events, only those species that are dependent on corals for food show major declines. In the Seychelles, Spalding and Jarvis (2002) found that the overall structure of fish communities had changed very little despite very large decreases (3–20 fold) in living coral cover after the 1997–1998 bleaching event. The authors noted that a few individual fish species did show change, as was also discovered in a number of other studies. The Orange-spotted Filefish (*Oxymonacanthus longirostris*), which depends on coral, disappeared from Okinawan reefs rapidly after the 1998 bleaching event (Kokita and Nakazona 2001). Similar observations have been made for coral-eating *Chaetodon* fishes. Other coral-dependent species are expected to show major impacts. For example, over 55 species of decapod crustacean are associated with living colonies of a single coral species, *Pocillopora damicornis* (Abele and Patton 1976, Black and Prince 1983). Nine of these are known to directly depend on living pocilloporid coral colonies. Similar relationships exist for other coral genera. If reefs lose the coral genera and species that support the numerous coral-dependent organisms, many other organisms will almost certainly become extinct.

In summary, even with warming at the rates predicted in lower-edge scenarios put forward by IPCC (+2°C by 2100; IPCC 2001b), it is likely that many tropical near-shore communities will change from coral-dominance to algal-dominance. This will almost certainly have major impacts on biodiversity, and change the ecosystem services currently being supplied by coral reefs. It is estimated that coral reefs contain the greatest number of marine species of any ecosystem (estimates range from 1 million to 9 million species). There is likely to be an enormous loss of species as climate change sets about transforming the basic structure of reefs like the Great Barrier Reef.

It is clear that Australia must meet these challenges by taking action. Existing studies need to be refocused so that the changes can be described in greater detail. Only then can the important changes to the industries and socio-economic systems that depend on coral reefs be designed. Science must drive policy changes that will ensure that the devastating impacts are minimised. Reef resilience (the ability to survive and ‘bounce back’ from stress) must become a primary goal of reef management—only if other stresses on reefs (such as over-exploitation and coastal run-off) are reduced is there a chance that reefs will have the resilience to survive the enormous increases in thermal stress being projected. Most importantly, major decreases in greenhouse gas emissions are required if ecosystems like coral reefs are eventually to recover. If we do not act strongly on greenhouse gas emissions over the next decade, coral-dominated ecosystems are almost certainly to be condemned to the past.

3.3 Existing and potential impacts from changing climate: Australia's coral reefs

Terry Done[1]

In the last two decades, summers with extreme temperatures and rainfall have made significant visual and ecological impacts on Australian coral reefs. Disturbance and population turnover in corals and associated communities are normal aspects of ecological dynamics in coral reefs, but there can be little doubt that global climate change has made the previously infrequent and localised 'coral bleaching' disturbance commonplace and widespread (Hoegh-Guldberg 1999). 'Coral bleaching' is a reduction of coral pigmentation and of the symbiotic algae (zooxanthellae) that are a primary source of nutrition to the coral host.

A spectrum of bleaching impacts can be defined. 'Sub-lethal' coral bleaching reduces the physiological and reproductive fitness of affected individuals; 'sub-lethal' bleaching at one reef thus has the potential to significantly weaken that reef's supply of coral larvae to other reef areas. A 'minor' coral bleaching event kills or injures a small proportion of corals at a place, but has little immediate impact on the composition and diversity of the local community. 'Catastrophic' coral bleaching can kill virtually all corals over an entire reefscape, sometimes including 'old-growth' individual corals or stands of corals. Catastrophic bleaching has poorly known but potentially serious flow-on effects on local reef architecture, biodiversity and fisheries production, and significant impact on reproductive output.

Data-sets relevant to bleaching impacts are limited up to the 1980s, but more targeted data have become available since the 1990s. Sea temperature data collected in situ (Lough in press) and remotely by satellites (Skirving et al. 2002) show extremely high sea-surface temperatures during the summers of 1997–1998 and 2001–2002. These were major potential bleaching years on Australia's north-west and north-east coasts, respectively, as has been confirmed by assessments of the coral reefs (www.gbrmpa.gov.au; Done et al. 2003a). The oceano-graphic pattern of the heating anomaly was patchy in relation to the distribution of coral reefs in both years. In 1998, most of the corals at Scott Reef (under a persistent 'hotspot' off NW Australia) died to a depth of 40 m (Heyward et al. 1999), whereas Ningaloo Reef and Rowley Shoals, some hundreds of kilometres to the south, were in cooler waters and showed no symptoms. On the Great Barrier Reef, the 1998 impact was mainly coastal—possibly a combined effect of the stresses of heat and the relatively fresh waters associated with flooding rivers (Berkelmans and Oliver 1999; Sweatman et al. 2001). In 2002, Flinders Reef in the Coral Sea (under a persistent 'hotspot') had damage similar to that at Scott Reef (Done et al. 2003a). The Great Barrier Reef was subjected to a complex mosaic of relatively hotter and cooler areas in summer 2001–2002. In the coolest areas (hundreds of square kilometres in extent), none of the reefs surveyed (each several square kilometres in area) had damage that could be attributed to coral bleaching. In the hottest patches of water, there was significant coral death, attributed to the bleaching event. There were complex patterns of coral mortality and survival within individual coral reefs that were related to habitat, water depth and species composition (Done et al. 2003a).

At the Great Barrier Reef, extreme conditions of heat and rainfall are likely to become much more commonplace as climate changes. More

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extremely hot days are expected, threatening to increase the frequency and intensity of coral bleaching leading to coral death (Hoegh-Guldberg 2001) and cause potentially catastrophic transformations in coral communities by mid-century (Done 1999; Done et al. 2003b). Cyclone frequency seems likely to remain the same, but as events become more extreme, there may be increasingly severe destruction of reef communities, and the most destructive swathes may be broader (Pittock 1999). More extreme floods may cause coral to die from hypo-osmotic stress (Coles and Jokiel 1992) at ever increasing distances into the tract of coral reefs (King et al. 2002). A higher sea level will stimulate some reef-top communities of organisms that are currently limited by sea level, but others will be smothered as a result of redistribution of reef-top sediments (Wilkinson 1996). Increased atmospheric CO_2 concentrations will marginally lower the alkalinity of reef waters, raising the rate of chemical dissolution of existing reef limestone, and decreasing the rate of deposition and/or the strength of new limestone deposited by reef organisms (Kleypas et al. 1999).

An area of bleached corals. Both the white and the pastel coloured corals are 'bleached' as a consequence of loss of most of the microscopic symbiotic algae that normally live by the millions in every square centimetre of corals, and give them much darker tonings. This loss of algae is a response to heat stress and causes physiological stress in the corals. (Photo: T.J. Done)

To conclude, there appears to be a two-fronted threat to the natural balance between reef-building (coral growth, reef accretion) and reef-breakdown (coral death, reef erosion), which, over recent millennia, has produced the bulk volume and beautiful, complex architecture of today's coral reefs. The balance is being tipped both by more frequent and severe heat waves that stress, bleach and kill coral reef builders, and also by detrimental changes in seawater chemistry caused by increasing amounts of CO_2 in the atmosphere. The key uncertainties in this scenario are:

- the patchiness in both the environmental stresses and the ecosystem's vulnerability to those stresses; and
- the capacity of coral reefs to adjust to a changed environment without permanent loss of their essential attributes of beauty, biodiversity and productivity so valued by people.

In other words:

- Are there less vulnerable areas, and where are they?
- How fast can coral reefs adjust, relative to climate change, and how will it be manifest at all levels throughout the coral reef ecosystem, from individuals to local communities and regional reef systems?

These questions are all areas of active research.

3.4 Potential future impacts of climate change in Queensland rangelands

Chris Chilcott[1], Steve Crimp[1] and Greg McKeon[1]

Climate variability has been identified as the most important driver of change in Queensland's native and naturalised pastures (collectively known as the 'rangelands'). The failure to adequately manage for climate variability in the rangelands has been a major source of reduced resource condition and degradation. Recent reports by McKeon and Hall (2002) demonstrate how processes of degradation and recovery interact with climate variability. In particular, a combination of heavy grazing pressure and drought during the normal growing season has been shown to accelerate loss of desirable perennial species, leading to increased soil loss, reduced burning opportunities and woody weed invasion.

Climate change simulations indicate that enhanced seasonal climate variability and extremes can be expected. They will interact with current maladapted management practices to amplify the risks of resource degradation, and most likely will lead to long-term reductions in resource condition. There are several key factors adding to the risks for biodiversity from climate change: for example, it is likely that conditions will be much warmer and drier and that there will be increased disturbance from tropical cyclones.

By 2030, annual mean temperatures over Queensland are expected to have increased by 0.3 to 2.0ºC compared to 1990 values. Much larger ranges are projected for 2070, with increases from 0.8 to 6.0 degrees. For example, in Brisbane, the annual mean temperature was 20ºC in 1990, but it may increase to 20.3–22ºC by 2030 or 20.8–26ºC by 2070. These temperature changes, in combination with the consensus scenario predictions of little change in annual rainfall, imply a general decrease in soil moisture over Queensland. The decrease is projected to be most pronounced in the far interior.

There is an emerging consensus that maximum tropical cyclone wind speeds are likely to have increased by 5–10% by some time after 2050. This will be accompanied by increases of 20–30% in peak precipitation rates during tropical cyclones. Cyclonic disturbances are important in the dynamics of a variety of ecosystems: rainforests, inland streams, and the rangelands, where recruitment of both desirable and undesirable species can occur.

Climate change will result in impacts to many facets of natural resource functioning.

- To recover after over-grazing, woodland and herbaceous vegetation generally require sequences of above-average rainfall so that the plant populations and perennial root systems can build up. In a highly variable climate, there are an infinite number of combinations of climate and management that might trigger improvements in land condition, species composition or landscape functions. Improvements may not appear until well after the change in management or climate sequence has occurred.
- Ecosystem function, litter decomposition and soil fauna communities are highly sensitive to changes in environmental conditions (especially soil water, soil temperature, nutrient and carbon status). These organisms drive important ecosystem functions such as decomposition and nutrient

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mineralisation, and they maintain soil structure through burrowing and forming water stable aggregates. Climatic pulses are important triggers to the function of these organisms, and will determine how populations will change under climate change.

- Many vegetation types in southern Queensland regenerate successfully following the disturbance caused by broadscale clearing. While regrowth by woody communities is considered a management problem in a production landscape, it is critical to the sustainability of many ecosystem functions, and may have some positive biodiversity consequences. This ability to regenerate is a function of native vegetation retention levels and vegetation condition. As with other key ecosystem processes, regeneration capacity is principally driven by climatic factors and may be affected by climate change within the confines of varied land management regimes (such as fire and grazing).
- Recruitment and death in grazed woodlands are, for the most part, driven by climatic pulses. A series of above average rainfall events is required for recruitment, although it can also drive recruitment of weed species, an example being *Acacia nilotica* invasion into Mitchell grass plains. Incidences of tree dieback in mature canopies of grassy woodlands have been observed following extended periods of drought. In the Dalrymple Shire, between 1991 and 1994, there were large reductions in tree canopy cover, with tree death in some cases, probably because of the depletion of sub-surface soil water.
- Although a majority of the farming and grazing systems in Queensland are limited by water, periods of above-average and excessive rainfall lead to pulses of water loss via runoff or deep drainage. Removal of native vegetation tends to increase deep drainage (rainfall percolating to the groundwater) if the replacement pastures and crops have shallower roots or transpire for fewer days of the year than the native vegetation (as happens with winter dormant or frosted pastures). The degree to which removal of trees changes these two factors (rooting depth and ‘green days’) is currently poorly understood for pasture-woodlands in Queensland. Where groundwater systems cannot accept the increased recharge, there is likely to be salinisation of the soil or increased export of salt into rivers.
- Current research into thresholds for native vegetation retention does not consider the implications of climate change on landscape design or habitat condition. Most current research assumes complex native ecosystems can be modified down to some threshold, where most species and functions are retained. Below that threshold, the modification will result in significant declines in either species or function. However, the level of disturbance (be it from land management or from climate change) within a remnant could have a greater impact upon the functionality of remnant vegetation than the extent of fragmentation, thus changing thresholds.

If rangelands are to avoid permanent loss of resource condition and worsening regional degradation, some change in current management practices is necessary. One key change needed for the management of both grazing systems and parks is an appreciation of safe carrying capacity. This innovation to improve grazing land management is gaining momentum through State Government initiatives (such as the South West Strategy and the desert uplands initiative) and industry developments (such as the grazing land management education package funded by Meat and Livestock Australia). Safe carrying capacities are derived directly from

(1) graziers’ knowledge and experience of safe carrying capacity, and

(2) calculation of pasture growth, tree density and pasture condition for a given land type (using the GRASP model).

These calculations are limited in their capacity to deal with either climate variability or climate change because they are based on average experiences and past climatic records (generally prior to climate change).

As well as the largely off-reserve grazing management approach above, other strategic planning and tactical management activities are needed. The protection of biodiversity (both on- and off-reserve) depends almost entirely on the effectiveness with which in situ protection measures can be located, designed and maintained, particularly in the light of additional stresses introduced through climate change. Pressy and Taff (2001) believe that to measure the effectiveness of protected areas there should be an assessment of vulnerability bias (the extent to which reserves have been dedicated in parts of the region with most risk of vegetation loss) and of representativeness and efficiency. If such elements are included in reserve planning they could enhance the resilience of biodiversity to climate change.

3.5 The Western Australian Rangeland Monitoring System (WARMS) and its potential for detecting impacts of climate change

Ian Watson[1]

What is WARMS?

The Western Australian Rangeland Monitoring System (WARMS) is a ground-based system designed for primary production rather than biodiversity purposes. It indicates changes in the pastoral rangelands at broad scale, based on attributes of the soil and perennial vegetation at a set of representative sites (Watson et al. 2001). The emphasis is on detecting change rather than assessing condition.

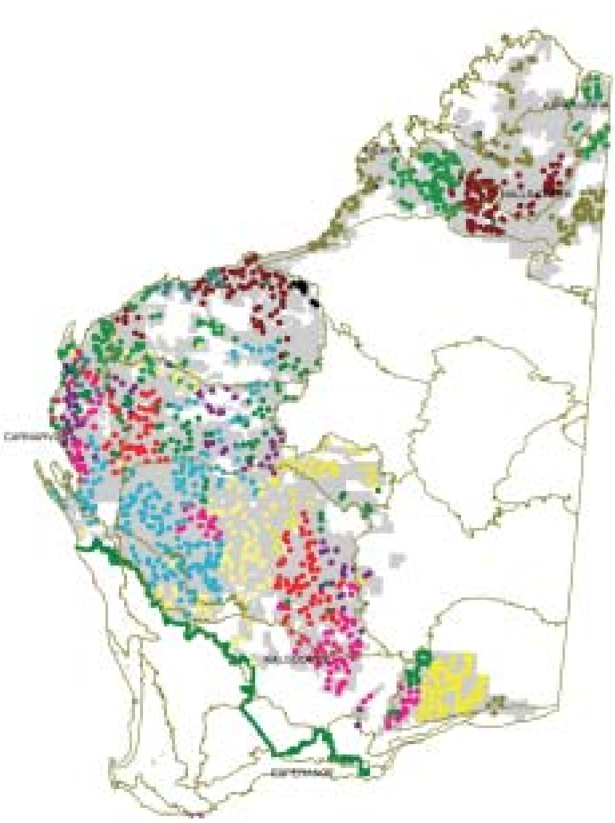

Figure 3.5.1. Locations of WARMS sites: greyed area is pastoral tenure; IBRA regions are shown with khaki lines; different site colours represent different years of reassessment

The current WARMS program began in 1993, although it emerged from an earlier system and so some sites have records (of varying quality) back to the mid-1970s.

There are about 1600 WARMS sites located within about 98,000,000 ha of pastoral rangelands in Western Australia. The average density therefore is about one site per 61,000 ha or just over three sites per lease (Figure 3.5.1).

WARMS is designed to provide information at the scale of vegetation type, IBRA (Interim Biogeographic Regionalisation of Australia) region or other regional scale, for use by government rather than individual managers.

There are two types of WARMS sites. Grassland sites are used in the Kimberley, Pilbara and northern Gascoyne. Shrubland sites are used in the shrublands from the Pilbara through to the Nullarbor. Vegetation type at the site determines whether a Grassland or Shrubland site is installed.

Grassland sites are reassessed on a three-year schedule and Shrubland sites on a five- to six-year schedule.

What is recorded at WARMS sites?

Site photo

Both Grassland and Shrubland sites use a standard photo, taken obliquely from about 2.5 m height for a defined trapezoid area of 132.5 m^2 that fits within the viewfinder of a camera. The photo composition is about 1/3 sky so that the general location as well as the specific photo area can be seen.

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Vegetation on Grassland sites

The frequency of all perennial species (mostly grasses) is assessed in 100 quadrats, each 0.5 m^2. Frequency is the number of quadrats (out of 100) in which the species are present. The crown cover of all woody species (>1 m height) is assessed using a Bitterlich stick. Site dimensions are about 50 m by 30 m. While the ends of the transects are permanently located, the individual quadrats are not; rather, they are 'thrown' evenly, 20 per transect.

Vegetation on Shrubland sites

A direct census technique is used to locate all perennial woody species (with at least a 5 year lifespan) individually. This technique allows the population dynamics to be determined (the survivors, deaths and recruits) because the same individual is located at each assessment. The maximum width and height (to 205 cm) of the living canopy is also recorded for each individual. Three permanent belt transects are used, with total area dependent on shrub density (range is 30 m^2 to 1200 m^2).

Landscape Function Analysis

Standard CSIRO Landscape Function Analysis (Tongway 1994; Tongway and Hindley 1995) is done on all sites. It assesses permanent and semi-permanent attributes such as position in the landscape, mode of erosion and the spatial arrangement of the patch and inter-patch zones, as well as assessments of the soil surface from a sample of 'query points' for the most prevalent patches.

Permanent and semi-permanent attributes

A number of permanent and semi-permanent attributes are also recorded for each site, such as location (with Global Positioning System), land-system, distance from water, paddock name, and so on.

Stratification and location criteria and their implications

Stratification at the regional scale

The sites have been installed on land held under pastoral tenure. Sites have been allocated to coarse vegetation groups based on an index of pastoral productivity, fragility and areal extent. This means that fragile productive systems (such as alluvial areas) are over-represented at the expense of robust and/or low productivity areas (such as hard spinifex).

Stratification at the lease scale

The sites have been allocated to leases on a *pro rata* basis, based on the regional stratification.

Location at the local scale

The sites have been installed so as to represent the full range of vegetation states across the local area, although the majority of sites are on the most common state. They were located on representative areas of land, using the largest grazed area within each paddock. They were located towards the centre, rather than margins, of each area of vegetation but not on extremely dynamic areas such as gully heads. They are typically at least 1.5 km from permanent water, and in the Gascoyne–Murchison region, for example, 75% of sites are between 1.5 km and 3.5 km from water (Watson and Thomas 2003). This means that small areas of vegetation or 'special' vegetation types (such as at the tops of breakaways, or in riparian zones) are not sampled, nor are there many sites beyond normal grazing radius of permanent water.

Potential outputs from WARMS for detecting impacts of climate change

The major factors driving change on each site are (in no particular order): demographic inertia, domestic livestock and other grazing (principally goats and kangaroos), fire, seasonal effects, other significant perturbations (such as insect damage), and probably climate change.

Possible effects of climate change that might be captured through WARMS include woody thickening (or decline) both in terms of plant density and cover, change in distribution of species across sites, shifts in species composition within sites, changes in species richness at the site scale and changed demographic rates (see Figure 3.5.2 for example, and Watson and Thomas 2003 for more detail).

Because the sites are point based, summaries can be prepared for any spatial aggregation, as

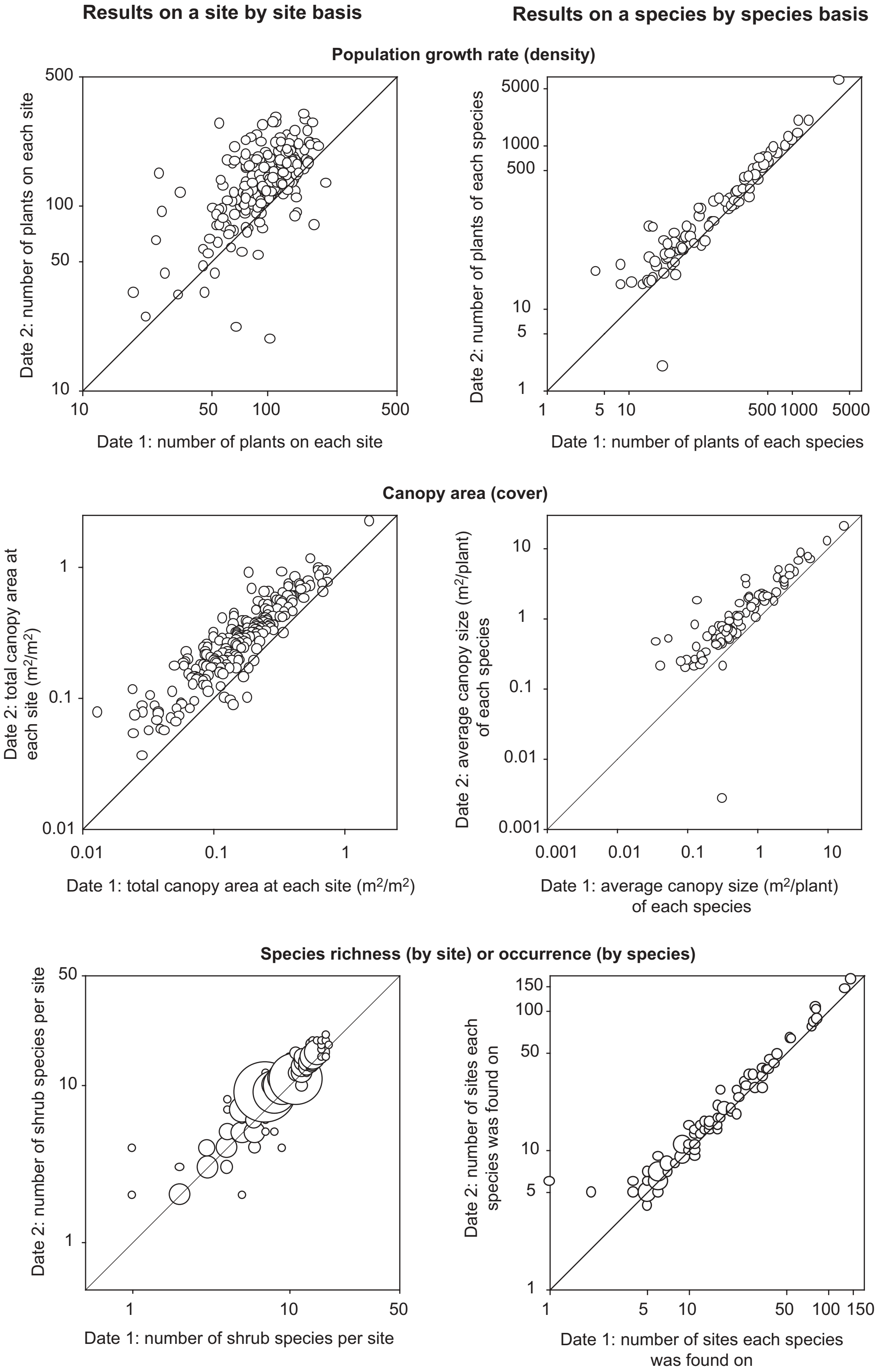

Figure 3.5.2. Changes on 223 reassessed WARMS Shrubland sites from the Gascoyne–Murchison Strategy area. Date 1 was between 1993 and 1997 and Date 2 was between 1999 and 2001. The average period between Date 1 and Date 2 was 5.3 years.

defined by the user. Because data are recorded to the species level, summaries can be prepared by species, functional group, turnover rate category or other categorisation determined by the question.

There are some privacy issues associated with the use of WARMS data. The greatest concern is that summaries of change should not be prepared for individual leases, since the system is not designed to report at the lease scale. In general, WARMS data are made available for *bona fide* scientific pursuits.

Other potential sites

There are a large number of other sites, installed for various purposes, which are now largely inactive but may still be useful to specific studies of climate change impacts (Watson et al. 2001). These include almost 4000 ‘old-WARMS’ and other miscellaneous sites (data from mid-1970s to early 1990s), old flightlines (1970s and 1980s) and about 30 or so exclosures (late 1960s to mid 1990s). The Rangeland Survey Program has also left behind about 4000 inventory-and-condition sites and over 80,000 traverse assessments of range condition at 1 km intervals from the late 1960s to the present. Ongoing pastoral lease inspections also provide traverse assessments for each station on a one- to six-year cycle.

3.6 Rangeland biodiversity and climate change: key issues and challenges

Anita Smyth[1]

Is there evidence of climate change impact on rangeland biodiversity?

Global climate change caused by increased rates of greenhouse gas emissions is a recent phenomenon that is now predicted to dramatically change the global thermal budget. We know that the Australian rangelands have been exposed to global warming and cooling events over tens of thousands of years (Frakes et al. 1987). As Australia drifted towards the equator, it passed through different climatic zones with changing wind systems and circulation of ocean currents that caused fluctuating thermal budgets. This geological evolution has mediated our present-day biodiversity leading to some global extinctions of less adapted species, the evolution of existing environments and species, and the isolation of others in refugia (Heatwole 1987). The way biota responded to these fluctuating global thermal budgets in the past is a good indication of the way they respond naturally to broad-scale climate fluctuations (Swetnam et al. 1999). All the same, we need to be cautious with this comparison, ensuring that present-day thermal budgets are matching similar budgets of the past—a significant challenge in historical reconstruction studies (Millar and Woolfenden 1999).

Can we detect present-day impacts?

