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The implications of climate change for biodiversity conservation and the National Reserve System: Final synthesis

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Executive Summary

Protected areas are a crucial component of strategies for conserving biodiversity; however, their selection and design are usually not informed about the impacts of climate change. To inform future management of protected areas in Australia under climate change scenarios, this project produced the first Australia-wide, assessment of the magnitude of ecological impact that climate change could have on biodiversity, using three state-of-the-art quantitative techniques. These analyses were then used in detailed ecological assessments of climate impacts and adaptation options in four major biomes—Hummock grasslands; Tropical savanna woodlands and grasslands; Temperate grasslands and grassy woodlands; and Sclerophyll forests of south-eastern Australia—using existing literature and technical information, as well as workshops that elicited local knowledge and concerns.

Spatial modelling approaches

The project assessed the significance of future climatic change for biodiversity in two scenarios (medium impact and high impact) and in two time frames (2030 and 2070) by running three different spatial analyses across multiple environmental layers and various types of biological information. Artificial Neural Networks (ANN) were used to classify current environments by vegetation classes (largely structural), and then this classification was applied to future environments. Generalised Dissimilarity Modelling (GDM) was used to estimate the sensitivity of species composition of communities to environmental variation. A Bayesian Belief Network (BBN) was used to incorporate observed and expert information to assess changes in suitability of environmental conditions for the alien invasive species buffel grass.

These analyses provide an index of “biotically scaled environmental stress”. By *stress* we mean a force likely to lead to aggregate change from the current state of biodiversity. By *biotically scaled* we mean that environmental variables have been weighted according to their relative importance for Australian biodiversity. The most important feature of this interpretation is that it describes change in the *environment* (the external drivers of ecological change), not the amount or type of change in *biodiversity* in response. Thus, these measures are free of many of the ecological assumptions—often implicit—that apply to most predictions of biodiversity impacts.

Environmental and ecological change

The project predicts dramatic environmental change due to climate change: these changes will be ecologically very significant, and will result in many novel environments quite unlike those currently occurring anywhere on the continent, and the disappearance of many environments currently occupied by Australian biodiversity. While biodiversity impacts from these changed environments may be buffered when species exploit natural variation in the environment, our results suggest that the magnitude of change will overcome these buffering effects by 2070. Changing temperature, moisture availability and fire regimes are likely to lead to changes in vegetation structure, and it is likely there will be a gradual turnover of species along vegetation-structure gradients. Historical habitat loss and fragmentation due to land clearing will exacerbate the impacts of climate change; land-use intensification, as a response to climate change in agricultural and forestry sectors, remains a major threat to biodiversity. Increases in fire weather across much of Australia are very likely, which could have significant impacts on composition, structure, habitat heterogeneity and ecosystem processes. Expansion of alien species capable of altering fire regimes (e.g. buffel grass) is likely, and changes in the interactions between species could be as important to ecological outcomes as geographic shifts in suitable environment. Changes in climate variability, as well as averages, could be important drivers of altered species interactions.

Adapting to climate change

Climate change is a fundamentally different biodiversity threat in its geographic extent, magnitude and speed of potential changes. It poses a significant challenge for conservation scientists and practitioners at a time when the science of climate change impacts is still developing and there is little certainty of the details of change. Our results suggest that we will need to examine the threat to a range of biodiversity values, then derive conservation objectives and programs that preserve ecological *processes* while allowing or even facilitating changes in biodiversity *states*. We need to increase the *efficiency* of limited conservation resources by focusing investment on those places or species that achieve the "greatest marginal loss avoided", but do this using robust strategy that are effective under a wide range of future magnitudes and types of change, and for a wide range of species.

The most appropriate local scale management response to the predicted high level of biotically scaled environmental stress will vary between regions. However, the project showed that the strategy underpinning the NRS is likely to be highly robust in the face of significant environmental change. Some expansion of the NRS may be needed to help biodiversity respond to the changing distributions of biotically scaled environments across the continent.

Iterative changes to management will allow a staged approach to adapting to high levels of future environmental change. A first step could be to focus on understanding the implications of different changes that might occur for different areas of conservation planning, and mainstreaming climate change into planning, rather than treating it as a separate threat to manage. The second phase would focus on conservation objectives, understanding that the choice between *encouraging* change, *managing* change, passively *allowing* change, or actively *minimising* change will affect management of protected areas. The third stage is to use information from the first two stages to revise management strategies and adaption pathways across a series of plans of management.

Key knowledge gaps

The science of biodiversity impacts is developing rapidly in Australia and internationally but biodiversity managers are now working with high levels of uncertainty. This project identified that a new discipline of climate change biogeography, which attempts to integrate the disparate approaches and information about climate change impacts, is needed. We will also need to have informed debate in science, policy and public domains about the social values associated with biodiversity, to develop suitable conservation objectives. This will require more information about region-specific impacts and their implications, and about landscape processes and features that facilitate persistence and adaptability of biodiversity. A richer body of science-policy knowledge is required to enable managers to determine and seek the information that will be useful to them, and to help researchers develop analysis tools and monitoring. Managers will also need more knowledge and tools to help them balance worthy but competing demands. Finally, we will need more understanding and better tools to help us deal with uncertainty.

Conclusions and implications for the NRS

This project showed that climate change is likely to lead to very significant and widespread ecological impacts. Although spatial environmental heterogeneity may help buffer the impact for some species, the buffering will vary regionally. There will be many threats to biodiversity, including alien species, altered fire regimes, and human uses of land and water due to adaptation in other sectors. As a result, we will need to reassess our conservation objectives, understanding that biodiversity and our biodiversity values will change. We will also need to consider regional social and ecological factors when developing management approaches, and these approaches will need to be robust in the face of high levels of uncertainty. The NRS is such a robust strategy, maintaining representativeness even in the face of climate change, but management of protected areas and landscapes will need to be adapted and revised over time. Gaps in science, management and policy knowledge and tools were identified, which will help direct management and research development.

1. Introduction

Observations and modelling reported over the last decade provide compelling evidence that the impacts of climate change on the world's biodiversity are likely to be significant. Many impacts have already been observed (Hughes 2000; McCarty 2001; Parmesan and Yohe 2003; Root *et al*. 2003; Walther *et al*. 2002), and many studies have modelled various potential impacts on biodiversity over the remainder of this century and concluded that widespread impacts can be expected for a large fraction of the world's terrestrial species, including a significant fraction likely to become "committed to extinction" during this time (e.g. Thomas *et al*. 2004).

Protected areas comprise approximately 12% of the Earth's terrestrial surface and are a crucial component of strategy for conserving biodiversity and supporting ecological processes beneficial to human well-being. However, their selection and design have usually not been informed by considerations of future global change (Lee and Jetz 2008). Studies on the impacts of climate change on protected areas (Halpin 1997; Rutherford *et al*. 1999; Scott *et al*. 2002; Tellez-Valdes and Davila-Aranda 2003) suggest that climate change will affect the ability of systems of protected areas to conserve biodiversity. While the impacts are potentially significant and there are many uncertainties about the specifics of climate impacts, there are a variety of strategies that can be taken to increase the effectiveness of biodiversity conservation programs under climate change (Dunlop and Brown 2008; Steffen *et al*. 2009).

The report from a workshop held in 2002, Climate Change Impacts on Biodiversity in Australia (Howden *et al*. 2003) contributed to the development of the National Biodiversity and Climate Change Action Plan. One of the goals of this action plan is to develop a "nationwide strategic approach to protect Australia's biodiversity from the impacts of climate change". The report from a subsequent workshop to identify research and management priorities with respect to climate change and biodiversity identified the priority "Develop mechanisms for factoring climate change into conservation planning, including the design of reserve systems, protected areas and off-reserve ecosystem management to accommodate future habitat requirements for species under climate change" (Hilbert *et al*. 2007). The National Reserve System (NRS) is a key element in protecting Australia's biodiversity and its ability to do so in the face of climate change was recently assessed in the report *Impacts of Climate Change for Australia's National Reserve System – A Preliminary Assessment* (Dunlop and Brown 2008).

This recent, preliminary analysis of the implications of climate change for the Australian NRS reported that the strategy of systematically protecting a diversity of habitats is robust and even more important for conservation under climate change, and that the bioregional framework adopted at a national level (i.e. the criteria of comprehensiveness and representativeness in combination with biogeographic regionalisation) is well suited to implementing this strategy.[1] However, the report did identify considerable differences between regions in the threats posed by existing pressures and climate change and the types of changes that might be experienced. The report also highlighted the need for analyses with more detailed regional-scale information to better inform reserve development and conservation management priorities. In particular, regional information is required to identify biomes likely to experience considerable or more rapid change, regions with inherently greater likelihood of species naturally adapting to climate change, and threats that are likely to be most important in different regions.

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[1] There are, however, significant gaps in the current implementation of the strategy (Ferrier *et al*. 2012; see also Figure 15).

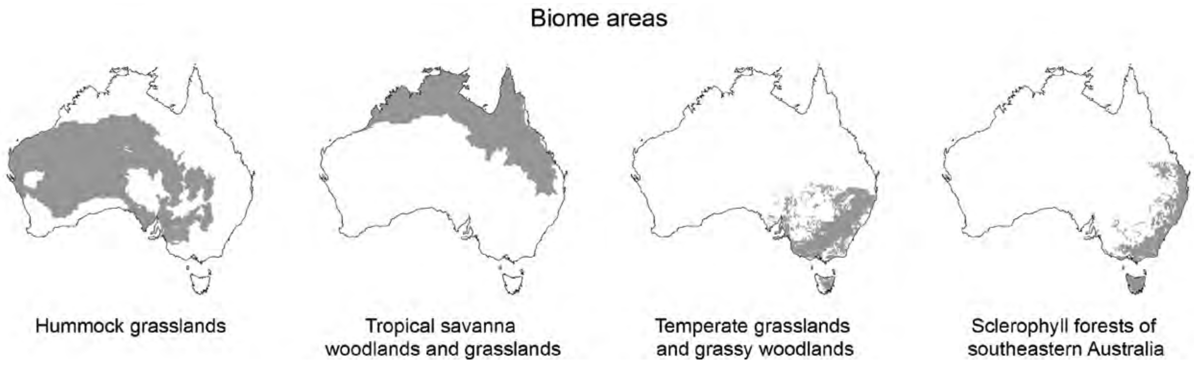
2. This project

The overall objective of this project was to provide information to assist Australian biodiversity policymakers and managers adapt to the realities of multiple and considerable impacts of climate change through regional management, planning for the development of the NRS, and the evolution of conservation policy. The project built upon the analyses, lessons and outcomes of the preliminary national assessment (Dunlop and Brown 2008) by focusing on ecosystem-level impacts and implications in four biomes (Figure 1): Hummock grasslands, Tropical savanna woodlands and grasslands (henceforth, savannas), Temperate grasslands and grassy woodlands (temperate grassy ecosystems) and Sclerophyll forests of south-eastern Australia (sclerophyll forests). This project incorporated information from regional and biome experts and undertook new impact modelling at continental and regional scales, as the project was focused on the implications of climate change for the NRS *in a landscape context*. We examined environmental and ecological changes and the issues for biodiversity regardless of tenure, then focused on how these might affect the NRS or how the NRS could contribute to management of these issues in the broader landscape.

The five main project activities were:

1. four biome-specific reviews of baseline information and the potential impacts of climate change on ecosystems within each biome, based on existing literature and workshops that elicit local knowledge and concerns, and collation of existing technical information about potential environmental and ecosystem changes.
2. quantitative modelling analyses of the potential ecological significance of climate change at the continental scale, using novel applications of two complementary biodiversity modelling techniques; novel modelling analysis of the potential impact of climate change on the distribution of an alien exotic species; four supporting technical reports are available that describe in detail the modelling methodologies, including our downscaling of climate model outputs to a 1 km^2 resolution for the entire continent
3. biome synthesis report for each biome integrating activities 1 and 2, with qualitative analyses of the implications of climate change for conservation in the biome and the NRS in particular
4. final synthesis report that draws on the ecological analyses in the biomes and the quantitative continental modelling to highlight and discuss key issues about climate change adaptation, biodiversity and the NRS
5. implications for policymakers developed through subsequent consultative processes, particularly addressing the communication challenges in translating technical material into succinct and credible “policy ready” format.

Figure 1. Maps of the four biomes studied in the project.



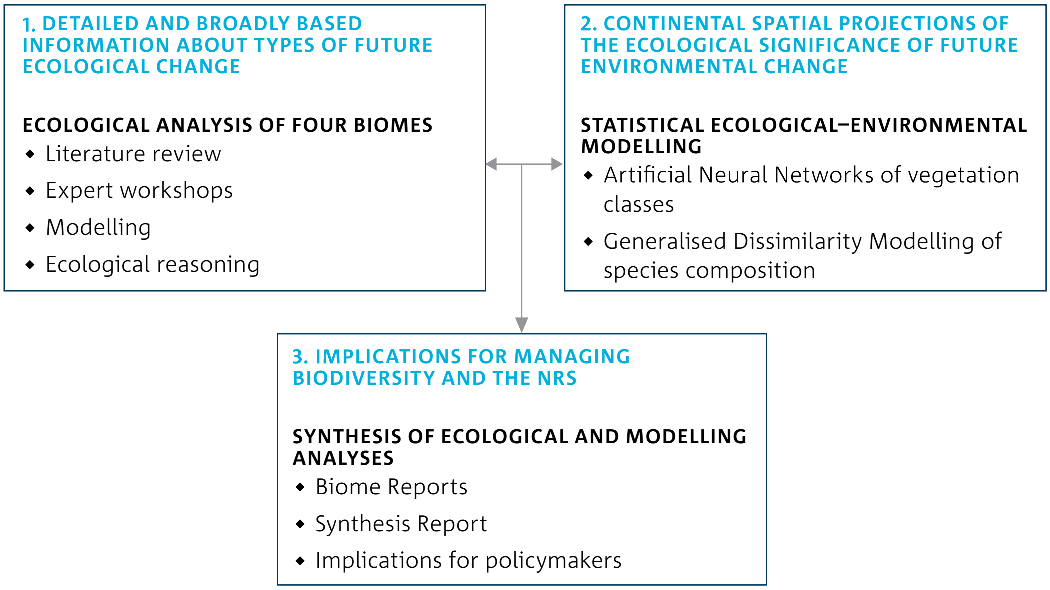
2.1 The project's framework

This project sought to provide information and insights about adaptation, that is, how to make policy and management decisions that will be effective in the face of climate change. The analysis of adaptation is underpinned by information about the possible impacts of climate change on biodiversity. Dunlop and Brown (2008) argued that it is important to base adaptation on an understanding of the full range of possible ecological responses to climate change, as opposed to focusing on a single change phenomenon. The problem is that, for most of the possible types of ecological responses to climate change, there is almost no information about the quantity of change that might be expected for the vast majority of species, ecosystems or regions. (This was a constraint of the first phase of this project, reported in Dunlop and Brown 2008). As a result, many of the international analyses of impacts and adaptation for biodiversity rely heavily on quantitative analyses of regional-scale shifts in species distributions. While these analyses are intuitive, readily available and spatially detailed, there is a wide range of uncertainties about the projection of species distributions (Pearson and Dawson 2003; Elith & Leathwick 2009; Sinclair *et al*. 2010), and such analyses are necessarily narrow in the scale and scope of ecological impacts and species they assess.

To address these constraints and make the insights about adaptation in this report as robust as possible, the project adopted a framework of using both information about a wide range of possible ecological impacts *and* spatial information about the quantity of change that might be expected (Figure 2).

1. Qualitative information about the *types of ecological changes* that might be experienced by species and ecosystems was drawn together and assessed using literature reviews and expert workshops focusing on the detail on the four biomes. This was augmented with quantitative analysis of the potential impact of climate change on the distribution of a widespread alien invasive species. This broadly based information provided an indication of the types of changes that managers and policymakers may need to respond to, but little indication of the magnitude of the challenge.
2. Quantitative information about the *magnitude of environmental change* across the whole continent was obtained from novel applications of two complementary ecological modelling techniques that each provides a broad index of the ecological significance of future environmental change. Each of the models was run with two climate change scenarios, essentially representing current emissions trajectory and optimistic emissions mitigation. The models both provide information about the possible magnitude of future change and the nature of its spatial variation at various scales, but they do not predict the ecological detail of that change.

Figure 2. The framework for the analysis in the project.



The methods of the ecological analyses of the biomes and the modelling are summarised in the following sections, and their results are described in detail in separate reports. This synthesis report draws on all of the analyses to highlight and discuss a series of issues potentially affecting the management of biodiversity and the NRS under climate change. While the modelling is quantitative and has a high degree of spatial detail, most of the conclusions drawn from it are based only on broad trends and on the existence of spatial variation, rather than specific predictions or local patterns. This minimises the sensitivity of the conclusions to the inherent uncertainty in any modelling and choice of environmental change scenarios.

2.2 Methods: biome analyses

The ecological assessments conducted by this project identified and explored a wide range of possible future impacts on species and ecosystems in four biomes. These are detailed in separate reports for the Hummock grasslands (Smyth *et al.* 2012), the Tropical savanna woodlands and grasslands (Liedloff *et al*. 2012), the Temperate grasslands and grassy woodlands (Prober *et al*. 2012) and the Sclerophyll forests of South-eastern Australia (House *et al*. 2012). These assessments used a combination of literature reviews, expert and stakeholder workshops, the modelling results and ecological synthesis. The assessment for each biome covered key ecological processes that make the biome distinctive, current conservation issues, how climate change may affect ecological processes and key species, and the implications of this for future management of biodiversity and the NRS in the biome. Workshop participation is outlined in Appendix 1. Brief summaries of the biome assessments are provided in Appendix 3.

2.3 Methods: continental modelling of environmental change

2.3.1 BIOTICALLY SCALED ENVIRONMENTAL STRESS

For this project we sought a method of transforming spatial projections of climate change derived from climate models into information that is more meaningful to those concerned with biodiversity and useful for informing policy and management at broad scales. In particular, the task was to translate scenarios of sets of modelled climate variables into a single measure reflecting the significance of future environmental change for biodiversity as it is distributed now. The goal of this transformation, or scaling, was to provide an index of the potential for future environmental change to drive ecological change. Such a scaling is complex because local environments are highly multidimensional, including many climate, soil and hydrological variables that are important for biodiversity, and biodiversity itself is multidimensional and will respond in complex ways to a changing environment.