Climate extremes

The present-day climate of the rangelands varies widely and unpredictably from place to place and through time (Pickup and Stafford Smith 1993; McKeon et al. 1998). For example, rainfall and sequences of events in the Alice Springs region based on 113 years of records show that several events of 50 mm rainfall (42 in total) can occur in a year, but many years can also pass without any (Stafford Smith and Morton 1990). This rainfall variability is reflected in the vegetation growth patterns. Substantial rainfall events produce a significant vegetation response that resembles a series of pulse and decay functions of growth and vegetation senescence respectively, over time. However, another key issue associated with detecting the impact of climate change on vegetation growth in the rangelands is that these pulse and decay vegetation responses may or may not form trends (Griffin and Friedel 1985; Friedel 1990; Pickup and Stafford Smith 1993). There is other evidence of vegetation responses to climate, as shown by a study on the Mitchell grasslands where primary and secondary floristic gradients were correlated with gradients in mean annual rainfall and temperature (Fensham et al. 2000). We also know that changing climate affects the frequency, intensity and extent of fire in the rangelands through variable fuel loads (Griffin and Friedel 1984).

Climate changes in both vegetation and hydrological cycles are also predicted to affect faunal biodiversity (Woinarski 2000), although the evidence appears weak for the rangeland biota (Whitehead 2000). Predictions for future biotic responses as described by climate envelopes have been attempted using various climate-change scenarios, but these scenarios have been shown to be very imprecise at least for northern Australia (Howden et al. 1998). Another important issue with assessing the impact of climate change on biodiversity using

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bioclimatic predictive approaches is that present-day distributions only reflect present-day climate and other environmental driving factors (H.A. Nix, pers. comm. 2002). Unless compared to historical predictions, the signals can be misleading because then it may be assumed that present-day distributions do not change. In the case of animals that are broad-scale seasonal migrants (such as wetland birds), that is not correct.

Megadiverse biome

The rich diversity of the rangelands is another feature that makes detecting impacts to climate change a real challenge. Over half of Australia's bioregions are in the rangelands. The landscapes are extremely fragile but support nine of 12 major vegetation types, and the land systems differ in their ability to recover once substantial change has occurred. Most of Australia's birds and reptiles can be found in the rangelands, but so can the world's highest mammalian extinction rates. Not only is this richness mediated by extremely variable climates but human activities and land uses also mediate present-day biodiversity.

Other key human environmental drivers

Grazing, artificial water sources, tree clearing, introduced predators and plants, and changes in fire regimes are highlighted, with good supportive evidence, in the National Land and Water Resources Audit as key drivers of impacts on rangeland biodiversity (Whitehead 2000; Woinarski 2000). These drivers operate in tandem to produce land degradation, habitat loss, habitat degradation and fragmentation, and overall homogenisation of ecological systems. The processes lead to a loss of biodiversity and shifts in its composition at all scales, from plot to regional and continental.

Climate change, which is a more incipient process, adds to this impact overall, especially through broad-scale habitat change. However, because of the very long, delayed responses by biota to climate change, less attention is given to studying the impacts of climate change on rangeland biodiversity, particularly when the other human environmental drivers are of greater importance to natural resources management in the shorter term.

Conclusions

Biodiversity of the rangelands has survived prolonged fluctuations in the global thermal budget in the past, but has never experienced the accelerated pace of present-day global climate change. Such rapid change is likely to speed up the extinction rates of climate-sensitive biota, although the time scales in which this may happen in the rangelands are unknown. Little research has been conducted on the impacts of climate change on rangeland biodiversity, especially fauna, and this is understandable as the evidence is much stronger for the more immediate impacts of other human activities and land-use practices in the rangelands. To fully understand the separate impact of climate change on biodiversity, we must seek innovative approaches for teasing apart the signal of climate impact on biotic response variables, and the 'noise' explained by natural diversity and other human environmental drivers. By identifying synergies with other biodiversity initiatives and adopting historical and present-day climate studies, opportunities for innovative approaches are likely to be forthcoming.

3.7 Advancing statistical science for climate research: a perspective from the Indian Ocean Climate Initiative (IOCI)

Eddy Campbell[1]

Climate research has traditionally advanced along two major lines of inquiry: observation and modelling. Statistical methods have been used widely in observational work, but to only a limited degree in modelling studies. It is common in modelling work, for example, to parameterise some relationships using available data, and statistical methods are often used to do this. However, the application of these methods tends to be ad hoc, and the resulting uncertainties not captured. In observational studies the statistical methods used are typically well established rather than contemporary, and require the application of often physically unreasonable assumptions. Chief amongst these assumptions would be stationarity and independence, and the climate system is unlikely to comply with either of them.

The Indian Ocean Climate Initiative (IOCI) is a 5-year project funded by the Government of Western Australia (WA). It is somewhat unique in that it has a statistical research capability as well as scientists from the more conventional fields of climatology, hydrology and climate modelling. The project has led to the development of new statistical methods for the study of nonlinear phenomena and for modelling climate extremes.

The IOCI has accumulated a substantial body of knowledge over the past 5 years. Quoting from the executive summary of the just published IOCI report *Climate Variability and Change in Southwest Western Australia*:

- Winter rainfall in the southwest of Western Australia has decreased substantially since the mid-20th century. This has altered the perceptions of the climate of the region even though a similar, albeit less severe, dry sequence was experienced around the beginning of the 20th century.
- Temperatures, both day-time and night-time, have increased gradually but substantially over the last 50 years, particularly in winter and autumn.
- The rainfall decrease was only observed in early winter (May–July) rainfall; late winter (August–October) rainfall has actually increased, although by a smaller amount.
- The winter rainfall sharply and suddenly decreased in the mid-1970s by about 10–20%. It was not a gradual decline but more of a switching into an alternative rainfall regime.
- The reduction in winter rainfall resulted in an even sharper fall in streamflow in the southwest.

There appears to be sufficient evidence to attribute the gradual warming to the enhanced greenhouse effect. The rainfall decline appears to be associated with a change in atmospheric circulation at about the same time. The reduced rainfall and circulation changes bear some resemblance to greenhouse changes projected by most climate models. The changes are not sufficiently similar to attribute them beyond reasonable doubt to greenhouse at this time. The current climate regime may simply be a mode of natural variability, which happens to be in line with greenhouse projections for the region. Southwest WA may therefore be experiencing a taste of its future climate.

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In terms of water resources, there is an urgent need to adapt to a climate of less rainfall and so reduced streamflow, with increased evaporation. Historically the water supply system has relied on occasional extreme winter rains to recharge the system. The change in the likelihood of extreme rainfall events is quite startling. Using Manjimup in southwest WA as an example, Table 3.7.1 shows the drop in probability of extreme rainfall, since 1930.

These estimates in the table were derived through some developments in the statistical modelling of extreme events. Our work in nonlinear methods has indicated that mid-Indian Ocean sea surface temperature may be implicated in the switch between the dry and wet seasons in the southwest. This has the potential to open up new lines of inquiry into factors influencing climate variability and change in the region.

The key question we should perhaps start with in climate research is: how can we best forecast the future? The next logical step is to apply the best available science to integrate physical understanding encapsulated in models and observations of the climate system. Contemporary statistical science offers some exciting developments for such integration, while also providing the means to capture associated uncertainties.

Table 3.7.1. A comparison of exceedance probabilities for extreme daily rainfall in 1930–1965 and 1966–2001, at Manjimup, WA

Daily rainfall (mm)	Probability (1930–1965)	Probability (1966–2001)
30	0.0132	0.00472
34	0.00837	0.00281
38	0.00543	0.00167
40	0.00448	0.00129
50	0.00181	0.000363
60	0.000835	0.000363

The climate system is very hard to understand and even harder to predict, so we should expect to undertake statistical research to make best use of the observations we make. It is not enough to apply textbook methods and then hope that our physical knowledge and intuition will make good. With crafted statistical tools we can ask more insightful questions of our data and develop new physical understanding.

3.8 Vegetation change related to climate change in Australian subalpine environments

Kerry Bridle[1] and Jamie Kirkpatrick[1]

Global warming has been a reality since the latter half of the twentieth century. Many models have been created to predict the impact of climate change. These models suggest that arctic and alpine regions will be greatly reduced in extent because of increases in temperature, and that plant species adapted to these cold climates are likely to become extinct as a result of competition from other species (Busby 1988). Much research has been carried out on the possible loss of biodiversity in these rare and species-rich biological environments (see Green 1998, Korner 1999, Theurillat and Guisan 2001). However, recent evidence suggests that while the general trend is for temperatures to increase across the planet, this may not be the case at a local scale (Salinger and Griffiths 2001, Doran et al. 2002).

A recent study of long-term climate records in New Zealand shows that there has been no significant change in the number of frost days at higher altitudes (Salinger and Griffiths 2001), despite there being a general decrease in the number of frost days across the country as a whole. This departure from the perceived norm of a trend of increased temperatures due to global warming has also been shown for a mountain environment in Tasmania (Kirkpatrick et al. 2002).

In Australia, climate predictions have been modelled at a national and a state scale. However, there has been no analysis of long-term climate records surrounding high altitude sites. Such an analysis would indicate whether the general climate change predictions are accurate and applicable at a regional level. These data would also determine whether the environmentally sensitive and nationally rare Australian alpine and subalpine belt is under threat from global warming as predicted in the literature (Scherrer and Pickering 2001). Furthermore, if links between changes in climate and changes in subalpine vegetation over the same time period were to be evaluated, the result would provide strong evidence for rejecting or accepting the predicted impacts of climate change on Australian alpine and subalpine vegetation.

Using the long-term data available from sites (Kosciuszko National Park for 1950s to present, Tasmania for 1973 to present and 1991 to present) we can explore ecological hypotheses about the sustainability of subalpine plant species, communities, lifeforms and functional groups. These existing long-term data-sets will provide an ecological context in which we can examine the resilience of alpine and subalpine plant communities to invasion by exotic or lowland species, driven by climate change or other disturbance factors (time since burning or grazing).

On a regional scale, the impact of global warming on alpine and subalpine plant communities has been speculated upon (see Scherrer and Pickering 2001, Theurillat and Guisan 2001), but little evidence exists of any impacts. Analysis, both of vegetation changes (especially lifeform groups or functional groups) in long-term monitoring sites in sensitive alpine and subalpine environments, and of changes in regional climate patterns, will show whether ecological processes are consistent across the Australian alpine zone. The Kosciuszko data-set provides an opportunity to test whether Australian alpine vegetation is responding consistently to global warming or whether the maritime environment of Tasmania differs from continental Australian alpine regions.

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Creating a Tasmanian peatland inventory, and assessment of the possible impacts of climate change on the carbon content of Tasmanian organic soils

Organic soils cover over 1,000,000 ha of Tasmania (Jarman et al. 1988). Organic soil deposits (bogs, peats, peatlands), especially raised bogs and blanket bogs, are extremely sensitive to environmental conditions. Raised bogs (dominated by *Sphagnum*) and blanket bogs (dominated by rushes and sedges) form in poorly-drained environments where there is more precipitation than evaporation. Tasmanian blanket bogs are of national and international significance. Tasmania contains the largest area of organic soil deposits in Australia, but there is currently no peatland inventory for Tasmania. No data are available on organic soil type, depth, or organic content. Therefore there is no estimate of carbon storage in these systems.

Limited climate data from western Tasmania indicate that evaporation exceeds precipitation during the summer months, especially February. These climatic conditions pose a threat to existing organic soil deposits, because a lowering of the watertable may result in oxidation and decay of the peat deposits. The watertable in several western Tasmanian blanket bogs has been 15–20 cm below the soil surface for much of summer 2000–2001 and autumn 2002, causing a probable increase in the release of carbon dioxide into the atmosphere.

Although peatlands are regarded as ‘carbon sinks’, it appears that they are likely to become (or may have already changed to) a carbon source, creating a positive feedback into the phenomenon of global warming. Therefore, data on the role of organic soil deposits as carbon sources or sinks are crucial input into any models of atmospheric carbon and climate change.

An inventory of Tasmanian organic soil deposits is necessary, with subsequent estimation of carbon storage within peatlands. The data collected in the project will offer valuable national insights into the role of peatlands in the carbon balance. Once these data have been collected, the project can attempt to quantify the possible impact of climate change on these organic soil deposits. It will also identify the potential magnitude of the carbon source that these deposits may form in the light of climate change.

The inventory will provide baseline surveys of a range of organic soil deposits across the state. This inventory may then be used to determine the impact of fire on organic soil deposits, if the fire history is known for a particular site. The removal of peats up to 1 m deep during a swamp fire on King Island in 2000 would have released significant amounts of carbon into the atmosphere. It has had a severe impact on the hydrology of the swamp system.

3.9 Impacts of global warming on the Snowy Mountains

Ken Green[1]

The Snowy Mountains contain the largest area of contiguous subalpine and alpine habitats in Australia. Other subalpine and alpine habitats occur as relatively isolated areas in the mainland Victorian Alps, and in the Central Highlands and higher peaks of island Tasmania. The large Snowy Mountains' area presents a unique opportunity to monitor regional changes attributable to global warming. Even a modest warming ('best case scenario' of only +0.6°C by 2070) will result in a 39% reduction in the area that receives 30 days of snow per year in the Snowy Mountains (Whetton 1998). Seasonal cover of snow is a major determinant of the animals living in the subalpine and alpine areas of the Snowy Mountains (Green and Osborne 1994, 1998).

There has been a significant decline in mean snow cover at Spencers Creek, as measured at the Snowy Mountains Hydro-electric Authority snow course (Osborne et al. 1998). The snow course has been visited weekly through the snow season since 1954. Examination of the data by decade shows a total of 2283 metre-days of snow in the 1960s, with a 20% reduction to the 1970s (1843 metre-days) and a further 10% reduction to the 1980s and 1990s (1655 and 1706 metre-days respectively). The last five years, occurring in the warmest decade of the century (Australian Bureau of Meteorology), had the lowest five-year average metre-days of snow of the series: 7.5% less than the previous lowest five years and 53% less than the highest five years (Green and Pickering 2002). For fauna sensitive to depth and extent of snowcover, this decline might be expected to be reflected in changes in its distribution.

Mammals and birds have responded to this 30% reduction in snow cover over the last 45 years. There is an increased penetration of feral mammals into alpine and high subalpine areas, and there is a prolonged winter presence of browsing macropods. The only three species of native mammal to increase in abundance with altitude are affected adversely by years of shallow snow. Birds are less constrained by altitude, but among migratory species there has been an observable change in timing of arrival in the mountains, with earlier arrival in the 1980s and/or 1990s compared to the 1970s. Of 11 species for which good data exist, seven arrived in the mountains at least a month earlier in the 1980s/1990s than in the 1970s. The implication of these trends is that predicted impacts of global warming on snow cover will result in a significant change in distribution of animal communities both geographically and through time.

To test this hypothesis, ongoing research is looking at:

- weekly recording of snow depth at the Whites River snow course (it has been recorded monthly since 1954). Whites River is close to long-term fauna-monitoring sites and is in marginal snow conditions at 1680 m. This area is expected to respond more quickly to changes than the snow course at Spencers Creek.
- date of ice breakup and September ice depth at Blue Lake. In the past thirty years there has been a two-month difference in the date of ice breakup. It has ranged between late October and mid December.
- snow depth, percentage snow cover, percentage of open flowers, and bird species

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present at seven 1 ha stations, 50 m apart altitudinally, from 1350 to 1650 m, on Disappointment Spur, and at a further two stations at 1600 m and 1650 m. This study is done four times a month from mid-August to mid-October and aims to document the relationship between snow duration, plant phenology and bird migration. Tracks of macropods are also recorded and are related to snow depth and extent and proportion of uncovered shrubs.

3.10 What's the link, if any, between recent changes in distribution of Australian birds and greenhouse climate change?

Julian Reid[1]

Introduction

The mobility of birds allows them to respond rapidly to changes in the environment, generally as a distinctive biotic group, over a range of spatial scales.

Therefore, birds may be a good and early indicator of climate change. However, birds have the same capacity to respond to any environmental change, whether human-induced climate change, natural climatic variability, disturbance events or a host of other human-induced landscape changes. How can we tell the difference?

First, we have to demonstrate beyond reasonable doubt that a change in distribution has occurred or is occurring over the relevant time and spatial scales. Geographically, range changes ought to be fairly steady and pervasive. I examine in more detail the specific requirements and sufficient and necessary evidence to meet the conditions for change attributable to global warming and other 'greenhouse' effects.

Range changes that meet greenhouse climate change criteria within Australia

- Range expansion to the south (or a move to higher altitude)
- Range contraction from the north (or a move to higher altitude)
- Pervasive range shift across a range front, not isolated occurrences
- Steady range shift over the past few decades, as opposed to earlier responses to massive land-use change coincident with European occupation

For a discussion of these criteria see Hughes (2000).

Range changes in Australian birds

The breadth of range changes is quickly sketched to eliminate those types of movements and range shifts that cannot be construed as evidence for 'greenhouse'-induced changes.

Reversible range shifts

Irregular, short-term range shifts (periods of a few years or less) are a striking characteristic of many native Australian bird species. Two examples suffice. Nomadism allows many species to exploit geographic shifts in food resources, and many species have been described as 'locally to continentally nomadic', depending on the scale at which these range changes typically occur. Related phenomena, and topical currently (September 2002), are drought-induced, extraordinary movements that take species well outside their customary range, usually towards the southern, eastern and presumably northern coastal regions. There are many reports in Australian ornithological circles currently of large influxes of a wide range of species, but particularly waterbirds, to coastal areas where the majority of ornithologists reside. These are episodic and temporary distributional changes and so cannot be ascribed to greenhouse effects.

Range expansions

Many native species historically considered to be typical of Australian arid and semi-arid regions

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have invaded temperate parts of Australia over the past 100 years. In some cases, these species are still steadily expanding to the south and into higher altitudes. The Galah *Cacatua roseicapilla*, Little Corella *C. sanguinea* and Crested Pigeon *Ocyphaps lophotes* are the best examples (Blakers et al. 1984) and the latter species' colonisation of the Australian Capital Territory in the last 20 years has been closely monitored and documented. It is widely agreed that, rather than climate change, it is land-cover and land-use changes (primarily vegetation clearance and provision of artificial water sources) that have caused these southern range expansions, and similar expansions along the eastern seaboard.

Many non-native bird species have colonised Australia and substantially expanded their ranges from initial entry and release points. Their range expansions have proceeded in all directions and in some cases aggressively continue; for example, the Indian Mynah *Acridotheres tristis*. The mynah's main direction of expansion has been north in accordance with its climatic provenance. Again climate change is not implicated, though urbanisation and land-use change is.

Range contractions

Many native species are in serious decline across all parts of the continent. Range contractions often occur at the periphery of a declining species' range first or most clearly, though this is by no means general (Brown 1984).

Are there any species with northern range limits inside the northern Australian coast exhibiting a steady pervasive range contraction southwards? This would provide firmer evidence of greenhouse impacts, particularly if the range were not also contracting from the south. Even stronger evidence would be provided by an accompanying range extension southwards. Exploratory research is required to see if these patterns emerge.

Torresian species expanding south

(1) Landbird occurrence: Figbird *Specotheres viridis*, Channel-billed Cuckoo *Scythrops novaehollandiae*, Common Koel *Eudynamys scolopacea*, Australian Brush-turkey *Alectura lathami*.

(2) Waterbird occurrence and breeding: Black-necked Stork *Ephippiorhynchus asiaticus*, Pied Heron *Ardea picata*.

We have to decide whether these range expansions are more parsimoniously attributable to land-use and landscape transformation than climate change. There does appear to be a strong trend for Torresian migratory landbirds to be extending south. The first three species listed are migratory landbirds, but they are all fruit-eaters, so other factors need to be investigated.

Conclusions

Are birds necessarily good indicators of pervasive climate change? Might they not be too responsive (vagile)? For a start, birds are endothermic and so are substantially buffered against the direct impacts of temperature change. Birds tend to use large amounts of space, from the scale of the individual home range to that of the population and species. Physiologically then, they seem to be tolerant of a broad climatic range and, being long-lived, also tolerant of weather and short-term climatic variability.

Multiple causes of shifts in distribution can be difficult or impossible to disentangle, particularly if there are direct and indirect effects as well as interactions between causes, operating in tandem. ENSO episodes and their impacts on distribution patterns exemplify this problem (Reed et al. 2000). Climate change is likely to alter the timing and magnitude of ENSO reversals and so have an indirect role in these effects in addition to its direct effects. Teasing apart indirect effects and interactions will be problematic (but see Martin 2001).

Organisms which have particular life-history traits tightly controlled by temperature may be the best candidates to screen for climate change impacts already underway (see McGeoch 1998). Examples include certain phenological (life cycle) phenomena in plants, and ectothermic animals (such as insects). Montane areas may provide the best arenas for study here because steep gradients are conducive to sharp zonal patterning.

Conversely, extensive flat regions where climate gradients are gentle (such as the broad open plains of inland Australia, like the tundra of the

Northern Hemisphere) provide a potential arena for large shifts in geographic range over tens to hundreds of kilometres for those organisms or ecological indices capable of rapid adjustment. Birds certainly satisfy the criterion of rapid adjustment potential.

The recent Australian ornithological literature, including the regional journals and newsletters, reports the pervasive southward shift along the eastern seaboard of a range of Torresian bird species. The selection of species involved includes many more than the four species cited and warrants close study. It may also be fruitful to examine the stability of northern range limits of Bassian bird species, separating the effects of climate changes from those of land-cover change and comparing the northern limits to the stability of their range limits on other fronts.

The answer to the question in the title of this contribution is … we don’t know!

3.11 Birds and climate change

Michael Weston[1]

Existing impacts

As identified in the paper by Hughes, a range of studies suggests that breeding seasons are altering in response to climate changes. In Australia, as discussed by Reid, there are also some shifts in species distributions towards the south or along changing rainfall contours. Further analysis is needed to determine if these changes are associated with climate change.

Potential impacts

On the basis of existing understanding, there is a large range of likely potential impacts of climate change on birds in Australia.

Being relatively mobile, most birds will probably fare better than many other life forms. However, the ability to move and colonise varies among birds, and those least able to disperse or colonise may face extinction, particularly where new habitats are distant or where intermediate habitat is unsuitable. There is also likely to be varying ability among bird species to adapt to changing habitats and food sources, and this will tend to put more pressure on species that need specific habitats (habitat specialists) than on generalists. In addition, some other processes (such as fragmentation of habitat) may reduce the ability of species to adapt.

One of the solutions in such cases may be to establish habitats that can act as 'stepping stones'. However, some efforts to minimise social or economic impacts may further disadvantage some habitats and the birds that use them. For example, efforts to prevent coastal erosion associated with rises in sea levels will also have an impact on the Hooded Plover because they breed in the upper beach and adjacent dunes. Lastly, these impacts may vary geographically, as critical parts of the range may be affected while the bulk of the range may remain suitable; for the Swift Parrot for instance. As there is little information known about many of the above factors, predictions of the impact of climate change are difficult.

Birds Australia databases

Birds Australia owns a number of databases on birds that may be useful for assessing the impact of climate change on birds (and other elements of biodiversity, depending on one's faith in birds as indicators). The following table lists the current Birds Australia databases. Of these, two are of particular note as substantial long-term data-sets.

- The Atlas of Australian Birds is an ongoing database that contains information about distribution and relative abundance (frequency of occurrence) at the contininental scale.
- The Nest Record Scheme database contains data on bird breeding (timing, etc.). It is mostly computerised, but needs some verification.

Birds Australia wants to be a partner in research about climate change and birds. There are some limiting factors—we are limited in resources. Also, our organisation has made an enormous investment in these databases and so we wish to protect our intellectual property. Thus, access to these data involves:

1) formal data-sharing agreements (large data requests have to be referred to our Research and Conservation Committee), and

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2) some funding to cover extraction time (covering costs only).

3) Additionally, the analysis and interpretation of Atlas data are not straightforward activities, and we will need to negotiate any staff involvement. Ideally, we would like to be involved in the analysis of these data, and encourage any grant applications or proposals to factor in some funding for our involvement.

If you are interested in using Birds Australia data, please contact Michael Weston, email: m.weston@birdsaustralia.com.au .

Table 3.11.1. Birds Australia data-sets, and their scope in timeframe, geography and species. Asterisked rows are probably of greatest interest.

NAME	**SCOPE** (time scale)	**SCOPE** (geographical)	**SCOPE** (birds)	**TYPE**
*Atlas of Australian Birds	1997–1981 (1) 1998–2001 (2)	Australia, including territories and territorial waters	All wild birds	Location with some count data of wetland birds
Australian Bird Count (ABC)	1989–1995	Australia	Mainly bush birds (passerines)	Location and numbers
AWSG Banding Database	From 1981 ongoing	Australia	Waders (shorebirds)	Morphometrics and movements
AWSG Colour-flag Database	From c.1995 ongoing	Australia	Waders (shorebirds)	Movements
Beach Patrol		Australia	Seabirds	
Bird Monitoring at Engine Ponds	1997–2002	Engine Ponds, Sydney	Mostly waterbirds	Total counts
Bird of Prey Watch (BOP Watch)	1986–1990 (1) 1996–2000 (2)	Australia	Raptors	Transect counts within regions
Birds in Backyards	2000–2002	Sydney and surrounds	Terrestrial urban birds	Location, counts, nests, vegetation
Birds in Tree Hollows	1997	Victoria	Hollow-nesters	Breeding information
Birds on Bore Drains	1998	Roxby Downs, SA	All	Presence/absence
Birds on Farms	1995–1998	E and SW Australia (1080 sites)	All	Point surveys
Birds on Golf Courses	1990s		All	Counts by habitat
Corner Inlet Oyster Farm	1989–1990	Corner Inlet, Victoria	Mostly waterbirds	Counts
Freckled Duck Count	1987–1988	Victoria	Waterbirds	Site counts
Gulf Plains Conservation Framework				
HANZAB (Handbook of Australian, New Zealand and Antarctic Birds)	1980–2004	Australia, New Zealand, Antarctica	All	Comprehensive literature review
HEC (Hydroelectrical Commission) windfarm counts	1999	NW Tasmania	Moving birds	Moving birds
Homebush Bay	2000–ongoing	Homebush Bay, Sydney, NSW	All at site	Site counts
Kooragang (Rehabilitation of Waterbird Habitat on Ash Island)	2001–2002	Ash Island, Newcastle	Mostly waterbirds	Total counts/ behaviour
Little Terns	1989	E and N Australia	Little Terns with notes on other species	Counts and information on breeding
Melbourne Airport	1996–2000	Melbourne Airport	Airport birds	Counts in grids

(*continued next page*)

Table 3.11.1 *continued.* Birds Australia data-sets. Asterisked rows are probably of greatest interest.

NAME	**SCOPE** (time scale)	**SCOPE** (geographical)	**SCOPE** (birds)	**TYPE**
Murray-Darling Basin Waterbirds	1993–1996	Murray-Darling Basin catchment: scattered across the Basin in four states and the ACT	Wetland birds	Location/count/some breeding records
National Hooded Plover Counts	1980–2001	Australia	Waders (shorebirds)	Location and numbers
National Wader Counts	From 1981	Australia ongoing	Waders (shorebirds)	Location and numbers
*Nest Record Scheme (NRS)	From 1964 ongoing	Australia	All breeding wild birds	Breeding details
Orange-bellied Parrot counts	From 1984 to present	SE Australia	*Neophema* and coastal seed eaters	Counts by site
Pt Lillias and Avalon Saltworks	1994–1995	Pt Lillias and Avalon Saltworks, Victoria	Waders and waterbirds	Location and numbers
Pt Wilson Counts	(mid 1990s)	Pt Wilson, Victoria	Waders (shorebirds)	
Question of Survival Bird Survey	1993	Australia	All	Site counts
Recent Ornithological Literature	1998 onwards	Worldwide	All	Bibliography including abstract
Regular Wader Counts	1986–1990	Australia	Waders (shorebirds)	Location and numbers
Rolling Bird Survey (RBS)	(mid 1980s)	Australia	Mainly bush birds (passerines)	Abundance
Red-tailed Black Cockatoo (RTBC)		W Victoria and SE South Australia	RTBCs 1. Sightings 2. Nest site 3. Flock count	Sightings, nests and flock counts
Seabird Atlas		SE Australia	Seabirds	
Summer Waterfowl Count (Victoria)	1987–1992	Victoria	Waterbirds	Site counts
Swift Parrot Counts at Melbourne Airport	1999	Melbourne Airport	Mostly bush birds	Transects and flowering phenology
Sydney Airport Birdstrike Information Retrieval Database (BIRD)	1988–2002	Sydney Airport	All birds	Bird strikes
Sydney Airport Foraging Data	1998–2002	Sydney Airport	All birds	Location and abundance
Sydney Olympic Park Authority /OCA	1996–2002	Sydney Olympic Parklands	All birds	Location counts
Tasmanian Shorebirds	1998–2002	Tasmania	Shorebirds	
Vicgroup Rushworth banding data	1996–present (planned till 2016)	Rushworth State Forest, Victoria	Mainly bush birds (passerines)	Captures, recaptures, morphometrics
Victorian Wetlands Survey	1989–1992	Victoria	Wetland birds	Location and numbers
WA Hooded Plovers	1995–ongoing	SW Western Australia	Hooded Plovers	Location and numbers, breeding information
WA Waterbirds	1981–1985	SW Western Australia	Wetland birds	Location and numbers

3.12 Palaeoecological perspectives on climate change and its impact on biodiversity

Simon Haberle[1]

Introduction

Palaeoecological data provide valuable insights into past climate variability, the process of climate change under the influence of greenhouse-gas forcing and the nature of ecosystem response, and survival under rapidly changing conditions. Consideration of long-term (1000–100,000 years) as well as short-term (10–100 years) timescales should be incorporated into biodiversity planning.

Long-term climate change

The northwards progression of Australia since the Tertiary has led to progressive aridification, the emergence of a biota adapted to complex cycles of climate change, and the appearance of short growing seasons in the south.

The last 2 million years have been dominated by glacial climates in which mean land temperatures were as much as 9°C cooler than present in the interior of Australia (Barrows et al. 2000). Therefore, many species are maladapted to present-day (interglacial) conditions. The continent is large enough to cover a wide range of climates, and so habitats have been preserved for species capable of migration. Currently, rare species are often those with limited capacity to disperse or habitats that have diminished during interglacials; for instance, *Wollemia nobilis* (Wollemi Pine, Blue Mountains), *Swainsona recta* (Purple Pea, springtime plant of grassland steppe).

Palaeoceanographic records of past sea-surface temperatures from the Coral Sea have shown that there was an increase in temperature of around 4°C around 245,000 years ago (Figure 3.12.1). This temperature increase may have been related to the development of the Western Pacific Warm Pool leading to the formation of the Great Barrier Reef, an increased temperature gradient across the Pacific Ocean, and the onset of El Niño–Southern Oscillation activity (ENSO) (Isern et al. 1996). A resultant increase in climatic variability could then explain the trends towards increased burning and the development of more open vegetation (Kershaw et al. 2002). The combination of higher precipitation resulting from increased sea-surface temperatures and climate variability might also have allowed the expansion of both complex rainforest and sclerophyll vegetation into adjacent areas.

Abrupt climate change

Recent palaeoclimate research has revealed that the Australian landscape has been influenced by abrupt climate change events during the last 10,000 years. The onset of modern ENSO periodicities around 5000 years before present (BP) followed by an abrupt increase in ENSO magnitude around 3000 years BP are key time periods of rapid change in climate variability and therefore ecosystem disturbance. Disturbance is seen as a major determinant of forest structure, and more frequent and intense storm events or drought–fire events have the potential to drastically shorten the turnover period for trees and thus alter forest composition. This can be seen in high-resolution (ten year sampling intervals) pollen records spanning the last 10,000 years from the Atherton Tablelands (Lake Euramoo) and Southern New South Wales (Bega Swamp). There, increased disturbance related to altered fire regimes around 5000 years BP resulted in long-lived shade-tolerant trees becoming rare, and a collapse of dominant tree species (Figure 3.12.2).

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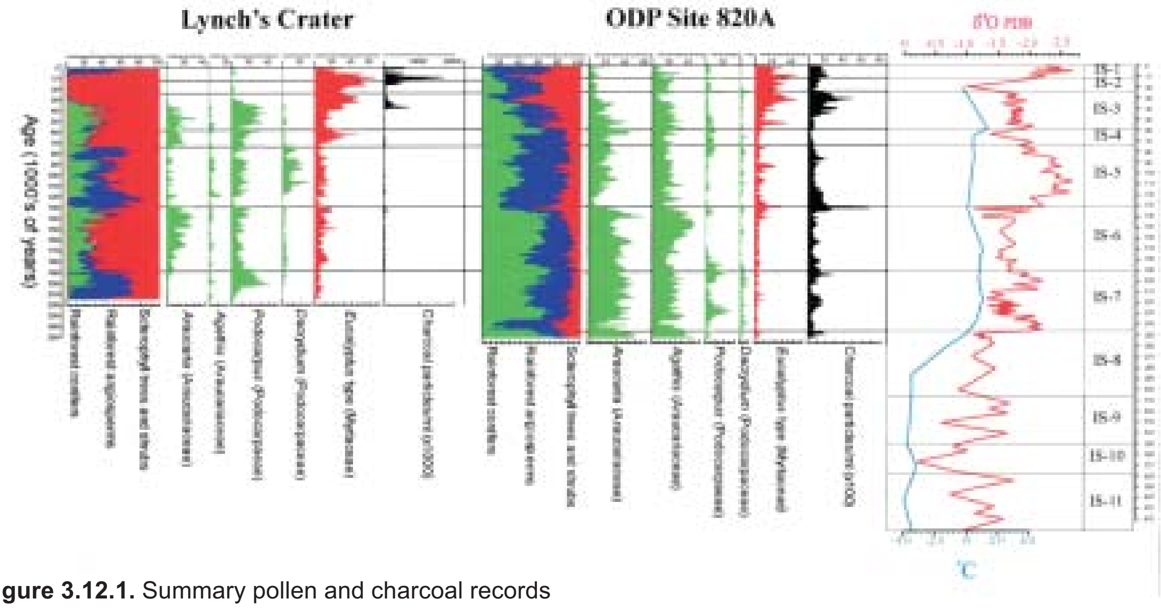

Figure 3.12.1. Summary pollen and charcoal records from terrestrial and marine records in north-east Australia (Kershaw et al. 2002) compared to the extended $\delta^{18}O$ record of ODP 820 (Peerderman et al. 1993) showing a rise of approx. 4°C in sea-surface temperatures at the end of Isotope Stage 8 (IS-8)

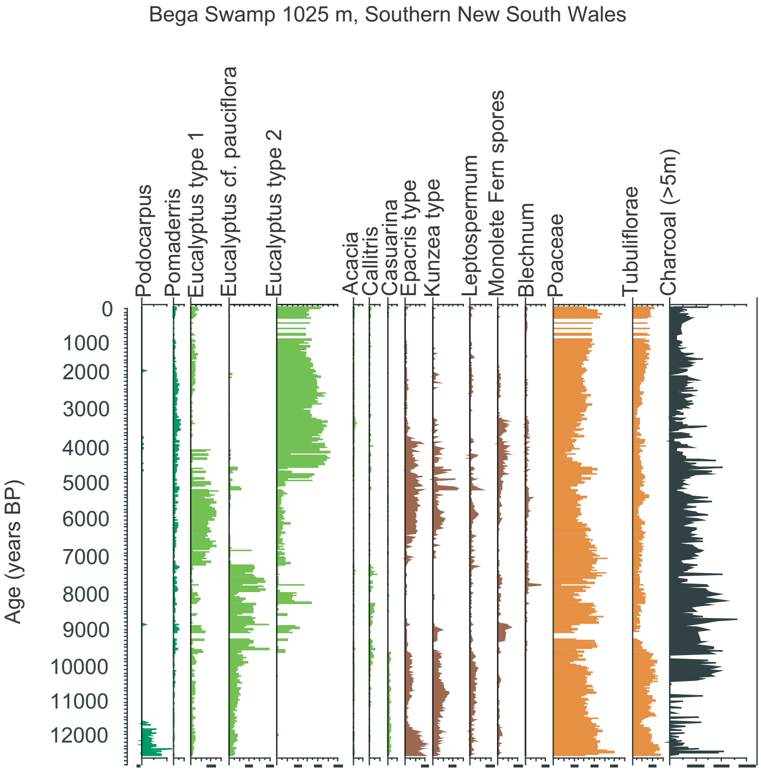

Figure 3.13.2. High-resolution pollen diagram from Bega Swamp, southern NSW, shows periods of major species collapse during the Holocene possibly related to changing disturbance regimes (burning) at a time of gradual climate change (Green et al. 1988)

Human impacts

Aboriginal land-use practices in existence for over 50,000 years have had a major impact on vegetation distribution and the survival of large marsupials in Australia (Bowman 1998). However, by far the greatest impact on biodiversity, and this is reflected in many palaeoecological records, has been the arrival of Europeans around 220 years ago. Altered fire regimes, forest clearance, and the introduction of herbivores and weeds have led to fragmented biomes that are likely to exacerbate the impact of rapid climate change events on future regeneration and the migration potential of plants and animals. Unprecedented rates of vegetation change (Dodson and Mooney 2002) combined with the introduction of exotic species can fundamentally change ecosystem structure through competitive exclusion of available resources. Climate changes that increase the aggressiveness of exotic species, or reduce the competitiveness of indigenous species, will be significant. Understanding the rate of spread of weed species and their impact on biodiversity in the Australian landscape requires a multi-disciplinary approach—the development of an historical ecology.

Research areas

1. Comparison of climate models and palaeoecological data to refine our understanding of the interaction between climate and organisms through time.
2. Further research aimed at extending existing palaeoecological records and understanding how the Western Pacific Warm Pool influenced Australia’s climate, given that the region has already experienced rapid rises in temperature equivalent to those possible under the influence of greenhouse-gas forcing.
3. High-resolution studies of biotic responses during key time periods of abrupt climate change within a range of biomes (for example, 5000 years BP, 3000 years BP).
4. Multi-disciplinary studies examining the relative influence of human land-use change versus climate change, developing new techniques in palaeo-biodiversity and historical ecology.

3.13 Global change: the direct effects of the increasing concentration of atmospheric carbon dioxide on the climate and the biota

Sandra Berry[1]

Relationships between vegetation, CO_2 and climate

Ecologists and biogeographers routinely correlate distributions of organisms with variables that can be easily measured. There is a long history of relating distributions to precipitation and air temperature. The reason for this is that precipitation and temperature were the things that were measured a century ago. This approach does not make sense for at least two reasons. Firstly, vegetation modifies air temperatures through radiation and heat budgets. The optical properties of vegetation cover determine its albedo (α), and thus the amount of global solar radiation (R_s, in J/m^2/s) that it absorbs according to the energy budget

$$R_n = R_s(1-\alpha) + R_{Li} - R_{Lo}\ ,$$

where R_n (J/m^2/s) is the net all-wave radiation at the surface, and R_{Li} and R_{Lo} are the downward and upward fluxes respectively of longwave radiation. The partitioning of R_n is also affected by vegetation cover, as indicated by the simplified form of the heat budget equation

$$R_n = LE + H + \Delta G,$$

where L (J/kg) is the latent heat of evaporation, E (kg/m/s) is the rate of evaporation, H (J/m^2/s) is the heat convected to the atmosphere (which we measure as air temperature) and ΔG (J/m^2/s) is the change in the heat in the subsurface layers. When water is readily available at the surface, such as after rain or from transpiring leaves, LE will dominate the heat budget and ΔG and H will be small.

The second illogicality of the precipitation and temperature approach arises because plants require other resources, such as CO_2, O_2 and nutrients, in addition to water and energy, and the availability of these other resources (especially CO_2) varies through time (Barnola 1987). Variations in the concentration of CO_2 in the atmosphere through time are linked to the energy and heat budgets through spatial and temporal changes in vegetation cover, and water use efficiency of photosynthesis.

Changes in vegetation structure (but not distributions of individual species) in response to resource availability can be predicted using the TMS scheme (Berry and Roderick 2002a,b). In the TMS scheme the vegetation at a place is described according to the proportional representation of turgor (T), mesic (M) and sclerophyll (S) leaf functional types. The proportions of each leaf type can be plotted on a triangular diagram. The TMS scheme is a link between leaf properties, vegetation structure and environmental conditions, and can be used to predict responses of the vegetation to changes in both the seasonal and long-term availability of moisture, nutrients and atmospheric CO_2 concentrations. The underlying theory can also be applied to predict changes in vegetation structure in response to fire, livestock grazing and land clearance.

Direct effects of atmospheric CO_2 enrichment on the vegetation

Responses of plants to increasing concentrations of CO_2 can occur at all levels from leaves to ecosystems. There is evidence for change in leaf morphology, by decreases in specific leaf area

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and stomatal frequency (Peñuelas and Matamala 1990, Peñuelas and Azcon-Bieto 1992), and in the ratio of surface area to volume (Roderick et al. 1999), with increasing CO_2 concentration. The increase in ratio of leaf surface area to volume in trees and wild non-woody species is commonly associated with an increase in relative allocation to structural tissues (Pritchard et al. 1999) and increasing leaf longevity (Li et al. 2000). Increased flower production and reproductive output (fruits and seeds) have also been observed (Lawlor and Mitchell 1991, Osborne et al. 1997, Deng and Woodward 1998, Ziska and Caulfield 2000). At the plant level, there is evidence of increased water use efficiency (Drake and Gonzalez-Meler 1997) and increased tolerance of salinity (Rogers et al. 1994). At the ecosystem scale, when transpiration is limited by water availability, the increased plant water use efficiency resulting from higher CO_2 concentration would usually result in the available soil water being able to support more leaves (that is, either support more leaves for some of the time, or support the same leaves for more time) and hence more photosynthesis (Farquhar 1997, Owensby et al. 1999, Li et al. 2000). As the dynamics of moisture availability have been shown to largely determine the vegetation height and cover (Specht 1972, 1981), a change in ecosystem water use efficiency can also be expected to modify competition dynamics at a site. In environments enriched in CO_2, the mass concentration of dry matter in woody stems is likely to increase rather than decrease (Roderick and Berry 2001), and this would enable woody stems to escape from the flame zone in grasslands (Higgins et al. 2000), and would presumably assist woody vegetation to establish on some grassland sites. All these factors could potentially affect the distribution and the relative abundance of plant species and consequently animal species as CO_2 concentration increases.

3.14 Potential global warming impacts on terrestrial ecosystems and biodiversity of the Wet Tropics

David W. Hilbert[1]

Introduction

Globally, forest clearing is thought to be the greatest threat to biodiversity in the tropics, and rates of clearing are certainly highest there, particularly in tropical Asia. Climate change is sometimes discounted and has been less studied in tropical regions than in temperate, boreal or arctic ecosystems. However, preliminary studies indicate that climate change is a particularly significant threat to the long-term preservation of the animals and plants in the Wet Tropics World Heritage Area.

The Wet Tropics is dominated by mountain ranges with altitudes varying sharply between sea level and over 1600 m. Environmental gradients associated with this complex topography largely determine species composition and general patterns of biodiversity. Partly because of extensive clearing in the lowlands, most rainforest is above 300 m and most of the regionally endemic species are cool-adapted upland species. The regionally endemic rainforest vertebrates generally are distributed over areas with a very narrow range in annual mean temperatures. Consequently, the biodiversity and regionally endemic species that are keystone elements in the Wet Tropics World Heritage Area may be under severe threat over the next few decades. An enormous loss of habitat leading to significant loss of biodiversity is possible. Ecosystem processes and the provision of ecosystem services (such as clean and reliable water) also could be severely affected by climate change.

Warming can have a particularly strong impact on mountainous regions like the Wet Tropics. The mountain tops and higher tablelands can be thought of as cool islands in a sea of warmer climates. These islands are separated from each other by the warmer valleys and form a scattered archipelago of habitat for organisms that are unable to survive and reproduce in warmer climates. Many of the Wet Tropics endemic species live only in these cooler regions. An additional likely effect of warming is a significant lifting of the base of the cloud-bank on tropical mountains. There is significant trapping of cloud-water droplets within cloud forests—so-called ‘cloud stripping’—which can considerably augment rainfall, especially in the dry season. Global climate simulations with a scenario of doubled CO_2 concentration show that the relative humidity surface is shifted upwards on tropical mountains by hundreds of metres during the winter dry season. This is the period when these forests are most reliant on the moisture from cloud contact. Because of their great sensitivity to climate, cloud forests are likely to display climate change effects in the very near future.

Have ecological and biological effects of warming already been observed ?

Palaeoecological studies in the Wet Tropics have demonstrated the extensive biogeographic changes that have occurred as a result of past climate change (Hopkins et al. 1993, 1996, Hilbert and Ostendorf 2001). However, there has not been any climate-change monitoring in the Wet Tropics, making it impossible to state whether warming in the 20th century has had an impact on the Wet Tropics flora or fauna or ecosystem processes. Monitoring in other parts of the world has identified a large number of ecological and biological changes due to recent climate change. For example, a lifting cloud-base

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associated with increased ocean temperatures has been implicated in the disappearance of 20 species of frogs in highland rainforests of Monteverde, Costa Rica.

Preliminary assessments of impacts in the Wet Tropics

Forest type, defined by structure and physiognomy, is an important habitat variable, although many trees and other organisms are not restricted to a single forest type. Therefore, the extent and distribution of forest types in the future is an important indicator of potential changes in biodiversity. Recent work (Hilbert et al. 2001a,b, Ostendorf et al. 2001) has found that the tropical forests of north Queensland are highly sensitive to climate change within the range expected early in the 21st century. Overall, the location and extent of rainforests are determined by rainfall and its seasonality, with some influence of soil fertility and water-holding capacity. But the type of rainforest and the kinds of organisms found there depend more on temperature.

In the Wet Tropics, one degree of warming can increase the potential area of rainforests as a whole, as long as rainfall does not decrease. However, large changes in the distribution of forest environments are likely with even minor climate change, and the relative abundance of some types could decrease significantly. Increased rainfall favours some rainforest types while decreased precipitation increases the area suitable for woodlands and forests dominated by sclerophyllous genera such as *Eucalyptus* and *Allocasuarina*. The area of lowland Mesophyll Vine Forest environments increases with warming, while upland Complex Notophyll Vine Forest environments respond either positively or negatively to temperature, depending on precipitation. Highland rainforest environments (Simple Notophyll and Simple Microphyll Vine Fern Forests & Thickets), the habitat for many of the region's endemic vertebrates, decrease by 50% with only a 1^{o}C warming. Using this model, we have mapped the current and potential future distributions (1^{o}C warming and –10% rainfall) of upland and highland rainforest types. Environments suitable for these forest types decline greatly and become very fragmented in this climate-change scenario. Obviously, if the upper range of predicted warming occurs (5.8^{o}C), no appropriate environments would remain within the Wet Tropics. Whether and where appropriate climates might come to exist further to the south, say in the Border Ranges, is unknown. However, regional rainfall patterns and topographic constraints imply that such new habitat would be very far removed from the Wet Tropics.

There are two published studies of climate change impacts on a vertebrate of the Wet Tropics focusing on the endangered Northern Bettong (Hilbert et al. 2001a) and the Golden Bowerbird (Hilbert et al. in press). Estimates of the potential habitat for the Northern Bettong in the future depend on whether they require tall open forests and whether rainfall increases or decreases. Assuming that tall open forests are not essential, habitat would decline if warming is accompanied by greater precipitation, and would increase if rainfall decreases. Our modelling of habitat for the Golden Bowerbird, a charismatic upland and highland endemic, predicts that the current habitat (1199 km^2 in several distinct patches) will shrink by 63% with one degree of warming and a 10% decrease in rainfall. Three degrees of warming and a 10% reduction in rainfall reduces potential habitat to only 28 km^2.

3.15 Impacts of global climate change on the rainforest vertebrates of the Australian Wet Tropics

Stephen E. Williams[1]

Climate change is a particularly significant threat to the long-term preservation of the biota in the tropical rainforests of Australia's Wet Tropics World Heritage Area. The Wet Tropics is dominated by mountain ranges with altitudes varying sharply between sea level and over 1600 m. Environmental gradients associated with a complex topography dominate the biogeography of the region (Nix and Switzer 1991, Williams et al. 1996). The gradient in altitude is the most significant environmental gradient determining species composition and general patterns of biodiversity (Williams et al. 1996, Williams and Pearson 1997). Most rainforest is above 300 m and almost all of the regionally endemic species are cool-adapted upland species (Nix and Switzer 1991, Williams et al. 1996).

Most of the regionally-endemic rainforest vertebrates are distributed over areas with a very narrow range in annual mean temperatures. The range of annual mean temperatures encountered within the distribution of most species is very small (between 1.8°C for *Cophixalus bombiens* and 9°C for the Leaf-tailed Gecko (*Saltuarius cornutus*)) with an average range of annual mean temperature across regionally-endemic species of just 5.5°C (Williams unpublished data). These data reveal just how significant an increase of several degrees would be. The implication is that even minor changes in temperature will have significant impact on available environments. Hilbert et al. (2001b) predict significant changes in the geographic distributions of vegetation types in the region, including a 50% decline in the extent of upland rainforest types if there is only a 1°C increase in temperature. The results, using neural network models, produce conclusions similar to those of the BIOCLIM models based on the distributions of endemic species discussed here.

Understanding patterns of biodiversity, endemism and species abundance in the Wet Tropics is a study of limiting factors at various geographic and time scales. On a regional scale, biodiversity has been limited by contractions in the extent of rainforest area during the Pleistocene, and subsequent episodes of expansion, both within the region (Williams and Pearson 1997) and between the regions (Winter 1988). Local assemblage structure and local species diversity are limited by the way vegetation structure varies from place to place within an area (Williams et al. 2002). Recent results (Williams

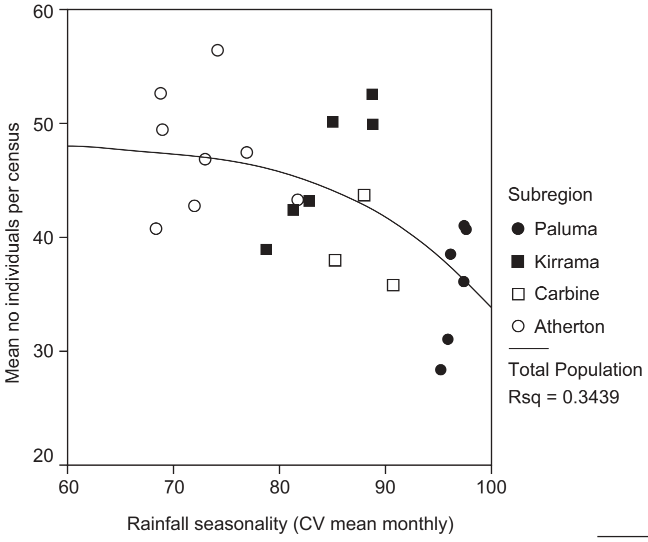

Figure 3.15.1. Rainfall seasonality and bird abundance

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unpublished data) show that the abundance of a species at local and at landscape scales is severely limited by short-term bottlenecks in the supplies of resources. Variability of rainfall from month to month is the most significant climatic variable explaining patterns of bird abundance (Figure 3.15.1). This is despite the fact that bird species richness and species composition do not vary across the same gradient. Similarly, variability of temperature from month to month limits the species richness and abundance of reptiles (Figure 3.15.2). Short periods of dry weather limit insect biomass (Frith and Frith 1985) and probably fruit biomass. A plausible hypothesis to explain these patterns is that short bottlenecks in available resources limit the population sizes of insect-eaters and fruit-eaters.

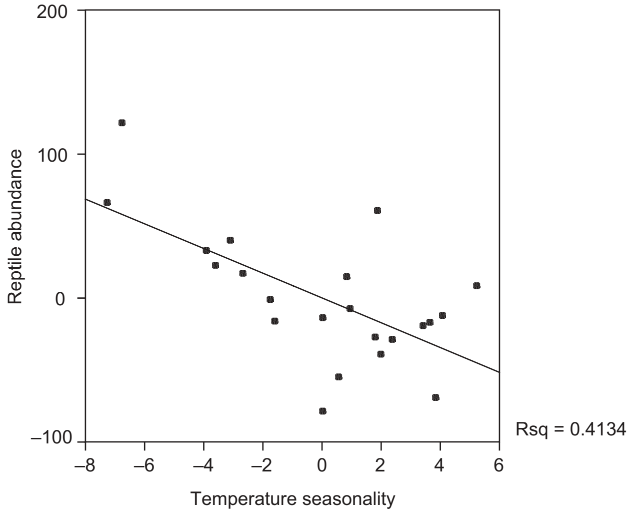

Figure 3.15.2. Relationship between reptile abundance and seasonality of temperature

Basically, the population sizes and diversity of species in a Wet Tropics habitat both decline when climate differs strongly from season to season. Variation between seasons is predicted to increase under greenhouse conditions.