We developed two methods for quantifying and projecting an index of the ecological significance of environmental change, each derived from analysis of the observed spatial relationship, over the continent, between a broad descriptor of biodiversity and a set of environmental variables. Artificial Neural Networks (ANN) were used to analyse vegetation classes, and Generalised Dissimilarity Modelling (GDM) was used to analyse patterns of species composition in broad taxonomic groups. Vegetation classes and species composition are well-known and -understood descriptors of biodiversity. While subject to some imprecision due to the variation in the definitions of classes and sampling effort, they both show strong and well-understood patterns across the continent, as well as at regional and local scales, reflecting altitudinal and climatic gradients as well as other spatial environmental variation. The two methods are conceptually similar in that they use these observed spatial relationships to calibrate models that scale multiple environmental variables and combine them into a single index for comparing contemporary environments between locations, with 0 corresponding to no ecologically significant environmental variation between locations, and 1, corresponding to environments that are so different there is no overlap in biodiversity.

The models were then run using climate variables from climate change scenarios to provide an index of the ecological significance of future climatic change at each location. We described this index as “biotically scaled environmental stress” since, while it does not predict how much change in biodiversity will occur, it provides an indication of the potential or force driving ecological change from the current state, analogous to a physical force that might contribute to the deformation or displacement of a physical object, subject to other intrinsic and extrinsic factors. (It is less similar to physiological stress, which applies to individual organisms and is not necessarily zero in the absence of climate change.) Spatial processing of the model outputs also allows analysis of novel and disappearing environments and the extent to which local environmental variability may provide buffering against environmental change.

While conceptually similar, the two methods use different modelling approaches and techniques to project future stress, largely due to the different nature of the biological descriptors being used; they also differed slightly in the choice of environmental variables. Below we describe, with simplified examples, the calculation of the two indices; in Section 2.3.5 we discuss interpretation, limitations and advantages of the indices.

2.3.2 CALCULATING BIOTICALLY SCALED ENVIRONMENTAL STRESS WITH ANN

The ANN method is a non-linear, multivariate classification of environments over all of Australia using the best available mapping of pre-European continental vegetation (pre-clearing major vegetation groups of the National Vegetation Information System, DEWR 2007) and maps of numerous environmental variables, including climate, soil and topographic variables. This method and its utility for climate impacts assessments is well documented by a number of publications (Hilbert and van den Muyzenberg 1999; Hilbert and Ostendorf 2001; Hilbert *et al*. 2001; Hilbert *et al*. 2007; Ostendorf *et al*. 2001), although this is the first time it has been applied for all of Australia. The classification estimates the suitability of the local environment for each of the 23 mapped vegetation classes at all locations. Figure 3 illustrates a hypothetical, small region that has three distinct vegetation types (V1, V2 and V3); a large number of environmental variables are known or estimated across the region, and there is an environmental gradient in mean annual temperature (T) across a transect such that T increases linearly along it from the south-west to the north-east.

For each location, the ANN classification estimates the suitability of the environment for all mapped vegetation classes using all the environmental inputs. In the figure, the curves in (A) simplify this in order to illustrate how the suitability for each class varies with temperature along a transect through the area in the current climate. Note that the suitability for each vegetation class responds non-linearly to the smooth environmental gradient and that, at many parts of the gradient, several vegetation types can have positive or even equal suitability. The output can be used to classify locations based on the largest suitability value as giving environments most suited to a specific vegetation class: in this case V1, V2 and V3. We mapped the vegetation environmental classes for all of Australia in this way, using all the spatial environmental variables and all the suitabilities of all vegetation classes.

Applying spatial climate change data changes the spatial suitability values, illustrated for the transect, by the curves in part B of Figure 3. Here, a constant increase in mean annual temperature across the transect essentially shifts the suitability curves toward the left, or south-west. Note that the suitability curves do not change, because these were defined by the ANN classification using the current climate and we do not expect them to change. Using this output to classify locations results in less of V1, the appearance of a new class (V4) and a spatial shift in V2 and V3 along the spatial transect. Using all the environmental data and all the suitability values for each vegetation class, we mapped the location of classified environmental types everywhere in Australia. Some locations will retain their suitability for the type of vegetation that is now there, while some will become more suitable to a new vegetation structure. Some of these transitions are illustrated in Figure 6. This is useful because it gives an indication of the possible direction of ecological change. But vegetation change is known to be a slow process that will lag rapid climate change and may be constrained by numerous ecological factors. It is also possible that new vegetation types with novel structures could develop in the future.

Part C of Figure 3 illustrates how we compare all the outputs of the ANN (suitability values) in the present and any future scenario to estimate biotically scaled

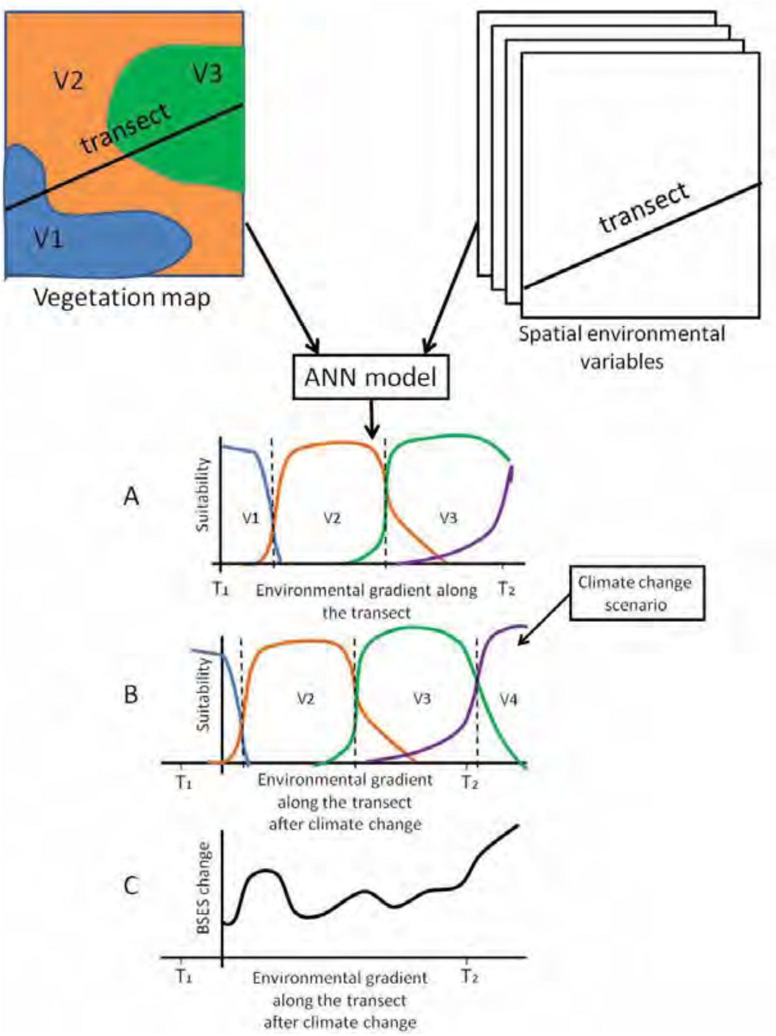


Figure 3. Illustration of how the ANN method is used in this report. See the text for explanation.

environmental stress. For each location, the vector output from the ANN classification (23 suitability values ranging from 0 to 1) is an objective, biotically scaled measure of the local environment. We used the Bray-Curtis metric to measure the dissimilarity between the vector for the current climate and that of a future climate scenario as a measure of environmental change. This measure of biotically scaled environmental stress is therefore referenced to vegetation types and structures. The curve in this figure is only an illustration of this kind of metric of environmental change, using the suitability values in parts A and B. It emphasises the non-linearity of biotically scaled environmental stress in geographic space, where the simplifying assumption is a uniform increase in temperature across the transect.

2.3.3 CALCULATING BIOTICALLY SCALED ENVIRONMENTAL STRESS WITH GDM

Generalised Dissimilarity Modelling (GDM, Ferrier *et al*. 2007) was used to model the potential sensitivity of the species composition of communities to environmental change (Ferrier *et al*. 2012). Models were built by analysing the dissimilarity in species composition (quantified with the Sorenson index) between pairs of locations across the Australian continent as a function of differences in climate, soil and terrain variables between these locations. The Sorenson index ranges between 0 (when two locations have exactly the same species) and 1 (when two locations have no species in common). This modelling approach was applied using data for various taxonomic groups, however we focus in this report on the results for vascular plants, based on occurrence records for more than 12,000 plant species at over 350,000 locations (1 km^2 grid cells) across the continent. This particular model predicts dissimilarity in vascular-plant composition between locations as a function of 23 environmental attributes. The most influential predictors in the model measure various aspects of precipitation (including seasonality), temperature (including maximum temperatures for both the hottest and coldest months), solar radiation (minimum and maximum monthly cloud-adjusted radiation), potential for plant growth (growth indices for micro-, meso- and macro-therm plants), and substrate (including geophysical surrogates based on magnetic and gravity mapping).

The GDM model developed for vascular plants was used to derive measures of biotically scaled environmental stress by comparing the current environment at a location with a future climate for that location (or, in some analyses, other locations). Thus the approach estimates stress for a given location of interest in terms of the dissimilarity in present-day species composition expected between two locations whose current environments differ by the same magnitude as the projected change in environment at the location of interest. It is important to note that GDM models compositional dissimilarity as a single number, and therefore it predicts only the expected level of change in composition, not the identity of species contributing to this change.