Microhylid frogs are another group where regional patterns of diversity are strongly related to consistent moisture levels throughout the year, and limited by low rainfall in the dry season (Williams and Hero 2001). Increased rainfall variation between seasons and a lifting cloud base both have serious implications for the long-term survival of most species of microhylid frogs.

Preliminary BIOCLIM modelling of the geographic distributions of a representative collection of vertebrates unique to the Wet Tropics suggests that global warming will have severe effects on the long-term survival of many species. A 1°C increase in mean temperature is considered a certainty and even this small increase is predicted to decrease the range of these rainforest species to a mean of 63% of their current range. A rise of 3.5°C (average scenario predicted) will reduce range sizes to a mean of 11% of current area and will completely remove the bioclimates currently occupied by 30 species of endemic vertebrates. There is a real possibility of between 30 and 50 species becoming extinct this century. Most upland species will disappear if average temperatures increase by somewhere between 1°C and 5°C (Figure 3.15.3 shows examples of predicted declines in range size). This would be calamitous in a region that has been preserved as a World Heritage Area mostly on the basis of the biodiversity values represented by these regionally endemic species.

In the models discussed above, only the effects of temperature have been considered. The effects of climate change will conceivably be much more severe. Increased CO_2 concentrations will

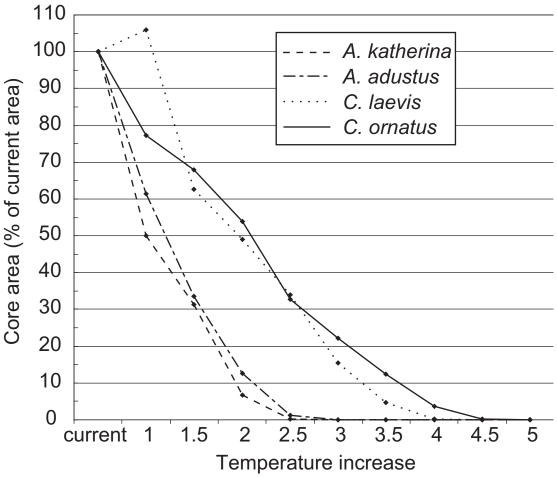

Figure 3.15.3. Rate of decline in distribution area of four species as mean temperatures increase

The Green-eyed Treefrog (*Litoria genimaculata*) (males 3–4 cm long and females 4–7 cm long), is endemic to the Wet Tropics and is relatively common throughout the rainforest. Males generally congregate along slow flowing streams. However females are often spotted throughout the forest, even at the tops of the canopy. (Photo: Stephen Williams)

reduce the nutritional value and increase the toughness of most foliage (Kanowski 2001). This will have significant detrimental effects on the abundance of leaf-eating species (ringtail possums and many insects, for example). Furthermore, predicted changes in geographic distribution will move species off nutrient-rich, basaltic soils and onto increasingly poor granitic soils at higher altitudes. It has already been shown that rainforests on these poorer soils support sparser population densities of ringtail possums and tree kangaroos (Kanowski 2001). Increasingly unpredictable rainfall may have significant effects too. Insect biomass has already been shown to decline during dry months (Frith and Frith 1985). These falls in insect biomass will probably have large impacts on insect-eaters and many other ecological processes at all levels of the food web. If the cloud base rises higher above the ground, species that need consistently wet conditions will be affected (microhylids, litter skinks, soil invertebrate faunas, microbes, etc.). Then all litter-feeding insect-eaters (many species of birds, skinks, microhylid frogs, dasyurid mammals, bandicoots, etc.) will be affected. Longer dry seasons will probably affect both the yield and the life-cycles of fruiting plants. These changes will undoubtedly cause many flow-on effects across the trophic levels (for instance, a decline in fruit biomass might result in decline in fruit-eaters that in turn will affect seed dispersal and plant recruitment processes).

Lampropholis robertsi (4 cm snout-vent) is a high altitude, regionally-endemic skink. It is generally restricted to above 900 m and has a very limited and fragmented distribution on mountain tops in the northern mountain ranges of the region. (Photo: Stephen Williams)

3.16 Effects of ‘greenhouse’ warming scenarios upon selected Victorian plants and vegetation communities

Graeme Newell[1], Peter Griffioen[1] and David Cheal[1]

Variability in climate is a natural phenomenon that has occurred throughout the Earth’s history. However, the warming of the Earth’s atmosphere over the last decade or so appears to be overriding these natural climatic fluctuations, and has led to serious alarm. The causes of these rapid changes in the atmosphere are not entirely clear, but they are most plausibly explained by a range of human-induced influences, such as increased concentrations of atmospheric carbon dioxide and other ‘greenhouse’ gases.

There has been considerable speculation about the effects of global warming on activities ranging from the future of tourism (for instance, Australia’s ski resorts), agriculture, forestry and human health, to the long-term survival of low-lying and coastal towns and nations. The effects of these putative changes in climate across these areas and activities vary from being beneficial to benign to potentially catastrophic. Considerable concern has also been raised about the potential effects of climate change upon biodiversity, with commentators suggesting that global warming is likely to have severe consequences for many species and biological communities (Newell et al. 2001). This paper describes a pilot project undertaken by the Flora Ecology Research Section at the Arthur Rylah Institute to examine the potential effect of enhanced greenhouse gases (that is, global warming) upon selected Victorian vegetation communities. This work builds upon similar studies conducted at the Institute in the past.

The bioclimatic profiles of 12 different plant species were modelled using ANUCLIM 5.1 software. A major innovation of this study was the integration of up-to-date regional climate models (courtesy of CSIRO Division of Atmospheric Research) into the process. This has allowed, for the first time, an examination of different combinations of both proposed changes to the global climate (that is, global climate models) and regional climate models that apply the global climate at the local level in a realistic manner. Using this new approach it has also been possible to model the bioclimatic profiles of species at five-yearly increments from the years 1990 to 2100.

Twelve plant species were selected either as representative of specific plant communities (for instance, swamp heathlands or alpine communities), or as individual species that were likely to decline or increase their range in a warmer environment. Predictions (to the year 2100) were made about the responses of these species to modelling processes. Results indicate that the bioclimatic profiles (that is, the amount of land surface in Victoria that is likely to provide the appropriate climate for a species) decline for each species over the time period and within each group of scenarios. These results suggest that the models may be overspecifying or overconstraining the bioclimatic profiles of species.

A suite of potential refinements has been suggested that essentially lead to a tighter selection of the bioclimatic variables that would be used for any particular species. This selection would be based upon both relevant ecological information and the biophysical information derived from ANUCLIM. Also, the model outputs could be incorporated into a geographic information system (such as ARCView), which

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allows for the development of more realistic scenarios for individual plant species and communities. These scenarios would be based upon our current knowledge of soils suitable for particular species, the distribution of remnant native vegetation across Victoria (that is, the real likelihood that a species can alter its distribution over the next 100 years), potential areas of salinity discharge, and so on. The incorporation of these refinements should lead to greenhouse modelling procedures producing outputs that have a biological reality. Then Victoria's land managers should be able to plan for the future in a more strategic and informed way. The further refinements and methodological investigations are being undertaken currently.

3.17 Impact of climate change on terrestrial antarctic and subantarctic biodiversity

Dana Bergstrom[1]

Patterns of climate change

There is firm evidence of recent climate change in antarctic and subantarctic regions. Trends show significant increases in annual surface air temperatures on all subantarctic islands where data have been collected. Changes in mean annual temperatures have been as high as +1.5°C over the last 30–50 years. These are among the most rapid rates of increase observed in the world.

On Australia's subantarctic Heard Island, an increase in mean annual surface air temperature of around 1.3°C over a 50-year time period (1948–2001) has been calculated (using linear regression models). Associated with this temperature increase there has been extensive glacial retreat. Between 1947 and 2000, approximately 35 km^2 of new terrain, including several large lagoons, has been exposed by ice retreat. This represents nearly 10% of the total area of the island. Using similar analysis methods, a similar rate of increase of annual surface temperature was reported for Macquarie Island, although with a more conservative analysis technique (ARIMA time series) this rate was scaled back to 0.3°C over 50 years. It still represents a total increase of around 16% and is within the range of current global change models.

On continental Antarctica, many areas are experiencing warming, including Australia's Casey station where the calculated trend in annual surface temperatures for the period 1959–1996 is +3.1°C/100 years. In other parts of Antarctica, very rapid warming has been documented on the Antarctic Peninsula, but local cooling has occurred in the Dry Valleys region, with increased surface ice on lakes and associated reduced primary productivity.

Signals in ice-sheet mass balance (significant to global sea-levels) are mixed. There is thickening in some areas and thinning in others, but the main message is that changes to the ice sheet can occur quite rapidly and the processes that cause these changes are poorly understood.

Apart from changes in temperature regimes, there are changes in other biotically-relevant environmental parameters such as precipitation, wind speed, evapotranspiration and UV. On Macquarie Island mean monthly precipitation has increased, while on other subantarctic islands, such as South Africa's Marion Island and France's Iles Kerguelen, precipitation has decreased dramatically. In Antarctica, the incidence of rain has increased in some locations. The significance of this is that rain increases the availability of free water to life. Conversely, temperature increase can reduce local supplies of snow or ice, lessening spring and summer melt run-off.

Inter-annual variability is very pronounced in the region and impacts of climate change may be more significant when considering the extreme events in contrast to the trends. The summer of 2002–2003 was significantly anomalous, with droughts on subantarctic islands, extreme summer sea-ice extents in some areas, and heat waves and flash flooding in the Dry Valleys and at the South Pole. At McMurdo a new maximum record of 10.5°C was recorded. Temperatures in January exceeded 10°C for more than five days—a temperature approximately 11 standard deviations above the

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mean for the month (–3.2 ± 1.48°C). On the eastern side of the Antarctic Peninsula, anomalous warm conditions contributed to the rapid and unparalleled break-up of an ice shelf (Larsen B) leaving newly revealed benthic areas available for colonisation. As unusual events like these become more frequent and intense, there is potential for ecosystems to undergo rapid change in structure and composition.

Impacts of climate change on biodiversity

(i) Impacts on current taxa: population level

Increased ambient temperatures (and for plants, increased CO_2) will allow many species to increase performance, improve reproductive capacity and increase their distribution. Many species are not currently living in optimal conditions. On the Antarctic Peninsula, the populations and distributions of two flowering plant species have shown dramatic increases over recent decades. On Macquarie Island, there is evidence of a bank of viable propagules of lowland species in upland areas, ready to grow when climatic conditions permit. On Heard Island there has been a trebling in the number of Black Browed Albatross in approximately 50 years. This appears to be related to increased breeding success because of a milder climate and more food being available as a result of new fishing practices around the island.

(ii) Impacts on current taxa: community level

The enlarging areas that have been freed of surface ice by glacial and snow-field retreat are allowing, and will continue to allow communities to expand their distributions. On Heard Island, land newly exposed during the last century has been rapidly colonised by plants and associated animals, increasing the biodiversity in these areas. However, areas where water will become less available will lose biodiversity.

Interactions between species, particularly species competition, pathogen–host interactions and predator–prey relationships, also respond to altered climatic conditions. Ultimately these interactions will alter community dynamics. For example, on Heard Island, a native creeping herb appears to be out-competing and overgrowing the dominant plant species (a cushion plant) and is found in many more plant communities now than in the mid-1980s. The warmer conditions

Heard Island—one of Australia’s World Heritage-listed subantarctic islands (Photo: Dana Bergstrom) are probably reducing the ratio of growth to respiration in the cushion plant, and it will retreat to higher altitudes (Heard Island is just under 3000 m in altitude) as it has done on warmer islands. On Macquarie Island, a related but endemic cushion plant species may not have space to retreat when lowland communities migrate to higher altitudes, because the island is low in profile (maximum altitude approx 400 m). As a result, the species may be lost in the future. Little is known about the temperature performance of a newly recorded plant virus. This virus does not appear to kill the host plant species, but the balance could be disrupted in the future.

(iii) Impacts on current taxa: alien impact

Better performance and wider distributions are also expected in many alien species that have been introduced to the region. It is predicted that the status of many of these species will alter from persistent to invasive, ultimately leading to a reduction in indigenous biodiversity. On Macquarie Island, rats are being found in upland herbfields where they were previously unrecorded, and there is anecdotal evidence of rats now having two litters per year compared to only one in the past. Rats are now having a negative impact on the reproductive success of the regional endemic megaherb *Pleurophyllum hookerii*.

(iv) Impacts on ecosystem processes

On subantarctic islands currently, nutrient turnover depends on the concentrations of detritivores (usually earthworms and insects) because conditions are too cold and wet for substantial bacterial decomposition. Peat accumulation is the norm. Increases in surface air temperatures may alter this balance. If so, the change would have flow-on effects into community structure and dynamics.

(v) Impacts on migration

It can be expected that as the climate warms, there will be successful migrations of species. However, the difficulty for scientists is to distinguish between alien arrival and natural arrival. The region’s biodiversity is recognised as missing functional groups. Elements of these functional groups can be expected to colonise and establish in the future—woody upright shrubs on subantarctic islands, for example, which would lead to major change in community biodiversity. The threat of introduction of more alien species is increased with climate warming because the number of species that can successfully establish is increased.

Evidence is emerging that the formation of the antarctic ozone hole is having an impact. During spring, approximately two-thirds of the protective ozone layer dissipates over the subantarctic and antarctic region, leading to greater penetration of UV-B radiation to the Earth’s surface. Maximum levels of UV radiation are occurring much earlier in the season than they did in the past, and lower and more damaging wavelengths are penetrating to the Earth’s surface. Among impacts identified are alterations in the production of protective pigments in some species, and reductions in the population sizes of insects.

Conclusion

Understanding the impact of climate change on subantarctic and antarctic biodiversity will remain one of the Federal Government’s antarctic research priorities for the near future. Models of these ecosystems will be simpler than models for continental Australia. They are part of ongoing research within the international RiSCC program (Regional Sensitivity to Climate Change in Antarctic Terrestrial and Limnetic Ecosystems: http://www.riscc.aq).

Chapter 4. Indicators of climate change

Lesley Hughes[1]

Introduction

There is now clear evidence that the relatively modest climatic changes over the past century have already had significant impacts on the distribution, abundance, phenology and physiology of a wide range of species. Recent reviews have documented many instances of shifts in species distributions towards the poles or upwards in altitude, and progressively earlier migrations and breeding (Hughes 2000, McCarty 2001, Walther et al. 2002, Parmesan and Yohe 2003, Root et al. 2003). The studies documented in these compilations are almost exclusively from the Northern Hemisphere, and an extensive review of species responses to recent climatic changes by the IPCC includes no Australian examples at all. As climate changes in Australia are consistent with global trends (see Howden, this report), it is likely that the lack of documented impacts is not because Australian species have been unaffected, but rather because long-term data-sets in which such trends could be detected are scarce (Westoby 1991). Our lack of systematic, long-term monitoring data on geographic distribution, phenology and other critical responses of Australian species will seriously hamper our ability to predict, adapt to, and mitigate the impacts of climate change on Australian biodiversity.

We need to devise a coordinated national indicator program to monitor the impacts of climate change in Australia. Therefore, one of the main aims of this workshop was to assemble experts from a wide range of disciplines to discuss species and systems that could form the basis of such a program.

What is an indicator?

An environmental indicator is a species or group of species that responds predictably and sensitively, in ways that are readily observed and quantified, to an environmental disturbance. Indicators are generally selected to act as surrogates of at least a subset of other organisms present in the same habitat. Indicators have been classified into a number of categories (Jenkins 1971, Spellerberg 1991):

- sentinels—sensitive organisms introduced into the environment as early-warning devices,
- detectors—species occurring naturally in an area of interest that may show measurable responses to environmental change such as changes in distribution or behaviour,
- exploiters—species whose presence indicates the probability of disturbance or pollution,
- accumulators—organisms that take up and accumulate chemicals in measurable quantities,
- bioassay organisms—organisms selected for use as laboratory reagents to detect the presence of particular chemicals.

Of these five categories, it is anticipated that detectors will initially be the most useful type of indicator for the purposes of monitoring climate change impacts. However, monitoring programs using sentinels may also be an option; they would provide an element of experimental control over the variation between individuals and environments, and therefore increase the signal-to-noise ratio.

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Indicators of climate change impacts

Species may respond to climate changes in a number of ways, including physiologically, phenologically (by adjusting the timing of life cycles) and in geographic distribution.

(i) Physiological indicators

Many physiological processes in plants and animals are sensitive to changes in greenhouse gas concentration (notably CO_2) and climate. The processes of photosynthesis in green plants and respiration in both plants and animals respond to CO_2 concentrations and temperature. Other physiological characteristics that may respond to climate change include diapause (dormancy) in insects and the breaking of dormancy in plants.

(ii) Phenological indicators

The life cycles of many species are strongly determined by climatic factors such as temperature and precipitation. Warmer conditions in spring as a result of climate change may lead to earlier onset of growth and flowering in plants. Species with a wide geographic distribution may not show the same phenological responses over the whole of their range; responses may show a gradation with latitude or altitude. Earlier emergence and a longer growing season may enhance the production and viability of seed in some plant species. Species that reproduce several times in a year (some weeds, many insects) may be able to produce more generations per year. Spawning in amphibians and egg-laying in birds are also expected to occur earlier in the season.

(iii) Distribution and abundance

Physiological and phenological responses to climate change, in combination with altered interactions between species, will influence the relative abundance and geographic distributions of most species. It is expected that the ranges of many species will gradually shift to the south (in the Southern Hemisphere) or upwards in altitude as climate zones change. These shifts will occur through the progressive extinction of local populations in areas that become unsuitable, and the progressive colonisation of new areas.

Criteria for selecting indicators

Once a list of potential indicators is produced, the following criteria can be used as a series of filters (as suggested by de Groot et al. 1995) to refine the selection.

Climate sensitivity

Appropriate indicators will be those species whose distributions, physiology or life cycles are predominantly sensitive to climate (especially temperature and precipitation) and less vulnerable to other changes in environmental conditions (such as land-use change, acidification, pollution). Species that respond to accumulated changes may be particularly suitable.

Availability of historical data

Where possible, indicators should be chosen where previous data have been collected. The data will serve as a baseline against which to monitor future change. Unfortunately, this criterion will rarely be met for Australian species because of the lack of long-term monitoring studies available.

Position within geographic range

Climate-related changes in performance will be detected earlier at the boundary of a species' geographic range than at its centre. Shifts in the boundaries between vegetation types (ecotones) may be particularly sensitive indicators.

Dispersal capacity

Species with the greatest mobility (flying animal species, plants with small wind-dispersed seeds) will be the most capable of shifting with climate zones and should thus indicate changes sooner than species with limited dispersal capacity.

Functional position in the ecosystem

Ideally, an indicator should be representative of a whole functional group (such as pollinators, or top predators). Changes in the response of the indicator could then be more readily generalised to other species.

Suitability for monitoring

Ideally, the indicator species should be easy to observe, recognise and identify. The cost of monitoring it should be minimal, and measurements should be readily repeatable.

Recommendations

1. Further evaluation of data-sets identified at the workshop

A systematic survey of long-term biological data-sets available in Australia should be undertaken to investigate whether useful baseline data exist, against which future, climate-induced change can be evaluated. This process was begun at the workshop. Resources are needed so that the usefulness of the suggested databases can be explored further.

It is suggested that experts in the fields covered by the databases be surveyed to provide information on the following issues:

- extent (number of years covered, number of species or regions)
- reliability (consistency of data collection)
- format (electronic *vs* hardcopy)
- sensitivity of species to climate (especially temperature and precipitation) in relation to other environmental variables (such as pollution, harvesting and landcover change)
- availability (whether privately or publicly held, and cost of data retrieval).

2. Survey of additional data-sets

The workshop participants came from a broad range of fields, but some important areas such as freshwater and estuarine ecosystems were not represented. It is recommended that experts from those areas be consulted, so that data-sets for those fields can be evaluated as described above.

3. Evaluation of potential indicators without historical data

Potential indicator species were identified at the workshop (Table 4.1) and in subsequent discussions. For several of these, there is little or no historical data available about their distribution or phenology; that is, they fit all the criteria outlined above except the second. For these species, it is recommended that further information be collected from both the published literature and relevant experts, so their potential usefulness for future monitoring programs can be evaluated, given that baseline data are still to be collected.

4. National monitoring program for climate change indicators

Once the previous three recommendations have been acted on, we will need to consider selecting a subset of indicators to form the basis of a national monitoring program. It is anticipated that some of these indicators will be those already being monitored (coral bleaching, alpine vertebrate distribution, for example). For others, there will need to be a commitment to begin collecting the baseline data.

An excellent model for a national monitoring program is the set of 34 climatic, environmental and socio-economic indicators of climate impacts selected in the UK under the auspices of the Department of Environment, Transport and Regions (DETR) (Cannell et al. 1999, http://www.nbu.ac.uk/iccuk/).

Table 4.1 Potential indicators identified at the workshop and in subsequent discussions

Indicators	Sensitivity	Comments, references and contacts
Physiological indicators		
Coral bleaching	Cumulative degree-days of sea-surface temperatures above various thresholds	Ongoing research program by Australian Institute of Marine Sciences (AIMS) (e.g. Jones et al. 1997, Berkelmans & Oliver 1999, Hoegh-Guldberg 1999, Lough 2000). *Acropora* spp. and other inshore coral species noted as being particularly sensitive (Ove Hoegh-Guldberg, pers. comm.).
Calcification in long-lived corals	Ocean temperatures	Annual variation in the density of calcium carbonate ($CaCO_3$) skeletons in some massive coral species such as *Porites* (Lough & Barnes 1997, Lough 2000) can be used retrospectively to monitor coral growth in a way analogous to the study of tree-rings. For each 1°C of temperature increase, calcification increases by approx. 0.3 g/cm^2/year and linear extension of the coral increases by approx. 3 mm/year.
Vegetation thickening	CO_2 and climate impacts	Vegetation thickening over the last 50–100 years has been recorded in environments such as semi-arid woodlands (Fensham & Fairfax 2002), and eucalypt savannas (Bowman et al. 2001) using historical collections of aerial photos, direct measurement and other techniques. Further measurement of this indicator has particular relevance to studies of carbon sequestration.
Distribution as an indicator		
Incidence and geographic location of arthropod-vectored diseases, e.g. malaria, Ross River fever	Temperature and precipitation impacts on mosquito vectors	Arthropod vectors (mainly insects) expected to move south, and previously-eradicated diseases such as malaria may re-emerge (Walker 1998)
Boundary of C_3/C_4 plant species in subtropics	CO_2, temperature and rainfall change	Recorded changes in the distribution and abundance of grass species reflect changes in temperature, rainfall and CO_2 concentration (Howden et al. 1999) due to changes in competition between C_3 (cool season) plants and C_4 (warm season) grasses
Boundary between rainforest and eucalypt woodland	CO_2, temperature and precipitation change	Expansion of rainforest into eucalypt forest and grasslands is well documented in Queensland over the past two centuries (e.g. Harrington and Sanderson 1994, Fensham and Fairfax 1996, Hopkins et al. 1996). Recent invasions of warm temperate rain-forest species to higher altitudes in northern NSW, and expansion of *Nothofagus* into eucalypt woodland on plateaus in the Barrington Tops region have also been documented (e.g. Read and Hill 1985). The relative roles of recent atmospheric and climatic change, relative to changes in fire regimes and long-term warming trends after the last glacial maximum, are unclear at present.
Tree establishment in sub-alpine zones	Temperature, duration and depth of snow cover	Encroachment by *Eucalyptus pauciflora* into subalpine grasslands near Mt Hotham, Victoria, has been documented by Wearne and Morgan (2001). Contact: Dr John Morgan, La Trobe University.
Composition and structure of alpine plant communities in long-term grazing exclosures	Temperature, duration and depth of snow cover	Trends in shrub senescence reported for shrublands in the Victorian Alps in plots fenced to exclude grazers since 1945 (Wahren et al. 1994). These trends have been interpreted mainly as slow recovery from grazing disturbance and post-fire regeneration, but may also reflect recent climatic changes.
Estuarine/freshwater vegetation boundary	Sea-level rise and saltwater intrusion	Dramatic expansion of some tidal creek systems in NT has occurred since the 1940s. In the Lower Mary River system, two creeks have extended more than 4 km inland, invading freshwater wetlands (Woodroffe and Mulrennan 1993; Bayliss et al. 1997, Mulrennan and Woodroffe 1998). Rates of extension of saltwater ecosystems inland in excess of 0.5 km/yr have been measured (Knighton et al. 1992). Over 17,000 ha of freshwater wetlands have been adversely affected and a further 35–40% of the plains is immediately threatened (Mulrennan and Woodrofffe 1998). Landwards transgression of mangroves into saltmarsh environments has also been documented in the estuaries of Queensland, NSW, Victoria and SA over the past five decades (Saintilan and Williams 1999). Multiple causes are likely, but include sea-level rise.

(continued next page)

Table 4.1 Potential indicators (continued)

Birds	Temperature and precipitation, sea-level rise (for sea bird nests)	Various databases, including the Australian Bird Census, held and collated by Birds Australia, may be analysed for climate-related trends. The most suitable species will be relatively sedentary with restricted ranges and/or specialised habitat requirements. Contact: Dr Mike Weston, Birds Australia.
Upland epiphytes in wet tropics	Temperature and precipitation, seasonality of rainfall, length of dry season, lifting of cloud base	Epiphytes are dependent on occult (mist) precipitation. Contact: Dr Dave Hilbert, CSIRO Sustainable Ecosystems, Atherton.
Alpine vertebrates (macropods and feral animals, e.g. horses)	Temperature, duration and depth of snowcover	Monitoring by Ken Green, NPWS*, indicates shifts in vertebrate geographic ranges to higher altitudes over the thirty-year period to 1999. Wildlife Atlas records indicate a higher maximum altitudinal distribution for all three macropod species and for four species of feral mammals (Green and Pickering 2002).
Range boundaries of flying foxes in eastern Australia	Temperature, precipitation, frost frequency	The range of *Pteropus poliocephalus*, the grey-headed flying fox, has contracted south from its northern boundary by about 750 km since the 1930s (Tidemann 1999). The black-heading flying fox, *P. alecto* has apparently extended its range south by a similar distance. Contact: Dr Chris Tidemann, Australian National Univ.
Colony formation in seabirds	Temperature, El Niño frequency and intensity	Colonisation of new breeding sites to the south of the historic range has been documented for at least 8 seabird species in the region between the Houtman Abrolhos and the Naturaliste and Leeuwin Capes, off the coast of WA (Dunlop 2001). Some of the shifts began as early as the 1920s, others in the 1950s and 1960s, while others did not begin until the 1990s. Impacts of El Niño via its effect on the Leeuwin Current may be responsible.
Phenological indicators		
Alpine plant phenology	Temperature increases and snow decreases, advancement of spring growing season	Some data are available in herbarium records (collated in electronic format by Dr L. Hughes, Macquarie University, from records at the National Herbarium). Some areas have been identified as being suitable for ongoing monitoring of flowering onset.
Arrival of migratory alpine birds	Temperature increases and snow decreases, advancement of spring growing season	A trend towards earlier arrival of migratory bird species in the alpine zone in the 1980s and/or 1990s, compared with the 1970s has also been documented (Green and Pickering 2002). For the 11 bird species for which there are sufficient data, the earliest record was in the 1990s for five species and in the 1980s for four. Contact: Dr Ken Green, NPWS.
Egg-laying dates of birds	Temperature and precipitation	Nest Record Scheme collated by Birds Australia (see above)
Australian plague locust emergence	Temperature and precipitation	Records held by Australian Plague Locust Commission
Behaviour in the sleepy lizard, *Tiliqua rugosa*	Temperature and precipitation	A long-term study on the sleepy lizard *Tiliqua rugosa* by Michael Bull and colleagues (Flinders University) since 1983 has documented changes in mating behaviour correlated with climatic changes (Bull and Burzacott 2002). Changes in the abrupt parapatric boundary of two reptile ticks for which the sleepy lizard is a host have also been monitored (Bull and Burzacott 2001). Contact: Dr Mike Bull, Flinders University
Economic/Agricultural indicators		
Trends in honey yields by region	Honey yields reflect changes in nectar and pollen production of flowers, which in turn reflect both climate and CO_2-induced changes to plant physiology and phenology	

*NPWS = National Parks and Wildlife Service

Chapter 5. Modelling biodiversity and climate change

Chris Chilcott[1], David Hilbert[2] and Mark Howden[3]

Modelling and analytical tools have been developed to assess the effects of climate change on biodiversity and biological function. A capacity to make predictions can give policy makers and regional planning groups some confidence to move forward, implement or change current policy instruments, identify critical thresholds of climate for important biomes, develop and test key indicators of change, and highlight iconic species or communities under immediate threat. In the future, modelling developments, particularly in process-based simulation models, will help us to better understand the effects of climate changes on biodiversity and assess the effectiveness of adaptation strategies.

Simulation models already exist that can be used to assess the impact of climate change on ecosystem function. The workshop focused on modelling tools that estimate the geographic distributions or 'climatic envelopes' of species or vegetation classes and how climate change would alter these, thus affecting biodiversity. However, they are just one type of several possible modelling approaches.

Models of species distributions or habitats can be dynamic, predicting time-dependent responses to a changing environment, or static, predicting equilibrium responses to a fixed set of independent variables (Prentice and Solomon 1991). Each of these types can be correlative (correlating observed presence and absence with observed environmental variables), or mechanistic (incorporating the ecological and physiological and/or other mechanisms responsible for an organism's responses to the environment) (Beerling et al. 1995).

Dynamic, mechanistic models have the advantage of being explanatory. They can be capable of some extrapolation beyond the environmental range used to develop the model. However, they require the modeller to have extensive knowledge about how the environment constrains a species' distribution (usually not available), or else they generalise from what is known about similar species. Dynamic, mechanistic models also require an accurate estimate of the time-course of climate change. However, the timing of climate change is quite uncertain and, for most species, the best or only information about environmental constraints is geographic presence data or, less frequently, both presence and absence. While explanation, in the sense of 'bottom-up' simulation, is an intellectually satisfying goal, we must also be pragmatic when faced with immediate needs, and recognise that explanations, in a reductionist, mechanistic form, are not always available or even necessary. Consequently, static, correlative models are an important and widely used tool for determining the responses of organisms to climate change (Guisan and Zimmermann 2000).

There are options (Howden et al. 1999) that provide intermediate pathways between the two extreme forms of models. These intermediate approaches combine existing knowledge (both quantitative and qualitative) about ecological

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responses into simple, but process-oriented models. A number of approaches were identified and discussed at the workshop. Their advantages and disadvantages are listed in Table 5.1

An important assumption of correlative models is that the species' distribution is currently in equilibrium with climate and is limited primarily by climate. In many cases these assumptions are not valid or cannot be tested. When applying a correlative model to altered climates, the modeller assumes that the climate variables continue to be correlated with whatever unknown variables actually control the distribution.

Correlative models are also highly sensitive to the accuracy of the data about distributions, on which they are based. This, plus the possibility of 'over-fitting' the model to too many climate variables, can lead to substantial underestimates of the potential range of species. When correlative models model vegetation types (rather than species), the issue of change in community composition in the face of environmental change is seen as important in some circumstances. Vegetation types defined by structure (Hilbert et al. 2001b) or plant functional types may be a more robust way to

Table 5.1. Types of modelling approaches for assessing climate change implications for biodiversity, examples of specific models and approaches, and some of the disadvantages and advantages of each

Modelling approaches	Examples	Points for and against (pros and cons)
Correlative approaches	BIOCLIM CLIMEX DOMAIN Habitat	As descriptive approaches, these models are unable to account for functional relationships. Instead they develop relationships from a species' existing environmental domain and presence. They predict other potential environmental domains where the species may occur, and changes in its distribution under altered climatic conditions. In most cases, the models are based on presence of species and cannot account for other determinants of species distribution: soils, species interactions and competition, or management and disturbance. Further, these approaches cannot account for the potential effects of faster change in CO_2 concentration. The models are user-friendly and only require data on climate and distributions (as comprehensive as is feasible). However, if applied naïvely, the models can result in major over-estimation of likely impacts.
Statistical approaches	General linear models. General additive models. Artificial neural networks.	Similar to correlative approaches except they use presence, absence and abundance data. They can also include categorical variables. They can be used to develop some analytical understanding of ecological limitations. These approaches are not 'packaged' and require a good understanding of statistical approaches. They are thus not particularly user-friendly. As with correlative approaches, it is assumed that the sample represents the entire habitat, that the species' distribution is principally determined by climatic conditions, and that the distribution is at equilibrium. More sophisticated approaches such as Artificial Neural Networks are considered something of a 'black box' and require some experience in their application.
Simple simulation models	GRASP	These models have been developed to gain an understanding of ecosystems and interactions, based on basic ecological and/or physiological data. They simulate the performance of an organism within an environment, based on factors such as climate, CO_2 concentration, soil and management. Their users require an understanding of ecological interactions. The models may be limited by available data, but will highlight limitations in the understanding of climate–species distribution interactions. They have the capacity to generate hypotheses and to test uncertainty with different climate change scenarios. Models of this type are important because they incorporate at least some management options, can explore some adaptations, and can deal with a large range of interacting factors such as CO_2 concentration, soil type, etc.
Bayesian approaches		Bayesian approaches are used in conjunction with other models. **For:** they are suitable for use when there is high uncertainty, and can build information for policy and science because they force the users to think about the nature of the data and the questions. Bayesian thinking can be thought of as parallel with processes of learning. **Against:** these approaches are not generally well understood, can involve highly complex statistics, and are not considered useful by everyone. Computer time is also an issue for some applications.

model future vegetation, but this approach will not provide information on composition.

When properly implemented and interpreted by users knowing the limitations, statistical and correlative models can be a useful ‘first filter’ for identifying locations and taxonomic groups that are most (and least) threatened by climate change. However, they cannot deal with 1) CO_2 concentration, which is the most certain aspect of climate change and likely to be very important with both positive and negative implications, 2) combinations of climate, CO_2 concentration, and soils that are outside the range already existing, 3) dispersal abilities of a species, and 4) management adaptations.

Where ‘hot spots’ or ‘hot species or communities’ are identified and where a wider range of ecological information is available, further analyses using simple simulation models (Howden et al. 1999) can more robustly identify impacts likely to result from multiple changes that have not yet been seen (in CO_2 concentration, rainfall, temperature, frost, for example). They can assess whether associated adaptation actions will be useful or applicable. Where such analyses can be made, the resulting knowledge could be used to plan monitoring programs and identify priorities for adaptation and options.

The following issues should be considered when choosing the most appropriate modelling approaches to use:

- How will the different types of models address hitherto unexperienced combinations of climate variables, such as high rainfall, high temperature and interactions with soil factors, fire and management?
- How do models address response to increased CO_2 concentration for which there is no precedent in the last 400,000 years?
- Any modelling program requires the monitoring of change as way of refining outputs and predictive capacity.

Previous climate change impact assessments for Australia

Several of these modelling approaches have been applied previously to Australian ecosystems and biota. They have been reviewed by Hughes (in press) and are summarised in Table 5.2 overleaf.

Table 5.2. Expected impacts of climate change and changes in CO_2 concentrations on various ecosystems and groups of organisms drawn from Australian studies (reviewed by Hughes in press)

Ecosystem/taxa	Expected impacts	Reference
Plant diversity in eastern Australia	Little change in plant diversity as the benefits of higher CO_2 levels offset the deleterious effects of higher evapotranspiration under a +3°C and +10% precipitation scenario	Rochefort & Woodward 1992
Tropical rainforest of north Queensland	Most of the forest types examined will experience climates in the future that are currently more appropriate to some other structural forest type. Highland rainforest environments (which are the habitat of many of the region's endemic vertebrates) are predicted to shrink by 50% with only a 1°C warming.	Hilbert et al. 2001a
Grasslands	Some limited changes in the distributions of C_3 and C_4 grasses. Higher temperature favours more southerly distributions, and higher CO_2 favours more northerly distributions.	Howden et al. 1999
Northern Australia, extensive freshwater swamps and floodplains	The low relief of these areas means that even small rises in sea level could result in relatively large areas being affected by saltwater intrusion. The result would be expansion of the estuarine wetland system at the expense of present-day freshwater wetlands.	Woodroffe & Mulrennan 1993, Bayliss et al. 1997, Eliot et al. 1999
Riverine ecosystems and inland wetlands	Assuming that water allocation practices do not change, the projected reduced river flows will reduce both semi-permanent and ephemeral wetland vegetation substantially. They will reduce breeding events for colonial nesting bird species and have negative impacts on many other taxonomic groups.	Johnson 1998, Hassall & Associates 1998, Roshier et al. 2001, Herron et al. 2002
Coral reefs	Bleaching from raised sea-surface temperatures, hypo-osmotic stress if the size of extreme floods increases, physical damage from increased cyclone intensity. If higher CO_2 concentrations in air lead to reduced alkalinity in sea water, substantial degradation of reef structure and composition is likely.	Coles & Jokiel 1992, Hoegh-Guldberg 1999, Leclerq et al. 2002
Alpine areas	Raised summer temperatures may not only increase the growth rates of existing shrubs but may also stimulate expansion of woody vegetation into areas now dominated by herbaceous species. If there is less snow cover, under-snow activity is likely to decline, but predation may increase and interfere with hibernation of mammals.	Williams & Costin 1994, Walter & Broome 1998
Eucalypt species	53% of 819 eucalypt species have current ranges spanning less than 3°C of mean annual temperature. 41% have a range spanning less than 2°C and 25% have ranges spanning less than 1°C. In addition, 23% of species have ranges of mean annual rainfall that span less than 20% variation. If even a modest proportion of present day boundaries reflect thermal or rainfall tolerances, substantial changes in the Australian tree flora may be expected in the future.	Hughes et al. 1996
Dryandra and *Acacia* spp. in Western Australia	The bioclimates of 28% of *Dryandra* species are predicted to disappear completely with a 0.5°C warming; this estimate increases to 66% with a 2°C warming. The bioclimates of 59% of *Acacia* species would disappear with a 1°C increase and all would disappear with a 2°C warming. In general, species are not predicted to track moving climate zones across the landscape, due to soil constraints, but instead to shrink to a smaller range within their current distribution.	Pouliquen-Young & Newman 2000
Mitchell grass (*Astrebla lappacea*)	Suitable and marginal bioclimates are predicted to decrease in northern areas by 23% and 44% respectively. However, only about 50% of these areas occur on suitable soils. Note that inclusion of CO_2 effects may significantly change these outcomes.	Chapman & Milne 1998
Vertebrates	Range reductions are suggested for the majority of species although a few might increase their range. For example in south-east Australia, of 42 species studied, 15 may have no suitable bioclimate if there is a 3°C rise in temperature. For some species (such as Mountain Pygmy Possum *Burramys parvus*, and some frogs) their bioclimate may disappear completely if mean temperatures rise 1°C or less. Higher CO_2 concentrations will tend to reduce foliage quality below critical levels.	Brereton et al. 1995, Dexter et al. 1995, Chapman & Milne 1998, Pouliquen-Young & Newman 2000, Hilbert et al. 2001b, Kanowski 2001
Invertebrates	The bioclimates of 92% of butterfly species are predicted to decrease, with 83% declining by at least 50% if mean temperatures increase by 2.1 to 3.9°C. Large changes in range are projected. About 10% of species studied are vulnerable due to particular life history characteristics. Foliage quality could be affected, as for vertebrates.	Beaumont & Hughes 2002, Johns & Hughes 2002

Chapter 6. Policy discussion

Michael Dunlop[1] and Mark Howden[1]

Background

There are many good reasons, relevant to community, science and policy, for developing a national policy program to address the likely future impacts of climate change on biodiversity. This section identifies a range of factors that could usefully be considered in the development of any such program. It also identifies existing policy programs that may include opportunities for both monitoring the impacts of climate change and initiating adaptations.

Definitions

To avoid any confusion in terminology, the following definitions are offered in the context of climate change and biodiversity policy.

Abatement and mitigation—management actions to decrease emissions of greenhouse gases or increase their sequestration by the environment. Most climate change action to date has focused on this aspect of climate change policy.

Impacts—the effect of increased greenhouse gas emissions and atmospheric CO_2 concentration (and other global changes) on physical and biological processes in both natural and managed systems.

Adaptations—responses that decrease the negative effects and capitalise on positive opportunities associated with impacts. Adaptations can be split into ‘autonomous’ (internal, automatic system adjustments such as evolutionary responses in natural systems) and ‘planned’ (where a deliberate intervention is made in an attempt to achieve a specific goal, recognising the change in environment).

Three information needs

To develop an effective policy response to the potential impacts on biodiversity of climate change, information will be needed, to:

- establish the *need* for a policy intervention,
- identify and compare alternative policy *objectives*, and
- develop and evaluate various possible delivery *mechanisms*.

It is likely that different types of information will be required for each of these needs.

- Information about the impacts of climate change on biodiversity will provide the weight of evidence required to justify investment in adaptation. Indicators of climate change and analysis of impacts could contribute substantially to this weight of evidence.
- To identify and compare adaptation objectives, there will need to be:

  (a) some knowledge of the scope of climate impacts; that is, just how large a potential impact is likely to be (areas, species, ecosystem changes). Scientific research can help identify the scope of changes.

  (b) knowledge and assessment of biodiversity ‘values’; that is, species, communities, ecosystems, ecosystem function, ecosystem services. The Biological Diversity Advisory Committee may choose to offer some guidance on the values of alternative biodiversity outcomes.

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- To develop and evaluate alternative policy mechanisms, policymakers will need information about the adaptation options that are feasible for different situations, and their costs and benefits. A range of general adaptation actions, and some factors to consider when assessing possible actions, were discussed at the workshop.

What is the scope of the problem? Establishing the need for action to manage the impacts of climate change on Australia's biodiversity

A clear message needs to be sent to both the community and governments, by policymakers, interested groups and researchers, about the impacts of climate change on biodiversity. The message should be based on clear, and preferably quantitative, information about the likely impacts. We need to be able to identify which aspects of biodiversity (that is, which species, communities and ecosystems services) are most likely to be affected, the scale of the severity of the impacts (for instance, an alteration of the geographic range of a few species, replacement of ecosystems, or the extinction of a large fraction of species) and the rate at which these impacts may occur.

Many in the community and government, and indeed many biodiversity researchers, do not have a good understanding of the potential impacts of climate change on biodiversity. For example, there is broad community awareness of coral bleaching, but there is confusion between coral bleaching and coral mortality. If we collect information about current impacts, and monitor future impacts, we will be able to educate the community about the nature and scope of likely future impacts. If there is widespread understanding of the issues, there is more likely to be support for public investment in adaptation action. Information about current and expected impacts is also needed to guide public and private biodiversity-conservation programs and to direct biodiversity research. Some of these issues are covered below.

Stressed and pristine ecosystems

Ecosystems that are already stressed as a result of human-induced or other disturbance are likely to be particularly vulnerable to climate change impacts. Any added stresses of climate change are likely to further decrease resilience. However, species in relatively pristine ecosystems may also be particularly vulnerable if barriers to upwards or polewards migration are present (for example, if the pristine ecosystems are habitat islands, adjacent to ranges, deserts, oceans, cities, or cleared areas), or if they are affected by invasive species or other changes in species interactions.

Winners and losers

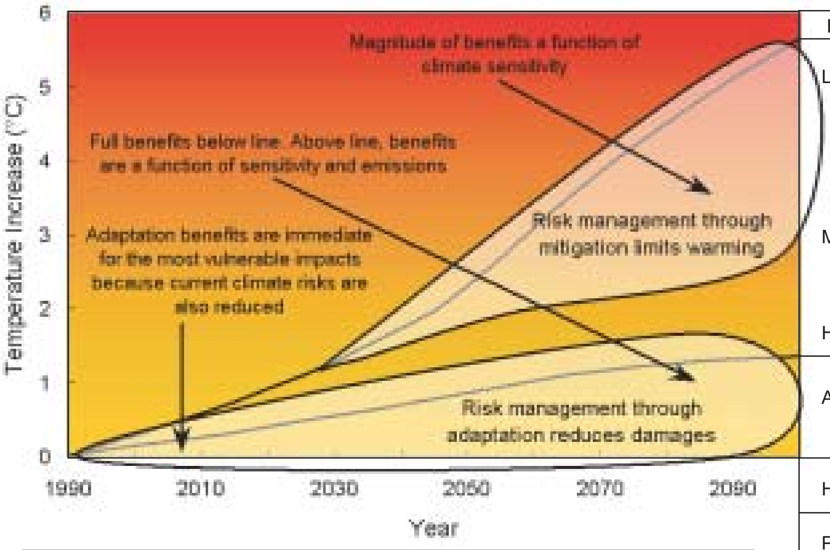
Many species are likely to be negatively affected by changes to mean temperature, rainfall, CO_2 concentration and disturbance regimes, and we may naturally tend to focus impact (and adaptation) assessments on those species. However, the greatest community and ecosystem impacts may come from those species that are *favoured* by changed conditions or disturbance and interact with other species (for instance, competitors, predators, invasive weeds, etc.). Such species could be native or exotic.

Uncertainty in impacts

The issue of what actions need to be undertaken is clouded in uncertainty. There are similarities with many other environmental issues in that there is a trade-off between requirements for short-term responses (mitigation) and longer term responses (adaptation). Both have tangible costs and largely uncertain, intangible benefits. In the case of climate change and biodiversity, we can think of structuring a rational decision in the form of a simple, commonsense equation that has five components.

The decision is a function of 1) the costs of mitigation, 2) the benefits of mitigation, 3) the costs of adaptation, 4) the benefits of adaptation, and 5) the interaction between these previous terms, because we would expect that a large mitigation effort is likely to reduce future adaptation costs and vice versa.

Unfortunately, it is not currently possible to produce adequate information to guide policy on any of the five components of the equation. Even the most studied components (immediate costs and benefits of mitigation) are hotly debated and unresolved. Economic analysts are highly



Probability	Consequence
Low probability, extreme outcomes	
Least likely	Considerable damage to most systems
Moderately likely Highly likely	Increased damage to many systems, fewer positives
Almost certain	Damage to the most sensitive, many positives
Happening now	Vulnerable to current climate

● Core benefits of adaptation and mitigation

Probability — the likelihood of reaching or exceeding a given level of global warming

Consequence — the effect of reaching or exceeding a given level of global warming

Risk = Probability × Consequence

Figure 6.1. Synthesis of risk assessment approach to global warming

The left part of the figure shows global warming based on the six SRES greenhouse gas emission marker scenarios (Jones 2000) with the zones of maximum benefit for adaptation and mitigation. The right side shows likelihood based on threshold exceedance as a function of global warming and the consequences of global warming reaching that particular level based on the conclusions of IPCC Working Group II (IPCC 2001b). Risk is a function of probability and consequence. SRES = Special Report for Emission Scenarios.

Source: Roger Jones, CSIRO, unpublished, © CSIRO.

polarised in their views. Some say that mitigation will benefit the economy while others suggest it will precipitate major economic losses. Nevertheless, the mitigation components are likely to bias the analysis due to factors such as the amount of prior research, and concepts such as application of discount rates to future (dis)benefits which favour short-term components at the expense of longer-term ones. Effective long-term policy decisions are likely to be assisted by information and uncertainty that is roughly balanced between the elements.

While this uncertainty is a difficulty to be managed in developing adaptation policy, dealing with such irreducible uncertainty is not an entirely new problem for public policy. For example, defence policy has to be developed in the context of considerable uncertainty and shifting threats and priorities. Similarly, many agricultural policies and farm management strategies are geared towards coping with the marked climatic variability in Australia. In addition, governments around the world are now beginning to take significant action to reduce greenhouse gas emissions and prepare for climate change, despite a very wide range in the modelled climate scenarios. In the face of this uncertainty about precise climate outcomes, they have the confidence to act as a result of the massive volume of good science coordinated by the IPCC.

Even so, the impacts of climate changes on Australia's biodiversity are uncertain. This is due to uncertainties in 1) the climate science (ocean–land–climate interactions), 2) projections of future emissions, and 3) knowledge of ecological responses. While improvements in climate and ecological science may reduce some of this uncertainty, there will always remain uncertainty in future emissions. At least half of the uncertainty in global warming is due to uncertainty in emissions scenarios. These are a function of economic, social, cultural, political and technological change: they are not amenable to scientific analysis. This should warn us against expecting too much from investing substantial resources aimed at reducing the uncertainty in the climate science. The investment can only reduce overall uncertainty to a limited extent. Hence, impact and adaptation policy will always have to deal with considerable uncertainty.

One approach to dealing with this is to focus, at least initially and where possible, on the lower end of the range of likely future climate changes, and develop strategies to cope with its impacts. This has the added advantage of enhancing our management of existing climate variability. At the same time, concerted actions to reduce emissions could avoid the need for adaptation to changes in climate at the more extreme end of the spectrum (see Figure 6.1).

This approach would focus attention on species and ecosystems that are most likely to be affected—that is, they are most sensitive to climate change. We suggest that these species will also be more seriously affected should climate change be greater than the minimum. However, if it becomes necessary to prioritise the use of limited resources for adaptation, focusing on species that are most likely to respond to adaptation actions rather than those most threatened by climate change, then a different approach might be required.

Much of the uncertainty in ecological responses to climate change results from interactions between different aspects of climate change and the complexity of interactions between species. For example, decreases in rainfall may impose stress on some plant species, but increased CO_2 concentrations may increase their ability to cope with less water. These responses may differ between species, leading to changes in competitive abilities and hence community composition. The CO_2 concentration may also alter the quality of some foliage, thereby affecting herbivores that depend on those plants. The direct effects of climate change on one species may be amplified, mitigated or transmitted to other species as a result of changed species interactions. For example, there may be alterations to habitat and to predator–prey interactions, competitive abilities and host–pathogen dynamics.

Information on climate impacts

The nature of the impacts of climate change on biodiversity can be determined by a combination of monitoring of specifically chosen indicators (climate variables and biological variables), modelling (shifting bioclimatic envelopes, physiological and ecosystem responses) and experimentation (climate manipulation and translocation). Future activity could include collating and mining existing time-series data to detect any climate-change signals, and setting clear agendas for future monitoring and research based on the information requirements identified for assessing impacts and adaptation.

Societal values

Impacts on biodiversity will affect the value society gains from biodiversity, quite apart from any desire to conserve it for other reasons. The ‘look and feel’ of ecosystems will change as species composition changes. Dominant species, familiar species, and less common species may all change; for example, farmers are already noticing and lamenting the loss of some woodland species. The attractiveness for tourists may change (for instance, by coral bleaching, rising cloud forests, decreasing snow depths and extent, drying waterways). Wild harvest may be affected (the productivity of fisheries may be affected, honey yield may drop as it has in past droughts); the resilience of agro-ecological ecosystems and the provision of other ecosystem services may also be affected. As the new science of identifying and quantifying the benefits that accrue from biodiversity develops, and the understanding of the biophysical impacts of climate change improves, a more detailed picture will emerge of the likely scope of the social and economic consequences of climate change impacts on biodiversity.

Table 6.1. Analogies between managing climate change impacts on biodiversity and healthcare management

Climate change action	Healthcare action
Managing existing climate variability better and reducing emissions	Primary prevention, reducing exposure to risk factors (e.g. giving up smoking)
Reducing other pressures on biodiversity; increasing ecosystem resilience	Health promotion (e.g. getting fit)
Preservation of species suffering from the impact of climate change	First aid and life support
Facilitating long-term adaptation	Treatment of a condition; healing
Prioritising investment	Triage

Adaptation objectives: what are we trying to achieve?