This approach to using GDM to assess biotically scaled environmental stress is illustrated diagrammatically in Figure 4. On the left-hand side of this diagram, a GDM model is fitted to compositional dissimilarities observed between pairs of surveyed locations (sites). The model-fitting process automatically identifies non-linear transformations of the original environmental variables (attributes) such that the summed environmental difference (distance) between each pair of sites (say *a* and *b*) correlates, as closely as possible, with the observed compositional dissimilarity between these sites. The curved line in the top-left graph represents the so-called “link function” used in GDM to account for the well-known asymptotic relationship between increasing environmental difference and observed compositional dissimilarity (the latter cannot exceed 1 once sites share no species). The “intercept” in this graph represents the observed compositional dissimilarity expected between two sites with identical values for all of the environmental predictors included in the model. This therefore accounts for the effects of sampling errors (including under-sampling of species) and of environmental and biological factors not included in the model.

On the right-hand side of Figure 4 the GDM model fitted to compositional dissimilarities observed between pairs of sites under present environmental conditions is used to estimate (project) the level of environmental stress expected under a given climate scenario. Here the non-linear transformations of environmental variables from the fitted model are used to calculate the biotically scaled environmental difference, and thereby potential stress, associated with any particular site (say *x*) given the environmental attributes of this site under present and future climatic conditions.

2.3.4 CHOICE OF REGIONAL CLIMATE SCENARIOS

The Intergovernmental Panel on Climate Change *Special Report on Emissions Scenarios* (SRES) (Nakicenovic *et al*. 2000) developed an internationally agreed set of scenarios of future greenhouse gas emissions for climate modellers to use in simulating future climates. These scenarios are based on distinct socioeconomic and geopolitical assumptions about the future. A range of Global Circulation Models (GCM) have been used to obtain coarse regional-scale projections of temperature and rainfall over various time periods based on these scenarios, along with parameters reflecting the sensitivity of the Earth system to elevated greenhouse gas concentrations. A range of climate projections are available for Australia from the OzClim website (CSIRO n.d.). The projections differ in their emissions scenarios, sensitivity parameters and the GCM used to create them. Consequently, there is a broad range of possible, simulated future climates that could be used in impact and adaptation studies such as ours. For this project we used a small but meaningful range of possible future climates.

We used two scenario-sensitivity combinations: the A1FI scenario (high fossil fuel dependence) with high sensitivity parameter and the A1B scenario (increasing use of renewable energy to meet increasing demand) with medium sensitivity parameter; we refer to these in this report as “high” and “medium” scenarios respectively. However, greenhouse gas emissions have reached or exceeded the trajectory of the A1FI scenario in the past decade (Rahmstorf *et al*. 2007); A1FI is actually closer to “business as usual” for the near future. The A1FI is the “worst-case” SRES scenario,

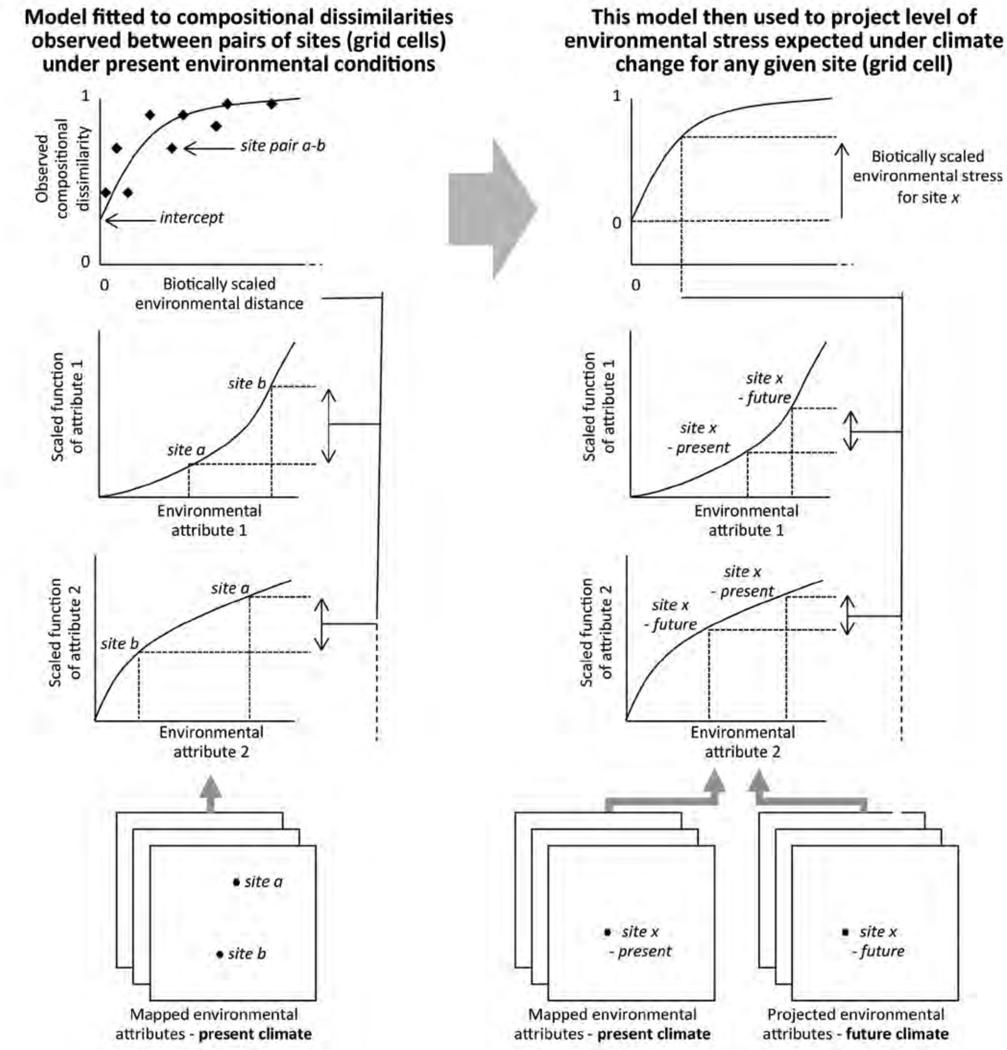


Figure 4. Illustration of how the GDM model is constructed with current environmental layers and observed species compositional patterns, and how it is then used in this report to project biotically scaled environmental stress. See the text for explanation.

and with the high climate sensitivity parameter it corresponds to a global mean temperature increase of approximately 3.8°C by 2070 and 5.5°C by 2100. The A1B scenario with medium climate sensitivity corresponds to approximately 2.4°C of global warming by 2070 and 3.0°C by 2100 (IPCC 2007).

This project used outputs for the CSIRO Mk3.5 GCM for the Australian region; these were further downscaled and used to derive additional climate parameters for the ANN and GDM modelling (Harwood *et al*. 2012). Different GCMs have different continental average climate changes and different spatial patterns (especially for rainfall). The CSIRO Mk3.5 model projections tend to be drier and warmer in the Australian region than many of the other international models.

2.3.5 ROBUSTNESS OF OUR ANALYSES

This report includes the first continent-wide, quantitative assessments of the significance of climate change pressure on Australia's terrestrial biodiversity (ANN and GDM results). These analyses were designed to be used in formulating broad adaptation options for large geographic areas, that is, the nation or very large biomes crossing states and territories. Consequently, our interpretation of these analyses uses the general, large-scale results rather than the spatial or ecological details and includes expert opinion and general ecological knowledge. Further research may justify using these results in finer-scale regional analyses.

Specific features of our continent-wide analyses that make them robust include:

- the models (ANN and GDM) use the best available biodiversity, climate, soil and terrain data with national scope

- we used two different quantitative analysis methods based on independent analysis techniques and biotic data
- the biotically scaled environmental stress concept we designed is *not* dependent on the largely unknown ecological responses to environmental stress
- their quantification used aggregate biodiversity measures, rather than individual species
- the broad policy-relevant conclusions were made considering a wide range of future climatic change and types of ecological response
- the fine-scale detail of the quantitative results were used very cautiously and in combination with commensurate expert knowledge from the biomes.

While the models use the best available data, some future environmental changes are not included in the quantitative analysis. For example, it is likely that future changes in atmospheric CO_2 concentration, altered disturbance regimes (e.g. fire, flood), and soil and landscape hydrological processes will be ecologically very significant. In addition, changes in species interactions will further change physical environments (e.g. through competition) and biotic environments (e.g. habitat, predation, diseases); and phenotypic, behavioural and evolutionary responses will enable some species to adapt to some levels of environmental change. In some situations, some of these factors may mitigate ecological responses to the factors that are included in the modelling; however, on average, it is more likely that these factors will add to environmental stress predicted in our analyses. Our qualitative ecological analyses in the biome studies did consider a range of these other factors.

One could make estimates about possible ecological responses to some of these other factors and modify the model results in a post-hoc fashion. But for the most part we have avoided doing so in this report for three reasons. First, it is essential that we clearly present the direct results of our analysis, as they are significant. Secondly, the spatial and temporal pattern and/or impacts of these additional variables on broad-scale biodiversity, as we use here, are largely unknown. Finally, our analyses include the primary, direct variables that are well known to influence biodiversity patterns at large scales. For example, while there are broad generalities about the impact of elevated CO_2 at the leaf-level, such as increased water use efficiency, the impact of these on plant growth, composition and structure will vary spatially due to local species composition, water and nutrient availability. As such, not enough is known about the future CO_2 impacts on broad-scale spatial patterns of biodiversity in Australia's often dry and nutrient-poor environments to enable a post-hoc inclusion of CO_2 effects at the resolution or extent of our models.