The United Nations Framework Convention on Climate Change sets out as an objective the stabilisation of greenhouse gas emissions within a time-frame sufficient to allow ecosystems to adapt naturally to climate change. However, there is considerable evidence to suggest that the likely rate of climate change may be faster than the rate of natural adaptation (autonomous coping through migration or evolution) for many species and ecosystems. This could result in substantial losses of biodiversity.

We need to decide on an appropriate objective for Australia in responding to the threat of climate-change impacts on biodiversity. To make the decision, we need to explore various components of both the threats posed by climate change and the responses of natural systems and their components. We suggest a three-fold objective is required. In the short-term the objective is to preserve sensitive elements of biodiversity against the immediate threat of climate change. In the longer term the objectives are both to facilitate adaptation to climate change and to mitigate against large changes.

This distinction is analogous to the difference between first aid and healing (see Table 6.1). These objectives recognise that changes to biodiversity are inevitable, but that human intervention could have a significant impact in reducing the negative consequences of that change. A separate, but equally critical objective, is to reduce the need for further preservation and adaptation by reducing future climate change itself through emission control and carbon sequestration. This is analogous to preventative health care.

Individuals within species are likely to respond to climate change in different ways. Hence, there are likely to be changes in species' genetics and population dynamics, assemblages of species, communities, ecosystem structure and functioning, and the goods and services provided by ecosystems. Some of these entities may be easier to preserve than others, and some may be judged by society as being of greater value (see Table 6.2). For example, even if all *species* survive climate change, differing environmental requirements and dispersal rates may make specific *communities* impossible to preserve in nature. Some species may be lost and gained from an ecosystem without substantially changing its structure and function. Similarly, one ecosystem may be replaced by another but with similar provision of water and carbon-processing services.

Pragmatically, the various objectives need to be assessed in the context of limited resources being available for investment on biodiversity conservation. There are interactions (both competitive and synergistic) between investments on biodiversity and other natural resource management issues. This raises the prospect of prioritisation and trade-offs in allocating resources. Is society prepared to decide that the conservation of some ecosystems may be too expensive to manage; or that there should be no effort to conserve a given species, so that a greater investment can be committed to another species that might have a greater long-term chance of adapting to a changed climate?

Table 6.2. Examples of different levels of biodiversity and comments on the possible practicality and value of preserving them

Entity	Comment
Intra-specific, genetic diversity	Important for future evolution and perhaps relatively easy to preserve for most species which can maintain large populations, but difficult for those with small or restricted populations.
Individual species	The best recognised unit of biodiversity. Possible to preserve a given individual species with generic biodiversity conservation actions and some specific climate change adaptation actions, but would be expensive for some species and difficult to assess for others (e.g. invertebrates, the most biodiverse group).
Species diversity	Similarly, it may be possible to preserve a diversity of species with combinations of generic and specific actions.
Specific assemblages or 'communities' of species	Many assemblages will be impossible to preserve in the long term, as the constituent species are likely to have differing responses to climate change. Indeed the popular concept of *communities* may not be robust or useful in the context of future climate change.
Ecosystem types in their current locations	Different types of ecosystems are strongly determined by climatic factors; hence it will be impossible to preserve some if not most ecosystems in their current locations, depending on the magnitude of future climate change.
Types of ecosystems somewhere	It is likely that many broad ecosystem types (e.g. temperate grasslands) will continue to exist (albeit not with the same assemblages of species) at some location. However, broad-scale management is unlikely to be able to preserve specific ecosystems with climatic and other requirements that cease to coexist in future climates.
Functioning and resilient ecosystems	There are likely to be demands for future emerging ecosystems to be 'healthy'; that is, their primary productivity, functioning and resilience should be similar to existing natural analogous ecosystems. Where this does not occur naturally in the future it may be hard to create via management, although the study of how ecosystems can be constructed is an emerging area of research.
Ecosystem services	There is likely to be substantial demand for the maintenance of those attributes of biodiversity that support human well-being, including life-supporting services and non-essential values. Where these do not occur naturally in the future they may be very hard to create with management.

The comments in the table represent one initial assessment and should be subjected to further scrutiny and value judgement. Contrasting views might suggest:

- saving species and rejecting communities is artificial—species are also human concepts, genetic variation is about the only fundamental and persistent biodiversity entity and covers all scales; and
- ecosystem function is not a good objective on its own—it may be possible to have good ecosystem function with low biological diversity, and zero 'Australian' species.

If such a triage approach were to be adopted, what would be the criteria for prioritisation: prospects for long-term adaptation? response to conservation investment? value to society? Do we have the information necessary to make those decisions?

Decisions about how best to invest in managing the various aspects of both climate change and biodiversity conservation should be made in a risk management framework, with an integrated rather than adversarial, approach to different objectives. Are our current institutions and policy programs up to the task?

Many, but not all, existing conservation programs are based, implicitly or explicitly, on the notion that what we want to conserve is 'exactly what we have now, where it is now'—a static view of biodiversity. While this notion is not consistent with a far more dynamic biogeographic or evolutionary perspective (10,000s of years), it is broadly consistent with the shorter-term anthropomorphic perspective (1–10s of years). Hence it has maintained currency. However, future climate change is very likely to result in a pattern of shifting mosaics of ecosystems in more human time scales (10–100 years), thereby undermining this static notion of biodiversity. To be effective, future conservation programs will have to acknowledge and accommodate this dynamic view of biodiversity. Indeed, in our highly modified landscapes, active management of these shifting mosaics will become increasingly important if we are to achieve conservation objectives.

Delivering on the objectives: adaptation options

A broad range of activities are likely to be required to effectively deliver on the objective of conserving biodiversity under climate change.

- Preserving currently intact natural habitat is and will continue to be the cheapest and most effective biodiversity conservation action.
- The dynamics of many Australian ecosystems, both natural and agricultural, are dominated by inter-annual climate variability, although the details of climate thresholds and sensitivities are not always currently well understood. Understanding and effectively managing for this variation is likely to be an essential part of on-going biodiversity conservation and the development of future adaptation programs.
- Many existing biodiversity conservation practices will be highly beneficial for meeting biodiversity conservation objectives under climate change, although there will be a need to do more of them and possibly to do them slightly differently.
- However, current conservation practice may need to be supplemented with activities specific to dealing with climate change in the longer-term (e.g. translocation).
- To guide adaptation actions for future biodiversity, there is an urgent need for monitoring of impacts and adaptations, understanding of climate sensitivities and species interactions and further development of both biodiversity and greenhouse policy.

Current biodiversity conservation effort is a broad mixture of activities, ranging from the generic to species-specific and site-specific activities. Some examples:

- measures aimed at increasing the robustness of ecosystems and preserving a large number of species: for example, reducing land clearing, limiting sediment and nutrient flow into waterways, establishing a connected, comprehensive system of reserved areas, maintaining bio-security, community education;
- targeted measures in situ, aimed at specific species but with multiple other benefits: for instance, pest control, fencing, revegetation, flora and fauna reserves; and
- intensive single species programs, such as *ex situ* conservation, captive breeding and reintroductions, perhaps even reconstruction (Tasmanian Tiger DNA, for example) but noting the high cost and significant ethical, technical and other issues associated with these types of activities.

Many of these activities could be beneficial for addressing the impacts of climate change on biodiversity. However, the nature and scale of the threats posed by climate change impacts may indicate that we need a different balance of investment in the various types of conservation activity. Under climate change, there are likely to be more species that are critically endangered, which will create added demand for expensive species-specific conservation actions. However, a more efficient long-term approach may be to make greater relative investment in generic conservation actions—aimed at increasing resilience and preventing as many species as possible from becoming endangered. Rapidly stabilising, then reducing atmospheric greenhouse gas concentrations would probably be most effective in minimising the long-term impact on biodiversity, but this faces political, economic and cultural barriers.

In many situations, substantial increases in the ability of species or ecosystems to cope with climate change may be achieved by reducing other threatening processes (for instance, stopping land clearing), especially if climate change is at lower end of the range of scenarios. In other situations, some climate-change-specific actions may be required. Broadly, those actions might include:

- increasing connectedness in the landscape,
- larger networks of protected areas,
- species translocations.

Given the potential scale of climate change and the likely shifts in species' climatic envelopes, substantial increases in connectivity across latitudes and altitudes may be required, through large-scale corridors and patches of habitat. Some practitioners suggest it may be more useful to think about *porosity* in the landscape, rather than corridors per se (which tend to constrain thinking to specific geometrical layouts). The essential feature that is required is enough connected habitat for large-scale ecological processes to continue. This could be achieved through coordination of vegetation management across land tenures and uses (for example, reserves, off-reserve protected areas and on-farm revegetation) and across scales (connecting remnants, at one scale, or biogeographic regions, at another scale, for example).

The need for increased connectedness in the landscape is not new: it has been recognised for decades, and climate change just adds to the need. Despite this existing need, progress, if any, has been very slow. The scale and potential threat of climate change might be useful in communicating the need for more immediate action. The potential risk that increased connectedness will lead to greater habitat for and movement of pests, weeds and fire also needs to be managed.

Translocation and *ex situ* conservation of species is likely to be a very cost-ineffective conservation mechanism, although it may be a last resort for some species; for example, threatened vertebrates and tree species that take a long time to become reproductively mature. A priority should always be to protect species *in* situ to try and avoid the need for more radical action. If translocations are necessary, they are likely to raise considerable ethical issues relating to impacts on species in the recipient areas and effective expenditure of funds. The expense of such programs is unlikely to have broad support if in situ conservation of other species or ecosystems is being neglected. A possibly less controversial form of translocation might be the proactive planting of 'future climatically appropriate' species, as opposed to local provenances, in revegetation programs.

Investments in adaptations to climate change are likely to be most effective if they are made in the context of broader natural resource management programs that, by their nature, have a broad range of objectives. Increasingly, multiple benefits are being sought from any single proposed investment. Hence adaptations with other benefits (such as water-table control, forestry), and existing actions that can be modified to provide adaptation benefits, are more likely to be viable. Similarly, a risk management approach to greenhouse policy can only be implemented if assessments of biodiversity impacts and actions are integrated with assessments of adaptation and impact in agriculture and other sectors, and with mitigation assessments. Thus, biodiversity adaptation policy should be coordinated with existing biodiversity and greenhouse policy, especially Australia's Forward Climate Change Strategy.

A number of major existing programs have biodiversity conservation as one of their objectives (see Appendix 1). These programs are likely to have considerable potential for monitoring climate change impacts and delivering adaptation actions, if they are given information about possible impacts and about identifying opportunities for adaptations. Information about regions and taxa that might be particularly sensitive would be useful for many existing programs. Regional-scale information could be readily used in the regional natural resource management (NRM) programs.

There is significant opportunity for collaboration between the research community and the groups delivering NRM programs, for both impact assessment and management of adaptation programs (especially in an adaptive management framework). Staff from Environment Australia and the relevant state agencies might play a critical role in facilitating information flows and brokering collaborations.

While there are very few documented opportunities for direct actions to promote adaptation to climate change in marine environments, it may be possible to decrease existing pressures on such ecosystems and increase their resilience by addressing land–sea linkages.

Given the uncertainties about future climate changes and about biological responses to these changes and the effectiveness of particular adaptation actions, it will be essential for adaptation programs to be managed in an active adaptive management framework. That is, where there is uncertainty, management actions should be designed specifically so that robust information about the outcomes of alternative actions is acquired and used to design further actions.

Information needs—filling the gaps

Investment and advice must be based on good science and information, particularly in the light of the significant uncertainties in future climate change and biological responses. Information can come from collating existing science, new research and adaptive management. This section lists many aspects of the information needed for developing policy responses to the impacts on biodiversity of climate change. Addressing these questions could help set research agendas and foster partnerships between the science and policy communities. It is recognised that these partnerships can and should be based on far more than application for and provision of research funding. The BDAC workshop provided a good start for the building of some science–policy relationships; priority should be given to creating and maintaining enduring linkages.

Impacts

How is biodiversity actually responding to climate change?

Modelling studies can provide very useful information about the potential scope of biological responses to climate change. However, it is essential that we also *measure* actual biological responses to past, present and future climate change, to complement, guide and validate modelling studies. A coordinated national monitoring program would greatly improve our knowledge of impacts as they occur and improve our capability to assess future risks and adaptations.

What is the scale of the expected changes in biodiversity?

At the regional scale, are we expecting changes in vegetation structural type, or are we simply expecting some species turnover within ecosystems resulting in a slightly different assemblage but similar ecosystem functioning? The answer to this question has consequences for flow-on effects and for options for adaptation; for example incarbon, nutrient and water budgets and other ecosystem services, conservation status, prognosis and management of threatened or restricted species. This question could be addressed with simulation analyses based on ecosystem-level and species-level biological processes, and by careful analyses of past climatic changes.

How fast will biodiversity respond?

For many of the causes and pathways of change, we know the probable direction of change but we don't know the sizes of the effects, interactions and feedback. For example, studies that overlie species' bioclimatic envelopes with future climate surfaces (and possible soil, topography, protected areas, etc.) may give an indication of the direction and possible extent of species migrations. Studies based on ecosystems' physiological responses to CO_2 concentrations provide complementary information. However, these studies give little information about the rates of migration and interactions that may actually happen. Predicted rates of climate change imply that migration rates will have to be many times faster than the rates of past migrations and faster than many species are likely to be able to migrate. Indeed, there is evidence that some species are still currently lagging thousands of years behind past climate change. What further analyses can be done to provide information about possible dynamics of the compositions of ecosystems and species migrations? This question could be addressed with targeted experimentation, simulation analyses based on ecosystem-level and species-level biological processes, and by careful analyses of past climatic changes.

How important is climate as a direct driver of change?

In what regions and for what species and ecosystems will direct effects (CO_2 concentration, temperature, rainfall change) or indirect effects (species interactions such as competition, predation, habitat, hosts, pathogens) be more important? In situations where indirect effects dominate, can studies of bioclimatic envelopes provide useful estimates of the scope of future changes?

Which regions, species and ecosystems are most vulnerable to the impacts of climate change?

Various arguments (which are not always consistent) have been used to suggest particular sensitivities to climate change. For example:

- mountains, because they frequently have species stratified on steep climatic gradients and are restricted in area;
- regions with low relief, where a small change in climate corresponds to a large geographic shift of favoured climate conditions;
- migratory species because they need a variety of habitats (winter migrating, breeding); and
- species with limited dispersal ability and/or that reproduce slowly.

Ecosystems that appear particularly vulnerable, on the basis of existing studies, include coral reefs, tropical rainforests and alpine areas.

Which species or ecosystems will be advantaged by climate change?

Some species that are otherwise restricted may be favoured by climate change, become invasive and become a threat to the persistence of other species.

Which processes and phases of species life cycles are most likely to be affected by climate change?

It is likely that different ecological processes determine the warmer (northern or lower) boundaries and cooler (southern or upper) boundaries of species or ecosystem distributions. Hence the different boundaries may move at different rates. The difference between these rates effectively determines whether a species will become extinct, invasive, or something in-between. Generally, establishment and death are the key phases of the life cycle that influence the abundance and distribution of species. Both phases are highly sensitive to extreme conditions or events—which are anticipated to increase in frequency and/or intensity with climate change. This provides us with a clear target for analysis of likely impacts and adaptations.

How will the impact of climate change on biodiversity affect economic and societal values?

From a human perspective, not all aspects of biodiversity may be of equal value. Some aspects may have high value in social or economic terms. If those aspects are lost, the impact may not correspond directly to any objective measure of the loss of biodiversity. It is important that we understand the impacts of these societal and economic values, as they are likely to be major drivers of any future action, and they should highlight priorities for action. Currently, there is no process to identify these values and how they might change.

Adaptations

How should existing biodiversity conservation actions be improved to account for climate change?

Many existing conservation actions will need to be maintained or enhanced to preserve biodiversity under climate change. However, there is frequently uncertainty about how conservation should be practised now, and this uncertainty will be amplified by climate change. More information is needed to understand the links between preserving biodiversity and

(a) flow regimes in waterways,

(b) habitat quantity and quality,

(c) landscape connectivity,

(d) invasive species, and

(e) the dynamics of small and isolated populations.

In addition, more needs to be understood about the characteristics that determine the resilience of ecosystems.

What scale of connectivity is likely to be most effective for maintaining ecological processes and preserving biodiversity under climate change?

Corridors and ‘stepping stones’ are frequently promoted as essential elements in landscape reconstruction and management, but there remains little information about their effectiveness. More information is required to determine how such elements should be designed to achieve biodiversity outcomes without simply increasing habitat and refuges for feral species, wildfire and new invasive species.

What are the requirements of a landscape that is resilient and robust under climate change?

How can resilience to the additional pressures and threats from climate change and the capacity to adapt naturally to future climates be increased in different environments? Indeed, are resilience and adaptability consistent or potentially contradictory characteristics? There is a substantial body of theory on resilient systems and a growing array of applications. There may be lessons from this work that can guide both conservation policy and conservation practice.

Is it practical to control the spread of native or naturalised species that may become invasive under climate change?

Species that can survive changes in climate per se, may be threatened by other species, both native and exotic, that are benefited by climate change. When and how might these threats be managed? Current quarantine and screening practices and weed and feral animal control programs may need to be modified to include climate change elements.

In which regions, and for which species, might reductions in non-climate-change pressures on biodiversity be sufficient to increase resilience to climate change?

For many species, ecosystems and environments there may be few direct actions that will reduce the impacts of climate change, but reducing other pressures may increase their resilience and adaptive capacity. For example, some land-based management actions may be useful for reducing the overall pressure on aquatic and marine ecosystems.

What characteristics define locations that could become climate change refuges?

Are refuges from past climatic changes likely to be important for natural adaptation to future climate change? Possibly not, given that past climate variations tended to be towards colder temperatures, whilst future ones are expected to be in the opposite direction. What role will active management play in determining and protecting future refuges? Can such places be identified and protected from present and short-term threats?

How should a shifting mosaic of ecosystems and species be managed?

Can we identify the direction (both geographical and ecological) in which ecosystems and species might be moving in response to climate change, and then facilitate (or slow) that movement? Are there general principles for such management, or does it have to be done on a case-by-case basis?

Can potential barriers to migration and adaptation be identified and mitigated?

Some barriers to migration may be obvious: for example, mountains, deserts, oceans and agricultural and urban land. However, other barriers (such as genetic paucity and small populations) may be less obvious except in a few well-studied species.

What are the risks associated with translocating species?

Captive breeding and species translocation are expensive, difficult and hazardous activities. Is it possible to predict and manage the risks of failure to establish (due to competition or insufficient habitat, for example) and the risks that some species may create a conservation threat via competition or predation?

Delivery

What information about impacts and adaptations will be useful to regional NRM planners?

The nature and scope of the impacts of climate change on biodiversity suggest the issue needs to be addressed and managed at a national level. However, and increasingly, conservation programs are being delivered through regional-scale processes. Can national-scale information be made useful for regional-scale management?

And is regional-scale delivery sufficient to achieve national biodiversity and climate change outcomes? What parameters would be useful for inclusion in the National Monitoring and Evaluation framework (a key part of the evolving regional NRM process)?

Can policy cope with the level of uncertainty about climate change impacts and the management options?

The large uncertainty about climate change, its impacts and possible responses to adaptations suggests that we need an adaptive management approach to guide and revise any adaptation program. However, responses to climate change and to adaptation management are likely to take place over decades or more. Can adaptive programs be developed that will be robust to the time lags and non-linearities in these biological responses?

How might trade-offs in adaptation or conservation investment be managed?

If a triage or other some other trade-off approach is used to prioritise investment, what criteria should be included (such as level of climate impact, effectiveness of adaptation action and value of the entity be conserved)? And how should the different criteria be assessed and combined?

Summary: Main policy recommendations

We have identified high priority actions for building a solid program for conserving biodiversity under the impacts of climate change. These can be separated into the five categories described below.

1. Understand and manage for climate variability

Understanding the current impact of climatic variability on natural and agricultural ecosystems will greatly help us to detect and manage future climate change. Actions might include management of:

- bushfire risk in relation to climate variability;
- grazing in relation to climate variability in the rangelands;
- water diversion and environmental flows in relation to climate variability;
- estuaries and coastal areas in relation to climate vaiability.

2. Preserve biodiversity that is sensitive to climate change

Preservation of existing biodiversity will always be the most effective and cheapest means of conserving biodiversity in the future. Many current conservation activities will also help conserve biodiversity under climate change, especially if given some enhancement. Actions include:

- preventing further land-clearing and loss of habitat;
- preventing introductions of new invasive species;
- reducing grazing in sensitive alpine areas;
- restoring environmental flows and water quality;
- minimising land salinity and in-stream salinity;
- reducing nutrient and sediment flows to rivers, wetlands, estuaries and oceans (especially important for the Great Barrier Reef and other reef systems).

Some actions specific to climate change may also be required, for example:

- suppression of species likely to become invasive under climate change;
- *ex situ* conservation of species that cannot survive future climates;
- including climate change threats as a mandatory consideration when drafting recovery plans for endangered species and integrated NRM plans.

3. Facilitate long-term adaptation

Some actions may be required to assist or augment the long-term and natural adaptation of biodiversity to climate change, for example:

- increasing the connectivity in the landscape, including corridors and ‘stepping stones’, especially along temperature- and other gradients;

- rehabilitating degraded habitat, including revegetation of cleared land and restoration of streams, rivers and wetlands;
- preserving locations that may become key habitat under future climates (for example, mountains and reefs to the south of those with potentially threatened species);
- ensuring that refuges are established and protected, and that species can migrate to and from them;
- translocating species (noting the risks involved).

4. Monitor, research and develop policy

For adaptation programs to be successful in the long term, substantial information is needed to address gaps in understanding. Some institutional issues may need to be managed. Actions should include:

- developing criteria for monitoring climate change impacts
- monitoring and assessing climate change and biodiversity impacts;
- designing adaptation actions to maximise information for future actions (that is, active adaptive management);
- ensuring that climate change impacts are integrated into all existing and future biodiversity conservation programs. For example, biodiversity conservation should be consistent with a shifting mosaic concept of ecosystems;
- developing new policy mechanisms to allow integrated risk management analysis of all greenhouse issues (mitigation and adaptation, costs and benefits), as opposed to a segmented, potentially adversarial, approach;
- raising the priority of climate change in research funding processes such as those of the Australian Research Council.

5. Mitigate climate change and reduce other pressures on biodiversity

There is no doubt that the tasks of preserving biodiversity under climate change and facilitating adaptation will be more achievable and less costly if the magnitude of future climate change is reduced. The greater the magnitude of future climate change the larger the number of species that will become threatened and the greater the likely need for investment to replace lost ecosystem services. When assessing the costs and benefits of mitigating climate change we must include the costs and benefits of adaptation associated with different emission scenarios.

Appendix 1. Existing Commonwealth programs

A wide range of existing policy programs have biodiversity conservation as one of their objectives. While few, if any, currently include climate change impacts in their assessments of biodiversity conservation needs, many of them could do so if the appropriate information were available. Similarly, adaptation to climate change could feasibly be added as a specific objective to some existing programs.

In some cases information about climate change or potential adaptation benefits may be sufficient to increase, or decrease, the priority of a proposed action; for example, in situations where revegetation and water-table pumping options were being compared primarily for salinity control.

There are several advantages of working within existing programs:

- the programs exist; therefore

  (a) a delivery mechanism is already established, and

  (b) the transaction cost of getting a new program up is avoided;

- any actions will be developed in an integrated context; mechanisms will exist for addressing trade-offs between different values or sectors, rather than having them emerge later as barriers to a specific adaptation action;
- there is generally a desire and role for climate change information in existing programs;

and disadvantages:

- in some cases agendas may already be set;
- there may be limited additional scope for work that does not conform with existing work plans/actions/targets;
- the existing approach might not work for the preferred climate change adaptations, e.g. mismatch of spatial or temporal scales;
- climate change impacts and the effectiveness of adaptations may have more uncertainty and a longer timeframe than competing objectives. Hence, without strong strategic input, the comparisons and trade-offs may favour better understood and shorter-term NRM issues.

Regional NRM policy framework

Commonwealth natural resources management (NRM) and environmental investments are mainly delivered via 'integrated regional plans'. These are essentially plans developed by regional bodies with some guidance and strategic input from state and Commonwealth governments. The plans must set targets for a number of specified issues and set out the actions that will be undertaken to achieve those targets. Funding of a plan is contingent on accreditation by the state and Commonwealth. The targets focus on natural resource condition issues and include biodiversity. This regional approach is the primary delivery mechanism for both the National Action Plan for Salinity and Water Quality (NAP) and the second phase of the Natural Heritage Trust (NHT II).

The plans are expected to include detailed trade-off analyses of different objectives, including objectives specified by the region as well as those proscribed by the state and Commonwealth. As such, different objectives (possibly including adaptations) essentially compete for priority with a regional body primarily determining the outcome, but there is a strong emphasis on actions that have multiple benefits. The programs also have a strong component of monitoring which is mainly concerned with evaluating progress towards targets, but will also include some general monitoring of resource condition. The investments can be used for capacity building (data and expertise) and facilitating land and water-use changes as well as for activities such as revegetation and fencing.

The NHT guidelines specify 10 areas of activity for investment; of these biodiversity and climate change issues could be covered directly in six areas and indirectly in two areas. The remaining two areas essentially cover productivity of agriculture and forestry (which will definitely have climate change issues). Hence, while the NHT does not explicitly include climate change adaptations, it does not exclude them.

NHT national investments

The NHT II also includes investments to address national and state priorities that generally involve activities at national or regional scale. Research, analysis, training and reserve acquisition are among activities covered by this stream. Measuring impacts and large-scale adaptation programs could fit into this category in the future, although it is highly competitive.

NHT local investments

The Envirofund provides small grants of up to $30,000 over a single year to community groups to address local biodiversity or resource use problems. The fund includes Bushcare, Landcare, Rivercare and Coastcare. If suitable adaptation actions could be developed at this scale, this might be an effective delivery mechanism.

Greenhouse and agriculture framework

The developing national framework for greenhouse and agriculture deals largely with reducing net emissions of greenhouse gases, but it also includes some opportunities for biodiversity adaptations. There is an emphasis on multiple benefits, such as planting for carbon sequestration and biodiversity benefit, although sequestration and economic uses are likely to have priority.

The framework includes identifying regions that are most likely to be affected and the monitoring of impacts. There may be opportunity to incorporate biodiversity into these activities.

Abatement programs

There are a number of abatement programs that are investing in planting of woody vegetation for carbon sequestration. Multiple benefits include forestry and forest products, but planting for conservation, especially with regard to climate change, could be possible. These programs include:

- Greenhouse Gas Abatement Program (GGAP),
- Bush for Greenhouse—a program supplying information about seeking maximum benefit from planting for carbon sequestration,
- National Carbon Accounting Scheme (NCAS):

  (a) ‘developing tools to identify the carbon benefits’ of revegetation for many purposes including biodiversity,

  (b) seeking synergies between NRM and greenhouse outcomes, such as via forestry, revegetation, vegetation management … greenhouse sinks … biodiversity,
- seeking to link greenhouse into regional NRM delivery:

  (a) NCAS, Bush for Greenhouse, adaptations strategies relevant to NRM.

Biodiversity toolbox

Biodiversity toolbox is an information kit developed by the Commonwealth Government primarily to help local governments with managing biodiversity. It is likely to be revised for the regional NRM framework, and there may then be an opportunity for including information on adaptation options.

National Reserve System

The National Reserve Scheme (NRS) aims to establish a comprehensive, adequate and representative (CAR) system of protected areas. Currently this includes minimal redundancy; that is, criteria are achieved as long as an ecosystem is *represented*. Climate change may indicate a need to reconsider the definition of adequate in the NRS, because diversity, redundancy, and geographic distribution will become increasingly important under climate change. Land acquisitions are covered by the NHT national investments.

State of the Environment

State of the Environment reporting is not a direct adaptation action. However, including specific impact and adaptation information in future reports may increase awareness of the issue. Those developing State of the Environment reports have indicated they are keen for usable indicators of climate impacts and adaptations.

Appendix 2. List of participants

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Appendix 3. Glossary

adaptations	responses that decrease the negative effects and capitalise on positive opportunities associated with impacts
benthic	associated with the bottom of a waterbody or the sea
bioclimatic range	areas of land that are likely to provide a climate appropriate for a species
biodiversity	the variety of life forms: the different plants, animals and micro-organisms, the genes they contain, and the ecosystems they form. It is usually considered at three levels: genetic diversity, species diversity and ecosystem diversity.
biomes	climatically controlled ecosystems with characteristic vegetation, occupying large areas, typically on more than one continent, e.g. coral reefs, grasslands
biotic	associated with living organisms
BP	before present
breakaways	land features in lateritic landscape, usually consisting of small escarpments
climate envelope	the range of climate conditions within which a species or ecological community can be found
decapod	ten-footed creature (usually crustacean)
detectors	species occurring naturally in an area of interest that may show measurable responses to environmental change, such as changes in distribution or behaviour
detritivores	consumers of detritus or dead biological materials
dinoflagellate algae	mobile planktonic algae with more than one flagellum (for propulsion), very important in marine and freshwater ecosystems
ecosystem service	benefit provided by a particular ecosystem
ecotone	transition zone between two or more vegetation communities, such as between grassland and forest
El Niño	a combined ocean and atmosphere pattern which results in an increase in sea-surface temperatures in the eastern Pacific off the east coast of North America but reduced sea-surface temperatures around Australia, resulting in lower than average rainfall and a smaller likelihood of cyclones in Australia
endemic species	species restricted to a particular geographic region or locality
endemism	occurrence of endemic species
endothermic	capable physiologically of maintaining a contant body temperature, as humans do; *ecto*thermic species have body temperatures that change with the temperature of their environment
ENSO	El Niño Southern Oscillation
exclosure	a fence around a patch of ground, meant to exclude animals
genetic	determined by or relating to genes
genetic paucity	very little genetic variation
global warming	anticipated increase in global temperatures resulting from human-induced emissions of greenhouse gases

greenhouse climate change	changes in global and regional temperatures, rainfall and other climate-related factors as a result of human-induced net emissions of greenhouse gases
greenhouse gases	gases such as carbon dioxide, methane and nitrous oxide, which act as a ‘blanket’ in the atmosphere, keeping in more outgoing radiation than there would otherwise have been, maintaining higher temperatures in the lower atmosphere and at the surface of the land and oceans
habitat generalists	species not confined to their range by a specific habitat
habitat specialists	species specialised to suit a particular habitat or niche
hypo-osmotic	a situation in which sea-water is less saline than usual, so that relatively fresh water diffuses into the cells of sea-living organisms by osmosis, damaging them
impact	an effect of increased greenhouse gas emissions and atmospheric CO_2 concentration (and other global changes) on physical and biological processes in both natural and managed systems
indicator	an environmental indicator is a species or group of species that responds predictably and sensitively, in ways that are readily observed and quantified, to an environmental disturbance.
IPCC	Intergovernmental Panel on Climate Change
La Niña	a combined ocean and atmosphere pattern which leads to an increase in sea-surface temperatures in the western Pacific and around Australia, resulting in higher than average rainfall and a greater likelihood of cyclones in Australia
mining of data	searching existing databases for patterns and relationships not part of the original data-collection scheme
mitigation	short-term relief; *see* abatement
monotonically	steadily, in one direction
mutualistic symbiosis	members of two different species living together, so that each benefits from the presence and metabolic activities of the other
net radiative forcing	increase in energy exchange at the Earth’s surface caused by an imbalance between incoming and outgoing radiation
palaeoecology	reconstruction of the relationships between past organisms and their environments, usually studied via fossils, pollen and charcoal in layers of soil
parapatric	having geographic or spatial distributions that abut but do not overlap
phenology	life-cycles
physiognomy	appearance
propagule	seed, spore, tuber, egg—something from which new life germinates or hatches
riparian zone	riverside zone of varying width, depending on context
sentinels	sensitive organisms introduced into the environment as an early-warning device
signal-to-noise ratio	ratio between the value that is being measured and interference from background occurrences
symbionts	species that live together closely
symbiosis	the situation of species living together closely
threatening processes	situations, usually caused by human activities, that reduce the quality of a habitat for a species, e.g. land-clearing, presence of feral animals
translocation	moving a species into a new area of suitable habitat which the species could not have reached without human assistance

References

Abele, L. and Patton, W.K. (1976) The size of coral heads and the community biology of associated decapod crustaceans. *Journal of Biogeography* 3: 35–47.

Allan, R.J. and D'Arrigo, R.D. (1998) Persistent ENSO sequences: how unusual was the 1990–1995 El Niño? *Holocene* 9: 101–118.

Barnola, M. (1987) Vostok ice core provides 160,000-year record of atmospheric CO_2. *Nature* 329: 408–414.

Barrows, T.T., Juggins, S., De Deckker, P., Thiede, J. and Martinez, J.I. (2000) Sea-surface temperatures of the southwest Pacific Ocean during the Last Glacial Maximum. *Paleoceanography* 15: 95–109.

Basher, R.E., Zheng, X. and Nichol, S. (1994) Ozone-related trends in solar UV-B series. *Geophysical Research Letters* 21: 2713–2716.

Bayliss, B., Brennan, K., Eliot, I., Finlayson, M., Hall, R., House, T., Pidgeon, B., Walden, D. and Waterman, P. (1997) *Vulnerability Assessment of Predicted Climate Change and Sea Level Rise in the Alligator Rivers Region, Northern Territory Australia.* Supervising Scientist Report 123, Supervising Scientist, Canberra.

Beaumont, L. and Hughes, L. (2002) Potential changes in the distributions of latitudinally restricted Australian butterflies in response to climate change. *Global Change Biology* 8: 954–971.

Beerling, D.J., Huntley, B. and Bailey, J.P. (1995) Climate and the distribution of *Fallopia japonica*: use of an introduced species to test the predictive capacity of response surfaces. *Journal of Vegetation Science* 6: 269–282.

Berkelmans, R. and Oliver, J.K. (1999) Large scale bleaching of corals on the Great Barrier Reef. *Coral Reefs* 18: 55–60.

Berry, S.L. and Roderick, M.L. (2002a) Estimating mixtures of leaf functional types using continental-scale satellite and climatic data. *Global Ecology and Biogeography* 11: 23–40.

Berry, S.L. and Roderick, M.L. (2002b) CO_2 and land use effects on Australian vegetation over the last two centuries. *Australian Journal of Botany* 50: 511–531.

Black, R. and Prince, J. (1983) Fauna associated with the coral *Pocillopora damicornis* at the southern limit of its distribution in Western Australia. *Journal of Biogeography* 10: 135–152.

Bindschadler, R. and Vornberger, P. (1998) Changes in the west Antarctic ice sheet since 1963 from declassified satellite photography. *Science* 279: 689–692.

Blakers, M., Davies, S.J.J.F. and Reilly, P.N. (1984) *The Atlas of Australian Birds*. Melbourne University Press, Melbourne.

Blumthaler, M. and Ambach, W. (1990) Indication of increasing solar ultraviolet-B radiation flux in alpine regions. *Science* 248: 206–208.

Bowman, D.M.J.S., Walsh, A. and Milne, D.J. (2001) Forest expansion and grassland contraction within a *Eucalytpus* savanna matrix between 1941 and 1994 at Litchfield National Park in the Australian monsoon tropics. *Global Ecology and Biogeography* 10: 535–548.

Bowman, D.M.J.S (1998) Tansley Review No. 101: The impact of Aboriginal landscape burning on the Australian biota. *New Phytologist* 140: 385–410.

Brereton, R., Bennett, S. and Mansergh, I. (1995) Enhanced greenhouse climate change and its potential effect on selected fauna of south-eastern Australia: a trend analysis. *Biological Conservation* 72: 339–354.

Brown, J.H. (1984) On the relationship between abundance and distribution of species. *American Naturalist* 124: 225–279.

Bruhl, C. and Crutzen, P.J. (1989) On the disproportionate role of tropospheric ozone as a filter against solar UV-B radiation. *Geophysical Research Letters* 16: 703–706.

Buddemeier, R.W. and Fautin, D.G. (1993) Coral bleaching as an adaptive mechanism. *BioScience* 43: 320–326.

Bull, C.M. and Burzacott, D. (2001) Temporal and spatial dynamics of a parapatric boundary between two Australian reptile ticks. *Molecular Ecology* 10: 639–648.

Bull, C.M. and Burzacott, D. (2002) Changes in climate and in the timing of pairing of the Australian lizard, *Tiliqua rugosa*: a 15 year study. *Journal of Zoology* 256: 383–387.

Busby, J.R. (1988) A biogeoclimatic analysis of *Nothofagus cunninghamii* (Hook.) Oerst. in southeastern Australia. *Australian Journal of Ecology* 11: 1–7.

Cannell, M.G.R., Palutikoff, J.P. and Sparks, T.H. (1999) *Indicators of Climate Change in the UK*. Centre for Ecology and Hydrology, Department of Environment, Transport & Regions (DETR) Available at http://www.nbu.ac.uk/iccuk/

Chapman, A.D. and Milne, D.J. (1998) *The Impact of Global Warming on the Distribution of Selected Australian Plant and Animal Species in Relation to Soils and Vegetation.* ERIN Unit, Environment Australia, Canberra.

Church, J.A., Godfrey, J.S., Jackett, D.R. and McDougall, T.J. (1991) A model of sea level rise caused by ocean thermal expansion. *Journal of Climate* 4: 438–456.

Coles, S.L. and Jokiel, P.L. (1992) Effects of salinity on coral reefs. In: *Pollution in Tropical Aquatic Systems.* Connell, D.W. and Hawker, D.W. (eds.), CRC Press, Florida, pp. 147–166.

Cook, E., Bird, T., Peterson, M., Barbetti, M., Buckley, B., D'Arrigo, R., Francey, R. and Tans, P. (1991) Climatic change in Tasmania inferred from a 1089-year tree-ring chronology of Huon Pine. *Science* 253: 1266–1268.

CSIRO (2001) Climate change projections for Australia. CSIRO Climate Impact Group, Aspendale, Vic, 8 p., http://www.dar.csiro.au/publications/projections2001.pdf

de Freitas, C.R. (1988) Perspectives on the impact of short-term climatic change in New Zealand. *New Zealand Geographer* 43: 169–198.

de Groot, R.S., Ketner, P. and Ovaa, A.H. (1995) Selection and use of bio-indicators to assess the possible effects of climate change in Europe. *Journal of Biogeography* 22: 935–943.

de la Mare, W.K. (1997) Abrupt mid-twentieth-century decline in Antarctic sea-ice extent from whaling records. *Nature* 389: 57–60.

Deng, X. and Woodward, F.I. (1998) The growth and yield responses of *Fragaria ananassa* to elevated CO_2 and N supply. *Annals of Botany* 81: 67–71.

Dexter, E.M., Chapman, A.D. and Busby, J.R. (1995) *The Impact of Global Warming on the Distribution of Threatened Vertebrates* (ANZECC 1991). ERIN, ANCA, Canberra.

Doake, C.S.M. and Vaughan, D.G. (1991) Rapid disintegration of the Wordie Ice Shelf in response to atmospheric warming. *Nature* 350: 328–330.

Dodson, J.R., and Mooney, S.D. (2002) An assessment of historic human impact on south-eastern Australian environmental systems, using late Holocene rates of environmental change. *Australian Journal of Botany* 50: 455–464.

Done, T.J. (1999) Coral community adaptability to environmental changes at scales of regions, reefs and reef zones. *American Zoologist* 39: 66–79.

Done, T.J., Turak, E., Wakeford, M., De'ath, G., Kininmonth, S., Wooldridge, S., Berkelmans, R., Van Oppen, M. and Mahoney, M. (2003a) *Testing Bleaching Resistance Hypotheses for the 2002 Great Barrier Reef Bleaching Event*. Australian Institute of Marine Science. Final Report to The Nature Conservancy.

Done, T.J., Whetton, P., Jones, R., Berkelmans, R., Lough, J., Skirving, W. and Wooldridge, S. (2003b) *Global Climate Change and Coral Bleaching on the Great Barrier Reef*. Australian Institute of Marine Science. Final Report to the State of Queensland Greenhouse Taskforce through the Department of Natural Resources and Mines.

Doran, P.T., Priscu, J.C., Lyons, W.B., Walsh, J.E., Fountain, A.G., McKnight, D.M., Moorhead, D.L., Virginia, R.A., Wall, D.H., Clow, G.D., Fritsen, C.H., McKay, C.P. and Parsons, A.N. (2002) Antarctic climate cooling and terrestrial ecosystem response. *Nature* 415: 517–520.

Douglas, B.C. (1991) Global sea level rise. *Journal of Geophysical Research* 96 C4: 6981–6992.

Dowdeswell, J.A., Hagen, J.O., Bjornsson, H., Glazovsky, A.F., Harrison, W.D., Holmlund, P., Jania, J., Koerner, R.M., Lefauconnier, B., Ommar, E. and Thomas, R.H. (1997) The mass balance of circum-arctic glaciers and recent climate change. *Quaternary Research* 48: 1–14.

Drake, B.G. and Gonzalez-Meler, M.A. (1997) More efficient plants: a consequence of rising atmospheric CO_2. *Annual Review of Plant Physiology and Plant Molecular Biology* 48: 609–639.

Dunlop, N. (2001) Sea-change and fisheries: a bird's-eye view. *Western Fisheries Magazine*, Spring, 11–4.

Dyurgerov, M.B. and Meier, M.F. (1997a) Mass balance of mountain and subpolar glaciers: a new global assessment for 1961–1990. *Arctic and Alpine Research* 294: 379–391.

Dyurgerov, M.B. and Meier, M.F. (1997b) Year-to-year fluctuations of global mass balance of small glaciers and their contribution to sea-level changes. *Arctic and Alpine Research* 29: 392–402.

Eliot, I., Waterman, P. and Finlayson, C.M. (1999) Predicted climate change, sea level rise and wetland management in the Australian wet–dry tropics. *Wetlands Ecology and Management* 7: 63–81.

Environment Australia (2001) *National Objectives and Targets for Biodiversity Conservation 2001–2005*. http://ea.gov.au/biodiversity/publications/objectives/

Etheridge, D.M. and Wookey, C.W. (1989) Ice core drilling at a high accumulation area of Law Dome, Antarctica. 1987. In: *Ice Core Drilling*. Rado, C. and Beaudoing, D. (eds), Proceedings of the Third International Workshop on Ice Core Drilling Technology, 10–14 October, 1988, Grenoble, France, pp. 86–96.

Etheridge, D.M., Steele, L.P., Langenfelds, R.L., Francey, R.J., Barnola, J.M and Morgan, V.I. (1996) Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and firn. *Journal of Geophysical Research* 101: 4115–4128.

Etheridge, D.M., Steele, L.P., Langenfelds, R.L., Francey, R.J., Barnola, J.M. and Morgan, V.I. (1998) Historical CO_2 records from the Law Dome DE08, DE08-2, and DSS ice cores In*: Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.

Farman, J.C., Gardiner, B.G. and Shanklin, J.D. (1985) Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction. *Nature* 315: 207–210.

Farquhar, G.D. (1997) Carbon dioxide and vegetation. *Science* 278: 1411.

Fensham, R.J. and Fairfax, R.J. (1996) The disappearing grassy balds of the Bunya Mountains, South-eastern Queensland. *Australian Journal of Botany* 44: 543–558.

Fensham, R.J. and Fairfax, R.J. (2002) Detecting landscape change in Australian savanna using aerial photography. II. The influence of rainfall and management history on vegetation cover. *Australian Journal of Botany* 50: 415–429.

Fensham, R., Minchin, P.R., Fairfax, R.J., Kemp, J.E., Purdie, R.W., McDonald, W.J.F., and Nelder, V.J. (2000) Broad-scale environmental relations of floristic gradients in the Mitchell grasslands of Queensland. *Australian Journal of Botany* 48: 27–38.

Frakes, L.A., McGowan, B. and Bowler, J.M. (1987) Evolution of Australian environments. In: *Fauna of Australia*. Dyne, G.R. and Walton, D.W. (eds.) Australian Government Publishing Service, Canberra, Vol. 1A, pp. 1–16.

Friedel, M. (1990) Some key concepts for measuring Australia's arid and semi-arid rangelands. *Australian Rangeland Journal* 12: 21–24.

Frith, C.B. and Frith, D.W. (1985) Seasonality of insect abundance in an Australian upland tropical rainforest. *Australian Journal of Ecology* 10: 237–248.

GCRMN (2000) *Status of Coral Reefs of the World: 2000*. Wilkerson, R. (ed.) Australian Institute of Marine Science, Queensland.

Graham, N.E. (1994) Decadal-scale climate variability in the tropical and North Pacific during the 1970s and the 1980s: observations and model results. *Climate Dynamics* 10: 135–162.

Green, K. (ed.) (1998) *Snow: A Natural History; An Uncertain Future*. Australian Alps Liaison Committee, Canberra.

Green, K. and Osborne, W.S. (1994) *Wildlife of the Australian Snow-Country*. Reed, Sydney.

Green, K. and Osborne, W.S. (1998) Snow as a selecting force on the alpine fauna. In: *Snow: A Natural History; an Uncertain Future*. Green, K. (ed.) Australian Alps Liaison Committee, Canberra, pp. 141–164.

Green, K. and Pickering, C.M. (2002) A potential scenario for mammal and bird diversity in the Snowy Mountains of Australia in relation to climate change. In: *Mountain Biodiversity: a Global Assessment*. Korner, C.H. and Spehn, E.M. (eds.) Parthenon Publishing, London, pp. 241–249.

Green, D., Singh, G., Polach, H., Moss, D., Banks, D. and Geissler, E.A. (1988) A fine-resolution palaeoecology and palaeoclimatology from south-eastern Australia, *Journal of Ecology* 76: 790–806.

Grevemeyer, I., Herber, R. and Essen, H.H. (2000) Microseismological evidence for a changing wave climate in the northeast Atlantic Ocean. *Nature* 408: 349–352.

Griffin, G.F. and Friedel, M.H. (1984) Effects of fire on central Australian rangelands. II Changes in tree and shrub populations. *Australian Journal of Ecology* 9: 395–403.

Griffin, G.F. and Friedel, M.H. (1985) Discontinuous change in central Australia: some implications of major ecological events for land management. *Journal of Arid Environments* 9: 63–80.

Guisan, A. and Zimmermann, N.E. (2000) Predictive habitat models in ecology. *Ecological modelling,* 135: 147-186.

Haeberli, W. and Beniston, M. (1998) Climate change and its impacts on glaciers and permafrost in the Alps. *Ambio* 27: 258–265.

Harrington, G.N. and Sanderson, K.D. (1994) Recent contraction of wet sclerophyll forest in the wet tropics of Queensland due to invasion by rainforest. *Pacific Conservation Biology* 1: 319–327.

Hassall and Associates (1998) *Climate Change and Managing the Scarce Water Resources of the Macquarie River.* Australian Greenhouse Office, Canberra.

Heatwole, H. (1987) Major components and distributions of the terrestrial fauna. In: *Fauna of Australia.* Dyne, G.R. and Walton, D.W. (eds.), Australian Government Publishing Service, Canberra, Vol. 1A, pp. 101–135.

Hennessy, K.J., Suppiah, R. and Page C.M. (1999) Australian rainfall changes, 1910–1995. *Australian Meteorological Magazine* 48: 1–13.

Herman, J.R., Bhartia, P.K., Ziemke, J., Ahmad, Z. and Larko, D. (1996) UV-B increases (1979–1992) from decreases in total ozone. *Geophysical Research Letters* 23: 2117–2120.

Herron, N., Davis, R. and Jones, R. (2002) The effects of large-scale afforestation and climate change on water allocation in the Macquarie River catchment, NSW, Australia. *Journal of Environmental Management* 65: 369–381.

Heyward, A., Smith, L.D., Halford, A.R., Rees, M. and Meekan, M.G. (1999) *Natural Variability at Scott Reef: Short Term Response of Coral and Fish Assemblages to a Severe Coral Bleaching Event.* Australian Institute of Marine Science, Queensland. 35 p.

Higgins, S.I., Bond, W.J., Winton, S. and Trollope, W. (2000) Fire, resprouting and variability: a recipe for grass-tree coexistence in savanna. *Journal of Ecology* 88: 213–229.

Hilbert, D.W. and Ostendorf, B. (2001) The utility of artificial neural network approaches for modelling the distribution of vegetation in past, present and future climates. *Ecological Modelling,* 146: 311–327.

Hilbert, D.W., Graham, A. and Parker, T. (2001a) Tall open forest and woodland habitats in the wet tropics: responses to climate and implications for the northern bettong (*Bettongia tropica*). *Tropical Forest Research Series No. 1.* Available on the web via http://www.TFRSeries.jcu.edu.au

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

Hilbert, D.W., Bradford, M., Parker, T. and Westcott, D.A. (in press) Golden bowerbird (*Prionodura newtonia*) habitat in past, present and future climates: predicted extinction of a vertebrate in tropical highlands due to global warming. *Biological Conservation.*

Hoegh-Guldberg, O. (1999) Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* 50: 839–866.

Hoegh-Guldberg, O. (2001) The future of coral reefs: integrating climate model projections and the recent behaviour of corals and their dinoflagellates. *Proceeding of the Ninth International Coral Reef Symposium. October 23–27, 2000.* Bali, Indonesia.

Hopkins, M.S., Ash, J., Graham, A.W., Head, J. and Hewett, R.K. (1993) Charcoal evidence of the spatial extent of the *Eucalyptus* woodland expansion and rain-forest contractions in North Queensland during the late Pleistocene. *Journal of Biogeography* 20: 357–372.

Hopkins, M.S., Head, J., Ash, J., Hewett, R.K. and Graham, A.W. (1996) Evidence of Holocene and continuing recent expansion of lowland rain forest in humid, tropical North Queensland. *Journal of Biogeography* 23: 737–745.

Howden, S.M., Walker, L., McKeon, G.M., Hall, W.B., Ghannoum, O., Conroy, J.P., Carter, J.O. and A.J. Ash. (1998) *Simulation of Changes in* CO_2 *and Climate on Native Pasture Growth. Evaluation of the Impact of Climate Change on Northern Australia Grazing Industries.* Final Report to Rural Industries Research and Development Corporation.

Howden, S.M., McKeon, G.M., Carter, J.O. and Beswick, A. (1999) Potential global change impacts on C_3–C_4 grass distribution in eastern Australian rangelands. *Proceedings of the VI International Rangeland Congress,* Townsville, Australia, pp. 41–43.

Howden, S.M. and Turnpenny, J. (1997) Modelling heat stress and water loss of beef cattle in subtropical Queensland under current climates and climate change. In: *International Congress on Modelling and Simulation.* McDonald, A.D. and McAleer, M. (eds.) Modelling and Simulation Society of Australia, Hobart, Tasmania. pp. 1103–1108.

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

Hughes, L. (in press) Climate change and Australia: trends, projections and impacts. *Austral Ecology*

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

IPCC (2000) *Special Report on Emissions Scenarios*. Nakicenovic, N. and Swart, R. (eds.). Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, p. 570

IPCC (2001a) *Climate Change 2001: The Scientific Basis. The IPCC Third Assessment Report, Working Group I report.* Albritton, D.L. and Meira Filho, L.G. (eds.) Cambridge University Press, Cambridge.

IPCC (2001b) *Climate Change 2001: Impacts, Adaptation, and Vulnerability. The IPCC Third Assessment Report, Working Group II report.* McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J. and White, K.S. (eds.) Cambridge University Press, Cambridge.

Isern, A.R., McKenzie, J.A. and Feary, D.A. (1996) The role of sea surface temperature as a control on carbonate platform development in the western Coral Sea. *Palaeogeography, Palaeoclimatology, Palaeoecology* 124: 247–272.

Jarman, S.J., Kantvilas, G. and Brown, M.J. (1988) *Buttongrass Moorlands in Tasmania*. Tasmanian Forestry Research Council Research Report No 2, Hobart, Tasmania.

Jenkins, D.W. (1971) Global biological monitoring. In: *Man's Impact on Terrestrial and Oceanic Ecosystems*. Matthews, W.H., Smith, F.E. and Goldberg, E.D. (eds.). The Colonial Press, USA, pp. 351–370.

Johns, C.V. and Hughes, L. (2002) Interactive effects of elevated CO_2 and temperature on the leaf-miner *Dialectica scalariella* Zeller (Lepidoptera: Gracillariidae) in Paterson's Curse, *Echium plantagineum* (Boraginaceae). *Global Change Biology* 8: 142–152.