The concept of biotically scaled environmental stress, and the metrics we used to quantify it, differ significantly from the dominant approach used previously to model the impacts of climate change on biodiversity: species distribution modelling (Elith *et al*. 2006). We suggest that our approach is, by design, more conservative. First, as discussed above, the stress concept relates to the force likely to drive changes in biodiversity, as opposed to the actual change in biodiversity. The modelling involves no implicit model about how biodiversity will respond to the predicted environmental change; therefore the analysis is free from any implicit assumptions and uncertainty about how species or ecosystems may change: how species will respond to shifting bioclimatic niches; how altered species interactions will change realised niches, rates of dispersal, differential responses to establishment, growth, reproduction, mortality; and so on. The net response of biodiversity to a changing environment remains a key uncertainty, and is likely to vary between species, ecosystems and biomes. Using this interpretation of the model outputs, analysts must *actively* make their own inferences about future ecological change based on the predicted future environmental change using knowledge of the ecology of the biodiversity and landscapes of interest. This contrasts with mapped climatic niches, which are often directly interpreted as predictions of future species distributions.

Second, these methods are based on analysis of patterns in aggregated entities or attributes of biodiversity, as opposed to the analysis of the distributions of individual species. In this way, these methods are arguably more capable of identifying any underlying *signals* of biodiversity sensitivity to environmental change by effectively averaging out the *noise* resulting from the effects of multiple biogeographic factors on individual species distributions. This has potential advantages and disadvantages, depending on the application of the results, and makes these approaches complementary to species distribution modelling.

Given that warming and drying are the main concerns for biodiversity in Australia, the use of a relatively hot and dry GCM model means the ANN and GDM results calculated with the A1FI scenario are representative of the levels of environmental change that policy and management would need to be able to accommodate if it were to be robust to the full range of climate changes anticipated by the IPCC. Different GCM models also vary in the spatial pattern of their change projections. In formulating the conclusions in this report we did not use the fine-scale detail of the model results to make inferences about change at specific locations (i.e. the actual levels of stress at specific locations, which would vary between GCMs). Rather, we highlight and use the more general and robust finding that stress is likely to vary considerably over space at multiple scales. This variation arises from underlying (current) spatial variation in the environment and the sensitivity of biodiversity to change, rather than spatial variation in change in the environment.

In summary, we believe our modelling results and overall interpretations are robust at large spatial scales and for formulating broad adaptation options and policy. Our modelling results *may* be applicable in detail for local regions, but further research would be necessary to establish confidence and robustness at finer scales.

2.3.6 COMPLEMENTARITY OF THE MODELLING METHODS

This project is quite unusual in that it used more than one analysis method. In particular, we used both the ANN and GDM methods for the common purpose of assessing biotically scaled environmental stress across the continent. A major objective of using two methods was to be able to assess the generality of our broad conclusions with regards to adaptation challenges. While the two methods produce different results in detail, the overall picture is largely the same. This increases confidence in the robustness of our conclusions. The two approaches are also complementary in the sense that they are based on different dimensions of biodiversity. The GDM method focuses on the *composition* of taxonomically similar communities of species, while the ANN method uses data that are more representative of ecosystem *structure*. While environmental change would be expected to change both ecosystem structure and composition (and the distributions of individual species), they may all change in different ways. For example, a reduction in the abundance of trees could lead to a forest becoming a woodland with no changes in species composition; and complete replacement of the tree species present at a site by another set, in the same density, would result in differing composition and no change in structure. Therefore differences in the spatial pattern of the biotically scaled environmental stress predicted with the ANN and GDM are to be expected. Difference should also be expected between these results and modelling of any individual species. Further work is required to determine what, if any, robust inferences about different types of future ecological change ecological could be made from the spatial differences and similarities between the various modelling approaches.

Similarly, differences should be expected in the magnitude of the biotically scaled environmental stress predicted with the two methods we used. The biotic data in the GDM analyses are at a finer scale in the biodiversity hierarchy, and vary at finer spatial scales, compared to the vegetation classes used in the ANN analyses. Therefore the GDM-based biotically scaled environmental stress metric would theoretically be expected to be more sensitive than the ANN metric. This was borne out in the results (Sections 3.2 and 3.3), illustrating how these approaches are complementary and consistent with expectations of ecological theory.

As well as modelling biotically scaled environmental stress, the project included modelling of the potential distribution of environments suitable for a single species, buffel grass, because this species may be particularly important for some of the biomes. The analyses provided an opportunity to develop and trial a novel method for modelling species habitat when data are poor but expert information is available, Baysian Belief Networks (Martin *et al*. 2012). The three methods also provide the opportunity for different analyses that are presented in the report.

3. Environmental and ecological change

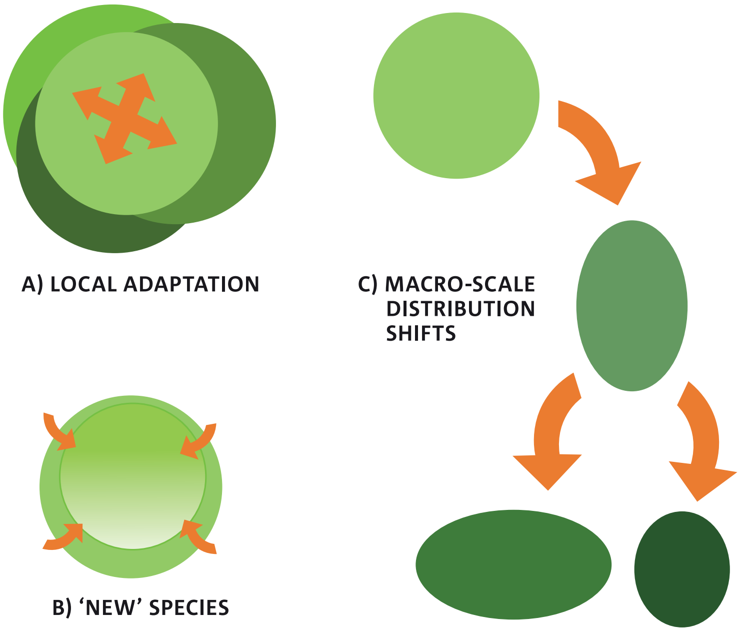
3.1 Understanding climate change as a foundation foradaptation

Shifts in species distributions towards the poles and upwards in elevation, and shifts in phenology (earlier spring and later autumn life history events) are the most frequently observed and cited ecological responses to climate change. Widespread observations of these impacts (e.g. Parmesan and Yohe 2003; Root *et al*. 2003) together with numerous modelling studies of shifts in bioclimatic niches (e.g. Thomas *et al*. 2004) have amply demonstrated that biodiversity will be affected by climate change and that the impacts are likely to be significant. Climate change will also affect biodiversity in many other ways; Dunlop and Brown (2008) reviewed many of the observed and predicted responses of species and ecosystems to climate change and introduced a schematic cascade of impacts and feedbacks. For the purposes of planning conservation strategies, it is likely to be necessary to assess the net responses and vulnerability of species and ecosystems resulting from the full range of ecological changes. However, despite a growing wealth of information about different impacts, as yet there is no biogeographic theory of rapid climate change that adequately integrates impacts at physiological, genetic, population and ecosystem levels to enable adequate predictions of which phenomena may dominate the responses of species and ecosystems in different environments or regions. As an interim attempt to synthesise various types of impacts in terms of different net ecological outcomes, Dunlop and Brown (2008) presented three conceptual models (Figure 5):

A) *In situ* or local adaptation: where change is characterised by alterations in the relative abundance of species, local-scale redistribution of species in response to fine-scale environmental variability, and changes in the structure and function of ecosystems, including some loss of species but no marked changes in composition at the regional scale.

B) "New" species: where change is characterised by the arrival and expansion of a relatively small number of species from other (neighbouring or distant) regions as environmental conditions suit their establishment. This includes exotic species and

Figure 5. Three conceptual models characterising how species' populations may respond to climate change. The arrows represent the movement of species between different areas of habitat in response to climate change. The different colours represent different environments; with darker greens representing areas where habitat becomes more suitable as the climate changes. B) shows a population contraction due to the arrival of new species.



species that were actually present in very small ("cryptic") populations, but which may become more important. Most of these species are likely to have little ecological impact, but some may dramatically alter ecosystem processes and structure, or suppress or exclude resident species.

C) Macro-scale distribution shifts: where change is characterised by the shifting of species along macro-scale environmental gradients as establishment, growth, reproduction and survival conditions change.

While the third model is the most familiar and often the only one considered in discussion of ecological impacts, there is very good evidence for the feasibility of each of these three conceptual models from a wide range of ecological literatures, but it remains impossible to predict how they may combine and which outcomes may dominate in different situations. Likewise, no one of these scenarios would necessarily be more likely to lead to greater loss of biodiversity.

Together, as a set of scenarios, these models can be used as a tool for planning conservation management, monitoring and research, to ensure a wide range of impacts and outcomes have been assessed. They are likely to have quite different conservation implications, for example, in relation to the importance of:

- the availability of habitat in different environments
- local and regional environmental diversity
- landscape connectivity, including stepping stones
- refuges
- spatial and temporal variation in resource availability
- threats in the landscape matrix such as fire, invasive species, land-use change, and water availability.

To explore how impacts may vary regionally, Dunlop and Brown (2008) assessed how the seasonality of primary production, and a range of consequential ecological processes, may change as a result of climate change. This highlighted regions not previously identified as vulnerable or likely to experience considerable ecological change. However, it was not quantitative, did not address all types of impact and used a limited amount of ecological information about each region. This report builds on the analyses in Dunlop and Brown (2008) by combining new quantitative spatial analysis about environmental change with detailed ecological information for four biomes.

3.2 Future environmental change could be ecologically very significant

The modelling undertaken in this project found that future climate change scenarios translate into very significant levels of biotically scaled environmental stress. These results suggest that, from the point of view of biodiversity, many local environments could be very different in the future compared with today. The GDM-based measure was derived for the 2030 and 2070 high-impact and medium-impact scenarios, while the ANN-based measures were derived for the 2070 scenarios only. Average values obtained across all cells on the continent are presented in Table 1; as expected, the GDM-based stress is higher than the ANN-based stress, reflecting the finer-scaled nature of biotic entities used to develop the GDM models (Section 2.3.6).

Table 1. Predicted biotically scaled environmental stress, based on the ANN modelling using major vegetation groups and GDM modelling of vascular-plant species composition averaged across all grid cells on the continent (± 1 standard deviation). The metrics vary from 0 (no change) to 1 ("completely different").

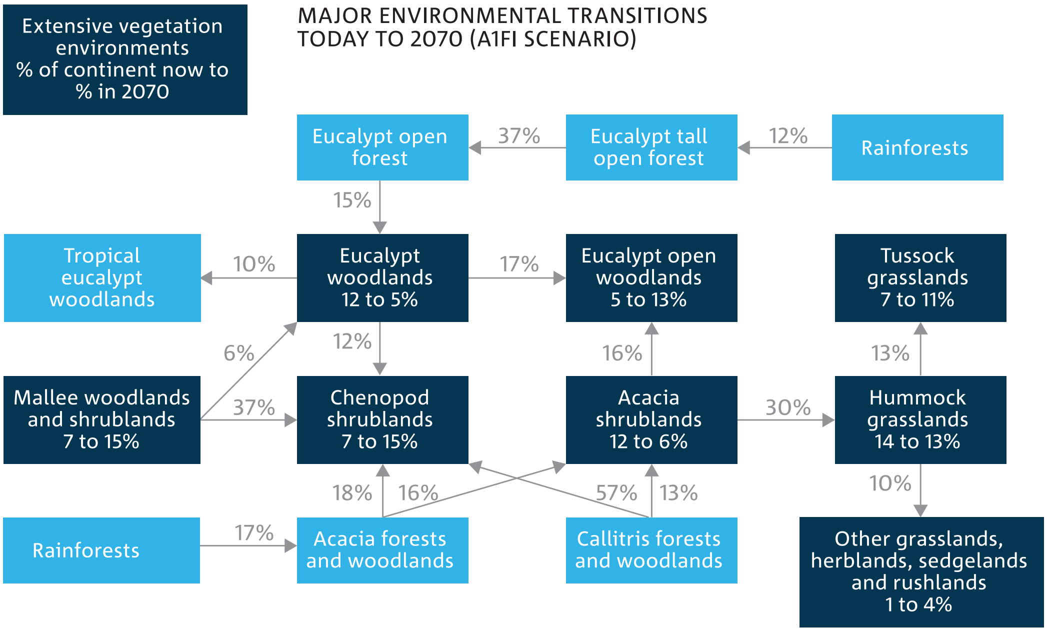
CLIMATE SCENARIO	BASED ON ANN MODELLING OF MAJOR VEGETATION GROUPS	BASED ON GDM MODELLING OF VASCULAR-PLANT SPECIES COMPOSITION
2030 Medium-impact	-	0.50±0.11
2030 High-impact	-	0.54±0.11
2070 Medium-impact	0.47±0.23	0.71±0.08
2070 High-impact	0.61±0.24	0.85±0.07

The results presented in Table 1 relate to potential changes at a local level—that is, the amount of change in biological character that might be expected to occur at any given location, in this case a 1 km2 grid cell. These results, on their own, tell only part of the story about the potential for change in biodiversity across the continent. As emphasised in Section 2.3.1, these modelling results are best interpreted as a relative, "biotically scaled", indicator of potential environmental change. Actual change in biological composition or structure resulting from climate change is likely to be shaped by many environmental and ecological factors and associated sources of uncertainty beyond those considered in this modelling, for example: altered concentration of CO2, altered environmental variability, biotic interactions, indirect effects of changed fire regimes, dispersal ability, lag effects, evolutionary adaptation and phenotypic plasticity. Some of these factors may add to the net environmental stress, and others may reduce it; some may reduce the ability of species to respond, and others may increase the ability of species to cope with or adapt to change in situ. The mediating impact of these factors is likely to vary spatially, and their importance will only be fully understood by monitoring change as it occurs. On balance, we suggest that climate change by 2070 could readily lead to future biodiversity (vegetation group and vascular-plant composition) being, on average, more different than it is similar to current biodiversity (i.e. change of 0.50 or more, Table 1). However, the changes will be much greater in some places than others (Section 3.3), and ecological change will be manifest in many different ways (Section 3.4).

The results above describe environmental change at a local level; these will aggregate and lead to change in the biological character at the continental scale. Further results from the ANN and GDM modelling suggest a potential for high levels of collective change. We illustrate this point using two examples drawn from the ANN and GDM results (for full results of analyses relating to this issue see Ferrier *et al*. 2012; and Hilbert and Fletcher 2012).

The first example, based on the ANN modelling and depicted in Figure 6, indicates how local changes could lead to significant changes in the proportional area of the continent occupied by environments suitable for different major vegetation groups. These results come from comparing the map of classified environments in the

Figure 6. Potential transitions between environments suitable for major vegetation groups (MVG), predicted by ANN modelling (2070 high-impact scenario). Selected environment types are shown as boxes. Yellow shading indicates environment types that are very widespread today or grassland environments, which increase by a factor of four. Numbers in the yellow boxes give the current and future area of the environment as a percentage of the entire continent. Percentages on the arrows indicate the proportion of the environment type that changes to different type. Actual changes in vegetation type would be expected to tend to mirror these environmental transitions, but they will depend on many factors. (Rainforests are included twice to simplify the diagram.)



current climate with mapped classified environments in the climate scenarios that are presented in the ANN report (Hilbert and Fletcher 2012). The general pattern is a decline in the area of environments that now favour trees and an increase in more xeric environments favouring open woodlands, chenopod shrublands and grasslands. It is expected that vegetation changes would tend to mirror these environmental changes, but the rate and nature of actual future vegetation changes will depend on many factors.

In the second example, GDM modelling was used to illustrate the potential for the emergence of novel or "no analogue" environments (Williams *et al*. 2007) on the Australian continent under climate change. Figure 7 maps, for each grid cell on the continent, the biotically scaled environmental difference between the future environment in the cell (under the 2070 medium- and high-impact scenarios) and the most similar current environment *from anywhere on the continent*. The darker purple colours on this map indicate areas with novel environments—that is, future environments that are more different than similar to any existing environments on the whole continent (stress greater than 0.50). This analysis suggests that climate change may result in more than just a spatial reshuffling of currently familiar environments and species assemblages. Climate change is likely to see the emergence of novel environments and the disappearance of many existing environments (see Ferrier *et al*. 2012; Hilbert and Fletcher 2012).

The magnitude of the potential changes predicted by the ANN and GDM modelling analyses puts climate change at least on a similar footing to other existing pressures on biodiversity. While other pressures have acute impacts locally, or impact specific groups at broader scales, few of these pressures are likely to result in continent-wide levels of change in species composition and ecosystem type of the magnitude predicted here (e.g. greater than 50% average change in species composition). Also challenging is the speed with which the environmental stress potentially leading to these changes is predicted to gain momentum. The GDM-based results presented in Table 1 suggest that such stress could be well entrenched by 2030. Knowing how to respond to this magnitude and rate of change poses a significant challenge for conservation scientists and practitioners alike (discussed in Section 4).

3.3 Environmental stress will vary spatially

Biotically scaled environmental stress is unlikely to be distributed evenly across the continent (Figure 6, Figure 7), and it follows that the potential for biological change is likely to be higher in some parts of the continent than in others. This likelihood is supported by various other results of the ANN-based and GDM-based analyses described in Hilbert and Fletcher (2012) and Ferrier *et al*. (2012).

For example, ANN-based patterns of biotically scaled environmental stress show considerable spatial variability across the continent (Figure 9); this is present both among and within major vegetation environments. Mean dissimilarity in each mapped major vegetation group between the environment under the current climate and that under two future scenarios are presented in Figure 8. Note that there is relatively little difference between the medium- and high-impact scenarios in 2070. This is partly since increasing environmental change adds little to the projected dissimilarity as the dissimilarity measure at a given location approaches 1. Comparing the current with the future climates, there is considerable variation in the impact of climate change among the environmental classes and this contributes to the observed spatial variability.

The GDM-based analysis also indicated strong spatial variation in future environmental change. For example, Figure 10 maps the predicted biotically scaled environmental stress (based on vascular-plant composition) for each 1 km^2 grid cell on the continent for each of four climate scenarios (these are the raw results that were averaged in Table 1). This suggests the potential for significant spatial variation in ecological impacts of climate change. Table 2 offers another perspective on the degree of spatial variation in these same results, by averaging predicted biotically scaled environmental stress within each Interim Biogeographic Regionalisation for Australia (IBRA) bioregion.