Johnson, B. (1998) Consequences for the Macquarie Marshes. In: *Climate Change Scenarios and Managing the Scarce Water Resources of the Macquarie River.* Hassall & Associates (eds.) Australian Greenhouse Office, Canberra.

Johnson, C.R., Dunstan, P.K., Hoegh-Guldberg, O. (2002) *Predicting the Long Term Effects of Coral Bleaching and Climate Change on the Structure of Coral Communities.* World Bank-UNESCO Targeted Working Group on modeling climate change, Miami Florida, USA.

Jones, P.A. (1991) Historical records of cloud cover and climate for Australia. *Australian Meteorological Magazine* 39: 181–189.

Jones, P.D. (1995) Recent variations in mean temperature and the diurnal temperature range in the Antarctic. *Geophysical Research Letters* 22: 1345–1348.

Jones, R.J., Berkelmans, R. and Oliver, J.K. (1997) Recurrent bleaching of corals at Magnetic Island (Australia) relative to air and seawater temperature. *Marine Ecological Progress Series* 158: 289–292.

Jones, R.N. (2000) Managing uncertainty in climate change projections: issues for impact analysis—an editorial comment. *Climatic Change* 45: 403–419.

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

Keeling, C.D. and Whorf, T.P. (2002) Atmospheric CO_2 records from sites in the SIO air sampling network. In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Dept of Energy, Oak Ridge, Tennessee, USA.

Kershaw, A.P., Van der Kaars, S., Moss, P. and Wong, S. (2002) Quaternary records of vegetation, biomass burning, climate, and possible human impact in the Indonesian-northern Australian region. In: *Bridging Wallace's Line: The Environmental and Cultural History and Dynamics of the SE-Asian-Australian Region*. Kershaw, A.P., David, B., Tapper, N., Penny, D. and Brown, J. (eds.), Catena Verlag, Reiskirchen, pp. 97–118.

King, B., McAllister, F. and Done, T. (2002) *Modelling the Impact of the Burdekin, Herbert, Tully and Johnstone River Plumes on the Central Great Barrier Reef.* CRC Reef Research Centre Technical Report 44. Applied Science Associates and the Australian Institute of Marine Sciences. Available at http://www.reef.crc.org.au/publications/techreport/pdf/techrep_44_king.pdf.

Kirkpatrick, J.B., Bridle, K. and Lynch, A.J.J. (2002) Changes in vegetation and landforms at Hill One, Tasmania. *Australian Journal of Botany* 50: 753–759.

Kleypas, J.A., Buddemeier, R.W., Archer, D., Gattuso, J.P., Langdon, C. and Opdyke, B.N. (1999) Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science* 284: 118–120.

Knighton, A.D., Woodroffe, C.D. and Mills, K. (1992) The evolution of tidal creek networks, Mary River, Northern Australia. *Earth Surface Processes and Landforms* 17: 167–190.

Kokita, T. and Nakazono, A. (2001) Rapid response of an obligately corallivorous filefish *Oxymonacanthus longirostris* (Monacanthidae) to a mass coral bleaching event. *Coral Reefs* 20: 155–158.

Körner, C. (1999) *Alpine Plant Life*. Springer-Verlag, Berlin.

Latif, M., Kleeman, R. and Eckert, C. (1997) Greenhouse warming, decadal variability or El Niño—an attempt to understand the anomalous 1990s. *Journal of Climate* 10: 2221–2239.

Lavery, B.M., Young, G. and Nicholls, N. (1997) An extended high quality historical rainfall data set for Australia. *Australian Meteorological Magazine* 46: 27–38.

Lawlor, D.W. and Mitchell, R.A.C. (1991) The effects of increasing CO_2 on crop photosynthesis and productivity: a review of field studies. *Plant, Cell and Environment* 14: 807–818.

Leclerq, N., Gattuso, J-P. and Jaubert, J. (2002) Primary production, respiration and calcification of a coral reef mesocosm under increased CO_2 partial pressure. *Limnol. Oceanogr*. 47: 558–564.

Li, J.H., Dijkstra, P., Hymus, G.J., Wheeler, R.M., Piastuch, W.C., Hinkle, C.R. and Drake B.G. (2000) Leaf senescence of *Quercus myrtifolia* as affected by long-term CO_2 enrichment in its native environment. *Global Change Biology* 6: 727–733.

Lough, J.M. (1998) Coastal climate of northwest Australia and comparisons with the Great Barrier Reef: 1960 to 1992. *Coral Reefs* 17: 351–367.

Lough, J.M. (2000) 1997–98: Unprecedented thermal stress to coral reefs? *Geophysical Research Letters* 27: 3901–3904.

Lough, J.M. (in press) Weather on the Reef: AIMS' automatic weather station network. *Bulletin of the Australian Meteorological and Oceanographic Society*.

Lough J.M. and Barnes D.J. (1997) Several centuries of variation in skeletal extension, density and calcification in massive *Porites* colonies from the Great Barrier Reef: a proxy for seawater temperature and a background of variability against which to identify unnatural change. *Journal of Experimental Marine Biology and Ecology* 211: 29–67.

Mann, M., Bradley, R. and Hughest, M.K. (1998) Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* 392: 779–787.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C. (1997) A Pacific inter-decadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* 78: 1069–1079.

Martin, T.E. (2001) Abiotic vs biotic influences on habitat selection of coexisting species: climate change impacts? *Ecology* 82: 175–188.

McCarty, J. (2001) Ecological consequences of recent climate change. *Conservation Biology* 15: 320–331.

McGeoch, M.A. (1998) The selection, testing and application of terrestrial insects as bioindicators. *Biological Reviews of the Cambridge Philosophical Society* 73: 181–201.

McGuffie, K. and Henderson-Sellers, A. (1994) Cloudiness trends this century from surface observations. In: *Proceedings of the International Minimax Workshop, College Park, Maryland*. Kukla, G.T. and Riches, M. (eds.), US Department of Energy, Washington DC, pp. 231–234.

McKeon, G.M. and Hall, W.B. (2002) Can seasonal climate forecasting prevent land and pasture degradation of Australia's grazing lands? *QNR14 Technical Report for the Climate Variability in Agriculture Program*. Queensland Department of Natural Resources and Mines.

McKeon, G.M. and Howden, S.M. (1993) Adapting the management of Queensland's grazing systems to climate change. In: *Climate Change: Implications for Natural Resource Conservation*. Burgin, S. (ed.), University of Western Sydney, Hawkesbury, pp. 123–140.

McKeon, G.M., Hall, W.B., Crimp, S.J., Howden S.M., Stone, R.C. and Jones, D.A. (1998) Climate change in Queensland's grazing lands: I. approaches and climatic trends. *Rangeland Journal* 10: 151–176.

Millar, C.I. and Woolfenden, W.B. (1999) The role of climate change in interpreting historical variability. *Ecological Applications* 9: 1207–1216.

Mitchell, W., Chittleborough J., Ronai, B. and Lennon, G.W. (2000) Sea level rise in Australia and the Pacific. *Climate Change Newsletter* 12: 7–10.

Morgan, V.I., Wookey, C.W., Li, J., van Ommen, T.D., Skinner, W. and Fitzpatrick, M.F. (1997) Site information and initial results from deep ice drilling on Law Dome. *Journal of Glaciology* 43: 3–10.

Mulrennan, M.E. and Woodroffe, C.D. (1998) Saltwater intrusions into the coastal plains of the Lower Mary River, Northern Territory, Australia. *Journal of Environmental Management* 54: 169–188.

Nerem, R.S. (1995) Global sea level rise variations from TOPEX/POSEIDON altimeter data. *Science* 268: 708–710.

Newell, G., Griffioen, P. and Cheal, D. (2001) The potential effects of 'greenhouse' climate-warming scenarios upon selected Victorian plant species and vegetation communities. Internal Communication, Victoria Dept of Sustainability and Environment.

Nicholls, N. (1997) Increased Australian wheat yield to recent climate trends. *Nature* 387: 484–485.

Nicholls, N., Drosdowsky, W. and Lavery, B. (1997) Australian rainfall variability and change. *Weather* 52: 66–72.

Nicholls, N., Landsea, C. and Gill, J. (1998) Recent trends in Australian region tropical cyclone activity. *Meterological Atmospheric Physics* 65: 197–205.

Nicholls, N., Lavery, B., Frederiksen, C. and Drosdowsky, W. (1996) Recent apparent changes in relationships between the El-Nino and Australian rainfall and temperature. *Geophysical Research Letters* 23: 3357–3360.

Nix, H.A. and Switzer, M.A. (1991) *Rainforest Animals: Atlas of Vertebrates Endemic to the Wet Tropics.* Australian National Parks and Wildlife Service, Canberra, Australia.

Osborne, W.S., Davis, M.S. and Green, K. (1998) Temporal and spatial variation in snow cover. In: *Snow: A Natural History; An Uncertain Future.* Green, K. (ed.) Australian Alps Liaison Committee, Canberra, pp. 56–68.

Osborne, J.L., Awmack, C.S., Clark, S.J., Williams, I.H. and Mills, V.C. (1997) Nectar and flower production in *Vicia faba* L (field bean) at ambient and elevated carbon dioxide. *Apidologie* 28: 43–55.

Ostendorf, B., Hilbert, D.W. and Hopkins, M.S. (2001) The effect of climate change on tropical rainforest vegetation pattern. *Ecological Modelling* 145: 211–224.

Owensby, C.E., Ham, J.M., Knapp, A.K. and Auen, L.M. (1999) Biomass production and species composition change in a tall grass prairie ecosystem after long-term exposure to elevated atmospheric CO_2. *Global Change Biology* 5: 497–506.

Parmesan C.P. and Yohe G. (2003) A globally coherent fingerprint of climate change across natural systems. *Nature* 421: 37–42.

Peerderman, F.M., Davies, P.J. and Chivas, A.R. (1993) The stable oxygen isotope signal in shallow-water, upper-slope sediments off the Great Barrier Reef (Hole 820A). *Proceedings of the Ocean Drilling Program Scientific Results* 133: 163–173.

Peltier, W.R. and Tushingham, A.M. (1989) Global sea level rise and the greenhouse effect: might they be connected? *Science (USA)* 244: 806–810.

Peñuelas, J. and Azcon-Bieto, J. (1992) Changes in leaf ^{13}C of herbarium plant species during the last three centuries of CO_2 increase. *Plant, Cell and Environment* 15: 485–489.

Peñuelas, J. and Matamala, R. (1990) Changes in N and S leaf content, stomatal density and specific leaf area of 14 plant species during the last three centuries of CO_2 increase. *Journal of Experimental Botany* 41: 1119–1124.

Pickup, G. and Stafford Smith, M. (1993) Problems, prospects and procedures for assessing the sustainability of pastoral land management in arid Australia. *Journal of Biogeography* 20: 471–487.

Pittock, A.B. (1999) Coral reefs and environmental change: Adaptation to what? *American Zoologist* 39: 10–29.

Plummer, N., Lin, Z. and Torok, S. (1995) Trends in the diurnal temperature range over Australia since 1951. *Atmospheric Research* 37: 79–86.

Pouliquen-Young, O. and Newman, P. (2000) *The Implications of Climate Change for Land-based Nature Conservation Strategies.* Final Report 96/1306. Australian Greenhouse Office, Environment Australia, Canberra, and Institute for Sustainability and Technology Policy, Murdoch Unviersity, Perth.

Power, S., Tseitkin, F., Vikram, M., Lavery, B., Torok, S., Holbrook, N. and Mehta, V. (1999) Decadal climate variability in Australia during the twentieth century. *International Journal of Climatology* 19: 169–184.

Prabhakara, C., Iacovazzi, R., Yoo, J.M. and Dalu, G. (1998) Global warming deduced from MSU. *Geophysical Research Letters* 25: 1927–1930.

Prentice, I.C. and Solomon, A.M. (1991) Vegetation models and global change. In: *Global Changes of the Past.* Bradley, R.S. (ed.), UCAR Office for Interdisciplinary Earth Studies, Boulder, CO, pp. 365–383.

Pressey, R.L. and Taffs, K.H. (2001) Sampling of land types by protected areas; three measures of effectiveness applied to western New South Wales. *Biological Conservation* 101: 105–117.

Pritchard, S.G., Rogers, H.H., Prior, S.A. and Peterson, C.M. (1999) Elevated CO_2 and plant structure: a review. *Global Change Biology* 5: 807–837.

Quayle, R.G. and Karl, T.R. (1996) *Climate Change Update; The State of the Climate—1996; A Summary of the 1995 Policymakers Report of the IPCC.* National Climatic Data Centre, Asheville, North Carolina.

Read, J. and Hill, R.S. (1985) Dynamics of *Nothofagus* dominated rainforest on mainland Australia and lowland Tasmania. *Vegetation* 63: 67–78.

Reed, D.C., Raimondi, P.T., Carr, M.H. and Goldwasser, L. (2000) The role of dispersal and disturbance in determining spatial heterogeneity in sedentary organisms. *Ecology* 81: 2011–2026.

Rex, M., Harris, N.R.P., Vondergthen, P., Lehmann, R., Braathen, G.O., Reimer, E., Beck, A., Chipperfield, M.P., Alfier, R., Allaart, M., Oconnor, F., Dier, H., Dorokhov, V., Fast, H., Gil, M., Kyro, E., Litynska, Z., Mikkelsen, I.S., Molyneux, M.G., Nakane, H., Notholt, J., Rummukaien, M., Viatte, P. and Wenger, J. (1997) Prolonged stratospheric ozone loss in the 1995–96 Arctic winter. *Nature* 389: 835–838.

Rochefort, L. and Woodward, F.I. (1992) Effect of climate change and a doubling of CO_2 on vegetation diversity. *Journal of Experimental Botany* 43: 1169–1180.

Roderick, M.L. and Berry, S.L. (2001) Linking wood density, tree growth and environment: a theoretical analysis based on the motion of water. *New Phytologist* 149: 473–485.

Roderick, M.L., Berry, S.L. and Noble, I.R. (1999) The relationship between leaf composition and morphology at elevated CO_2. *New Phytologist* 143: 63–72.

Rogers, H.H., Runion, G.B. and Krupa, S.V. (1994) Plant responses to atmospheric CO_2 enrichment with emphasis on roots and the rhizosphere. *Environmental Pollution* 83: 155–189.

Root, T.L, Price, J.T., Hall, K.R., Schneider, S.H., Rosenzweig, C. and Pounds, J.A. (2003) Fingerprints of global warming on wild animals and plants. *Nature* 421: 57–60.

Roshier, D.A., Whetton, P.H., Allan, R.J. and Robertson, A.I. (2001) Distribution and persistence of temporary wetland habitats in arid Australia in relation to climate. *Australian Ecology* 26: 371–384.

Rozema, J., Van de Staaij, J., Bjorn, L.O. and Caldwell, M. (1997) UV-B as an environmental factor in plant life: stress and regulation. *Trends in Ecology Evolution* 12: 22–28.

Sahagian, D.L., Schwartz, F.W. and Jacobs, D.K. (1994) Direct anthropogenic contributions to sea-level rise in the 20th century. *Nature* 367: 54–57.

Saintilan, N. and Williams, R.J. (1999) Mangrove transgression into saltmarsh environments. *Global Ecology and Biogeography* 8: 117–124.

Salawitch, R.J. (1998) A greenhouse warning connection. *Nature* 392: 551–552.

Salinger, M.J. and Griffiths, G.M. (2001) Trends in New Zealand daily temperature and rainfall extremes. *International Journal of Climatology* 21: 1437–1452.

Salinger, M.J., Allan, R., Bindoff, N., Hannah, J., Lavery, B., Lin, Z., Lindesay, J., Nicholls, N., Plummer, N. and Torok, S. (1996) Observed variability and change in climate and sea level in Australia, New Zealand and the South Pacific. In: *Greenhouse: Coping with Change.* Bouma, W.J., Pearman, G.I. and Manning, M.R. (eds), CSIRO, Collingwood, Australia, pp. 100–126.

Scherrer, P. and Pickering, C. (2001) Effects of grazing, tourism and climate change on the alpine vegetation of Kosciuszko National Park. *Victorian Naturalist* 118: 93–99.

Shindell, D.T., Rind, D. and Lonergan, P. (1998) Increased polar stratospheric ozone losses and delayed eventual recovery owing to increasing greenhouse-gas concentrations. *Nature* 392: 589–592.

Skirving, W., Mahoney, M. and Steinberg, C. (2002) *Sea Surface Temperatures Atlas of the Great Barrier Reef 1990–2000.* Available on CD-ROM from the Australian Institute of Marine Science or by emailing m.mahoney@aims.gov.au.

Skvarca, P. (1993) Fast recession of the northern Larsen Ice Shelf monitored by satellite images. *Annals of Glaciology* 17: 317–321.

Spalding, M. and Jarvis, G.E. (2002) The impact of the 1998 coral mortality on reef fish communities in the Seychelles. *Marine Pollution Bulletin* 44: 309–321.

Specht, R.L. (1972) Water use by perennial evergreen plant communities in Australia and Papua New Guinea. *Australian Journal of Botany* 20: 273–299.

Specht, R.L. (1981) Ecophysiological principles determining the biogeography of major vegetation formations in Australia. In: *Ecological Biogeography of Australia.* Keast, A. (ed.). W. Junk, The Hague, pp. 301–333.

Spellerberg, I.F. (1991) *Monitoring Ecological Change.* Cambridge University Press, Cambridge.

Stafford Smith, M. and Morton, S. (1990) A framework for the ecology of arid Australia. *Journal of Arid Environments* 18: 255–278.

Stone, R., Nicholls, N. and Hammer, G. (1996) Frost in northeast Australia: trends and influences of phases of the southern oscillation. *Journal of Climate* 9: 1896–1909.

Suppiah, R. and Hennessy, K.J. (1996) Trends in the intensity and frequency of heavy rainfall in tropical Australia and links with the Southern Oscillation. *Australian Meteorological Magazine* 45: 1–17.

Suppiah, R. and Hennessy, K.J. (1997) Trends in total rainfall, heavy rainfall events and number of dry days in Australia, 1910–1990. *International Journal of Climatology* 18: 1141–1164.

Sweatman, H., Cheal, A., Coleman, G., Delean, S., Fitzpatrick, B., Miller, I., Ninio, R., Osborne, K., Page, C. and Thompson, A. (2001) *Long-term Monitoring of the Great Barrier Reef. Status Report Number 5, 2001.* Australian Institute of Marine Science, 106 pp.

Swetnam, T.W., Allen, C.D. and Betancourt, J.L. (1999) Applied historical ecology: using the past to manage for the future. *Ecological Applications* 9: 1189–1206.

Theurillat, J.P. and Guisan, A. (2001) Potential impact of climate change on vegetation in the European Alps: a review. *Climate Change* 50: 77–109.

Tidemann, C.R. (1999) Biology and management of the grey-headed flying fox, *Pteropus poliocephalus. Acta Chiropterol* 1: 151–164.

Tongway, D. (1994) *Rangeland Soil Condition Assessment Manual*. CSIRO Division of Wildlife and Ecology, Australia. 69 pp.

Tongway, D. and Hindley, N. (1995). *Manual for Assessment of Soil Condition for Tropical Grasslands*. CSIRO Division of Wildlife and Ecology, Australia. 60 pp.

Torok, S.J. and Nicholls, N. (1996) A historical annual temperature data set for Australia. *Australian Meteorological Magazine* 45: 251–260.

Trench, R.K. (1979) The cell biology of plant–animal symbiosis. *Annual Review of Plant Physiology* 30: 485–531.

Trenberth, K.E. and Hoar, T.J. (1996) The 1990–1995 El Nino Southern Oscillation event: longest on record. *Geophysical Research Letters* 23: 57–60.

Trenberth, K.E. and Hoar, T.J. (1997) El Nino and climate change. *Geophysical Research Letters* 24: 3057–3060.

Vaughan, D. and Lachlan-Cope T. (1996) Recent retreat of ice shelves on the Antarctic Peninsula. *Weather* 50: 374–376.

Wahren, C.H., Papst, W.A. and Williams, R.J. (1994) Long-term vegetation change in relation to cattle grazing in subalpine grassland and heathland on the Bogong High Plains: an analysis of vegetation records from 1945 to 1994. *Australian Journal of Botany* 42: 607–639.

Walker, J. (1998) Malaria in a changing world—an Australian perspective. *International Journal for Parasitology* 28: 947–953.

Walter, M. and Broome, L. (1998) Snow as a factor in animal hibernation and dormancy. In *Global Threats to the Australian Snow Country*. Abstract of a paper presented at the Global Threats to the Australian Snow Country gathering, 17–19 February 2001 at Jindabyne, NSW. Australian Institute of Alpine Studies newsletter 1, http://www.aias.org.au/newsletters/newsletter1.htm#snow.

Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.R., Hoegh-Guldberg, O. and Bairlein, O. (2002) Ecological responses to recent climate change. *Nature* 416: 389–395.

Watkins, A.B. (2001) Seasonal climate summary southern hemisphere (Spring 2000): a third successive positive phase of the Southern Oscillation begins. *Australian Meteorological Magazine* 50: 295–308.

Watson, I. and Thomas, P. (2003) Monitoring shows improvement in Gascoyne–Murchison rangelands. *Range Management Newsletter* 03/1, 11–14.

Watson, I., Blood, D., Novelly, P., Thomas, P. and Van Vreeswyk, S. (2001) *Rangeland Monitoring, Resource Inventory, Condition Assessment and Lease Inspection Activities in Western Australia Conducted by the Department of Agriculture*. Report prepared for the National Land and Water Resources Audit, Canberra. http://audit.ea.gov.au/anra/.

Wearne, L.J. and Morgan, J.W. (2001) Recent forest encroachment into subalpine grasslands near Mount Hotham, Victoria, Australia. *Arctic Antarctic and Alpine Research* 33: 369–377.

Wentz, F.J. and Schabel, M. (1998) Effects of orbital decay on satellite-derived lower-tropospheric temperature trends. *Nature* 394: 661–664.

Westoby, M. (1991) On long-term ecological research in Australia. In: *Long-term Ecological Research.* Risser, P. (ed.) SCOPE, John Wiley and Sons, pp. 191–209.

Whetton, P. (1998) Climate change impacts on the spatial extent of snow-cover in the Australian Alps. In *Snow: A Natural History; an Uncertain Future.* Green, K. (ed.) Australian Alps Liaison Committee, Canberra, pp. 195–206.

White, W.B., Cayan, D.R. and Lean, J. (1998) Global upper ocean heat storage response to radiative forcing from changing solar irradiance and increasing greenhouse gas/aerosol concentrations. *Journal of Geophysical Research—Oceans* 103: 21355–21366.

Whitehead, P. (2000) A review of changes in the status of threatening processes. *Report to the National Land and Water Resources Audit by the Tropical Savannas CRC.* Darwin, pp. B1-125 to B1-324.

Wilkinson, C.R. (1996) Global change and coral reefs: impacts on reefs, economies and human cultures. *Global Change Biology* 2: 547–558.

Wilkinson, C.R. and Buddemeier, R.W. (1994) *Global Climate Change and Coral Reefs: Implications for People and Reefs.* Report of the UNEP-IOC-ASPEI-IUCN Global Task Team on the Implications of Climate Change on Coral Reefs. IUCN, Gland, Switzerland, 124 pp.

Williams R.J. and Costin A.B. (1994) Alpine and subalpine vegetation. In: *Australian Vegetation.* Groves, R.H. (ed.) Cambridge University Press, Cambridge.

Williams, S.E. and Hero, J.M. (2001) Multiple determinants of Australian tropical frog biodiversity. *Biological Conservation* 68: 1–10.

Williams, S.E. and Pearson, R.G. (1997) Historical rainforest contractions, localised extinctions and patterns of vertebrate endemism in the rainforests of Australia's Wet Tropics. *Proceedings of the Royal Society of London B* 264: 709–716.

Williams, S.E., Marsh, H. and Winter, J. (2002) Spatial scale, species diversity and habitat structure: small mammals in Australian tropical rainforest. *Ecology* 83: 1317–1329.

Williams, S.E., Pearson, R.G. and Walsh, P.J. (1996) Distributions and biodiversity of the terrestrial vertebrates of Australia's Wet Tropics: a review of current knowledge. *Pacific Conservation Biology* 4: 327–362.

Winter, J.W. (1988) Ecological specialization of mammals in Australian tropical and sub-tropical rainforest: refugial and ecological determinism. In: *The Ecology of Australia's Wet Tropics*. Kitching, R. (ed.). Surrey Beatty, Sydney.

Woinarski, J. (2000) A review of changes in the status and threatening processes. *Report to the National Land and Water Resources Audit by the Tropical Savannas CRC.* Darwin, pp. B1-125 to B1-126.

Woodroffe, C.D. and Mulrennan, M.E. (1993) *Geomorphology of the Lower Mary River Plains, Northern Territory.* Australian National University and the Conservation Commission of the Northern Territory, Darwin.

Woodroffe, C.D., Chappell, J.M.A., Thom, B.G. and Wallensky, E. (1986) *Geomorphological Dynamics and Evolution of the South Alligator Tidal River and Plains, Northern Territory.* North Australia Research Unit, Darwin.

Wright, W.J., de Hoedt, G., Plummer, N., Jones, D.A. and Chitty, S. (1996) Low frequency climate variability over Australia. *The Second Australian Conference on Agricultural Meteorology*, 1–4 October 1996, University of Queensland. University of Queensland Printer, Brisbane.

Zheng, X., Basher, R.E. and Thompson, C.S. (1997) Trend detection in regional-mean temperature: maximum, minimum, mean temperature, diurnal range and SST. *Journal of Climate* 10: 317–326.

Ziska, L.H. and Caulfield, F.A. (2000) Rising CO_2 and pollen production of common ragweed (*Ambrosia artemisiifolia*), a known allergy-inducing species: implications for public health. *Australian Journal of Plant Physiology* 27: 893–898.

Zuo, Z. and Oerlemans, J. (1997) Contribution of glacier melt to sea-level rise since 1865—a regionally differentiated calculation. *Climate Dynamics* 13: 835–845.

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