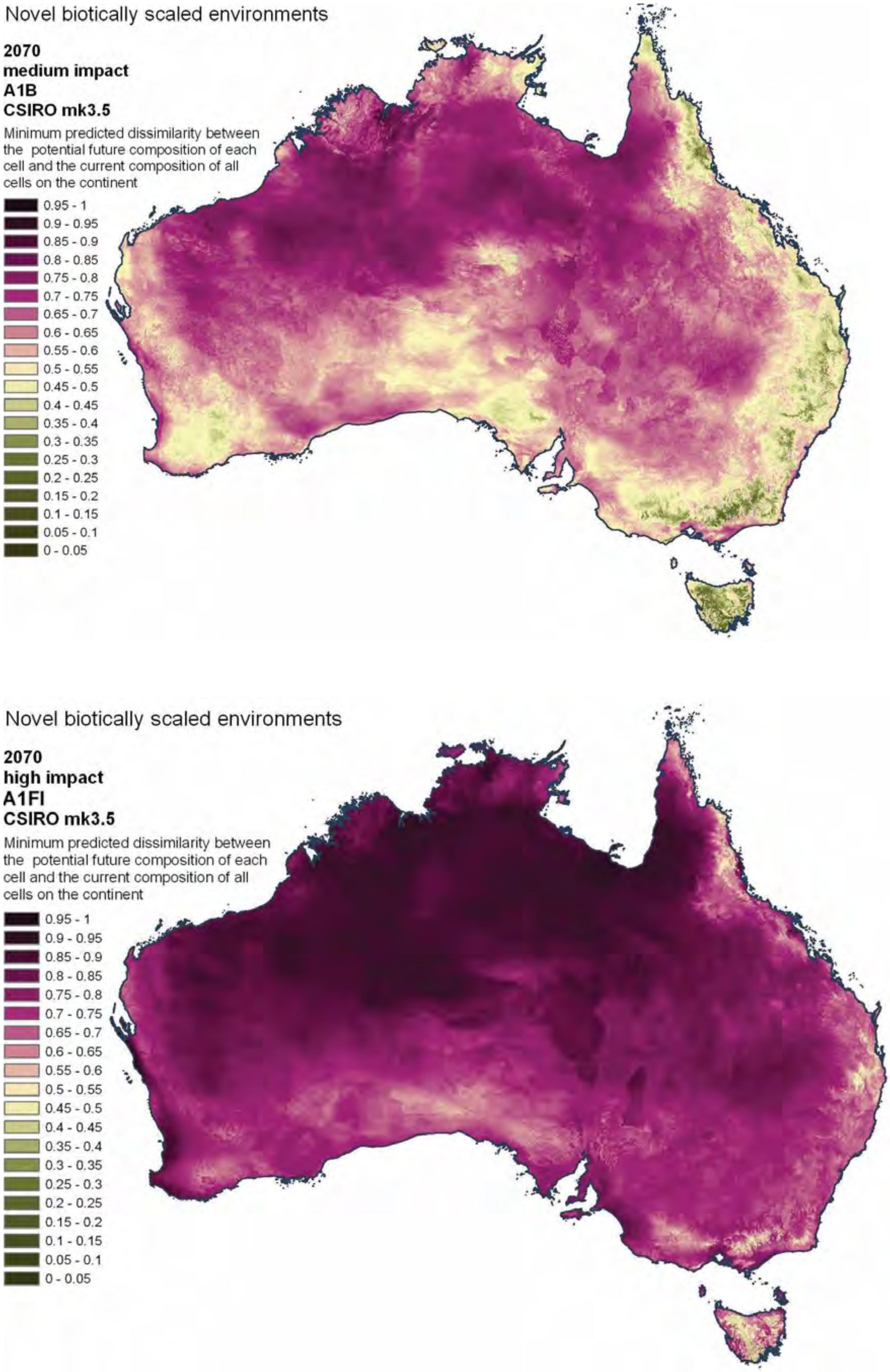
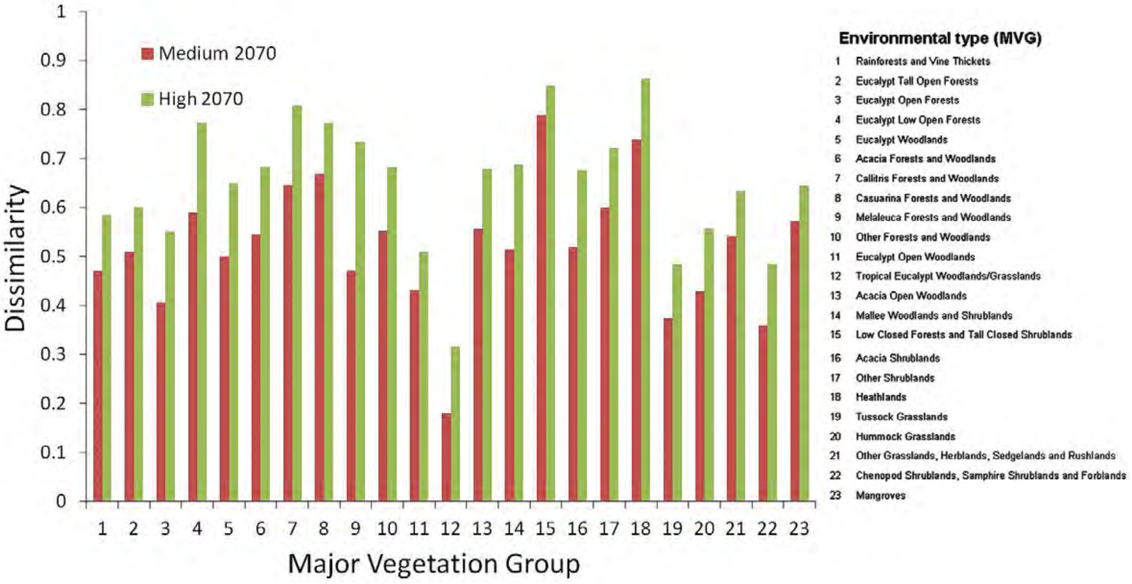


Figure 7. Novel biotically scaled environments under the 2070 medium- and high-impact scenarios, based on vascular-plant GDM modelling. The colours depict the biotically scaled environmental difference between the future environment at each point and the most similar current environment *from anywhere on the continent*. Greens (lower values) show where future environments are potentially ecologically similar to current environments somewhere on the continent. Purples (higher values) indicate where future environments could be ecologically unlike the environments currently occurring anywhere in Australia—they have no current analogues.

Figure 8. ANN-based predicted environmental dissimilarity in different environment types, under 2070 medium-impact and high-impact scenarios, averaged across all grid cells in each group. The biotically scaled environmental stress due to climate change is the Bray-Curtis dissimilarity between the model outputs for the current climate and each of the climate change scenarios.



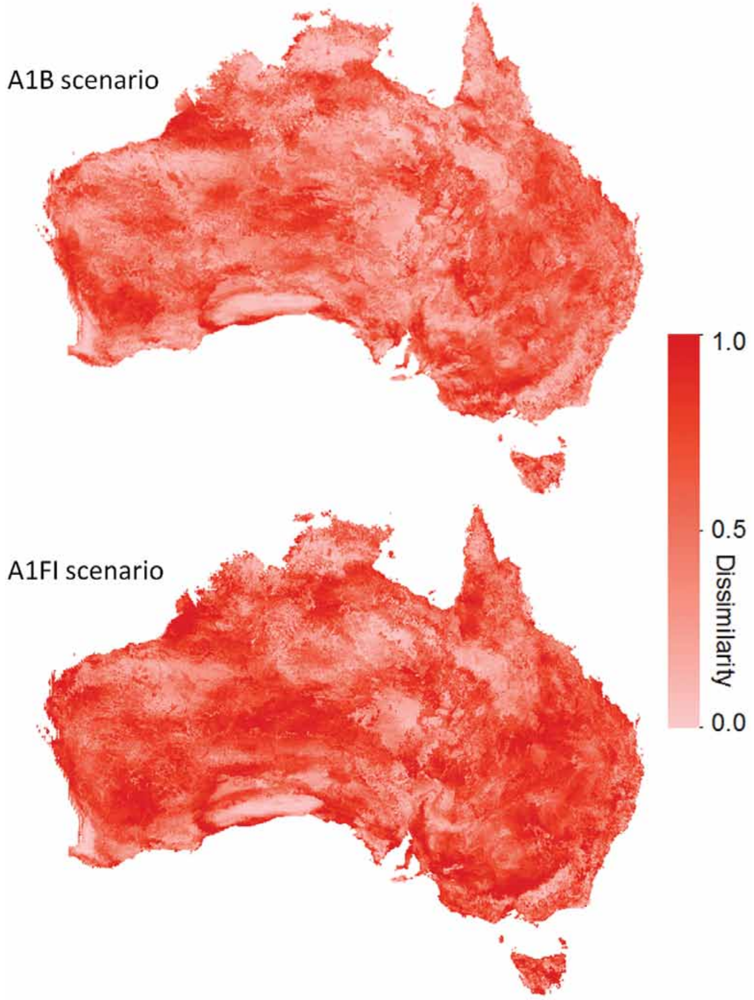


Figure 9. Maps of the environmental dissimilarity (biotically scaled environmental stress) estimated by the ANN method comparing the current climate with the medium-impact (A1B) and high-impact (A1FI) scenarios at 2070. the model outputs for the current climate and each of the climate change scenarios

Table 2. Biotically scaled environmental stress based on GDM of vascular-plant species composition of each 1 km² grid cell and four climate scenarios, averaged across all cells in each IBRA bioregion (2030, 2070; medium- and high-impact scenarios).

	2030	2030	2070	2070
IBRA BIOREGION	M	H	M	H
Continental mean	**0.496**	**0.537**	**0.709**	**0.853**
1. Murray Darling Depression	0.412	0.455	0.658	0.811
2. Naracoorte Coastal Plain	0.420	0.460	0.648	0.857
3. Victorian Volcanic Plain	0.408	0.453	0.636	0.840
4. South East Coastal Plain	0.478	0.522	0.683	0.853
5. South Eastern Highlands	0.410	0.453	0.632	0.837
6. Australian Alps	0.306	0.333	0.473	0.753
7. NSW South Western Slopes	0.427	0.482	0.693	0.856
8. Riverina	0.410	0.453	0.664	0.813
9. Flinders	0.471	0.502	0.640	0.816
10. South East Corner	0.501	0.542	0.689	0.844
11. Ben Lomond	0.337	0.365	0.513	0.713
12. Tasmanian Northern Midlands	0.359	0.397	0.567	0.756
13. Tasmanian South East	0.385	0.414	0.556	0.748
14. Tasmanian West	0.297	0.335	0.510	0.728
15. Tasmanian Southern Ranges	0.283	0.307	0.437	0.644
16. Tasmanian Central Highlands	0.283	0.307	0.441	0.644
17. Darling Riverine Plains	0.473	0.511	0.679	0.826
18. Mulga Lands	0.501	0.541	0.739	0.874
19. Simpson Strzelecki Dunefields	0.496	0.535	0.742	0.887
20. Sydney Basin	0.491	0.541	0.722	0.882
21. Channel Country	0.517	0.567	0.755	0.892
22. Brigalow Belt North	0.456	0.497	0.702	0.895
23. Nandewar	0.435	0.477	0.643	0.817
24. Cobar Peneplain	0.445	0.492	0.696	0.815
25. Broken Hill Complex	0.397	0.440	0.705	0.820
26. New England Tablelands	0.470	0.519	0.694	0.859
27. NSW North Coast	0.563	0.605	0.760	0.903
28. Central Ranges	0.460	0.493	0.704	0.874
29. Finke	0.447	0.466	0.650	0.852
30. Stony Plains	0.467	0.497	0.685	0.815
31. Gawler	0.327	0.358	0.577	0.758
32. Great Victoria Desert	0.365	0.402	0.604	0.759
33. Nullarbor	0.347	0.395	0.628	0.711
34. Hampton	0.436	0.462	0.695	0.745
35. Eyre Yorke Block	0.415	0.461	0.645	0.807
36. Flinders Lofty Block	0.408	0.451	0.683	0.812
37. Kanmantoo	0.439	0.483	0.673	0.866
38. Mount Isa Inlier	0.635	0.698	0.836	0.950
39. Gulf Plains	0.558	0.607	0.780	0.918
40. Cape York Peninsula	0.453	0.502	0.657	0.813
41. Mitchell Grass Downs	0.561	0.623	0.800	0.925
42. Wet Tropics	0.458	0.487	0.654	0.860

	2030	2030	2070	2070
IBRA BIOREGION	M	H	M	H
43. Central Mackay Coast	0.451	0.488	0.646	0.868
44. Einasleigh Uplands	0.462	0.501	0.666	0.839
45. Desert Uplands	0.489	0.550	0.791	0.921
46. Gulf Fall and Uplands	0.521	0.579	0.771	0.930
47. MacDonnell Ranges	0.459	0.498	0.717	0.898
48. Burt Plain	0.503	0.536	0.742	0.898
49. Tanami	0.629	0.655	0.792	0.907
50. Sturt Plateau	0.570	0.616	0.784	0.923
51. Ord Victoria Plain	0.628	0.661	0.789	0.911
52. Victoria Bonaparte	0.600	0.641	0.800	0.926
53. Gascoyne	0.577	0.619	0.734	0.851
54. Carnarvon	0.433	0.475	0.628	0.776
55. Central Kimberley	0.670	0.706	0.823	0.930
56. Coolgardie	0.387	0.430	0.630	0.770
57. Esperance Plains	0.426	0.461	0.597	0.752
58. Dampierland	0.587	0.627	0.772	0.893
59. Gibson Desert	0.575	0.631	0.772	0.899
60. Great Sandy Desert	0.659	0.690	0.801	0.909
61. Jarrah Forest	0.400	0.435	0.590	0.820
62. Warren	0.455	0.497	0.664	0.854
63. Little Sandy Desert	0.661	0.685	0.760	0.876
64. Mallee	0.404	0.432	0.559	0.739
65. Murchison	0.488	0.538	0.690	0.822
66. Northern Kimberley	0.584	0.624	0.780	0.905
67. Geraldton Sandplains	0.555	0.586	0.703	0.843
68. Pilbara	0.626	0.656	0.764	0.876
69. Swan Coastal Plain	0.536	0.570	0.691	0.854
70. Avon Wheatbelt	0.424	0.454	0.601	0.798
71. Yalgoo	0.504	0.530	0.656	0.828
72. Gulf Coastal	0.481	0.536	0.750	0.917
73. Daly Basin	0.481	0.534	0.728	0.908
74. South Eastern Queensland	0.540	0.581	0.724	0.855
75. Pine Creek	0.500	0.549	0.726	0.892
76. Brigalow Belt South	0.467	0.511	0.694	0.865
77. Central Arnhem	0.368	0.427	0.621	0.839
78. Victorian Midlands	0.399	0.440	0.618	0.837
79. Darwin Coastal	0.505	0.553	0.721	0.886
80. Tasmanian Northern Slopes	0.289	0.318	0.477	0.695
81. Arnhem Coast	0.384	0.421	0.589	0.799
82. Arnhem Plateau	0.503	0.550	0.699	0.864
83. Tiwi Cobourg	0.451	0.502	0.678	0.830
84. Davenport Murchison Ranges	0.666	0.698	0.826	0.931
85. King	0.358	0.392	0.546	0.744

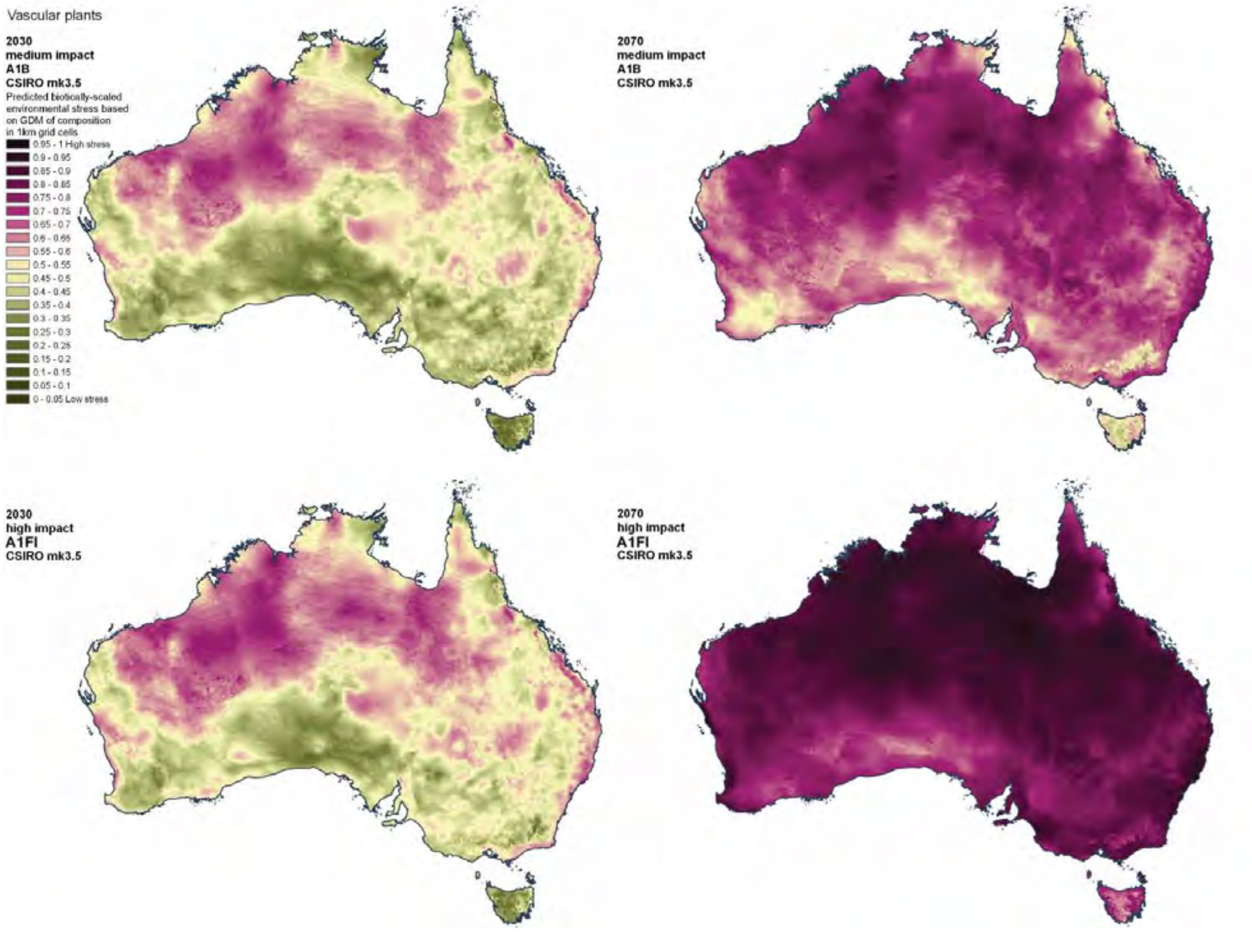


Figure 10. Biotically scaled environmental stress based on GDM of vascular-plant species composition of each 1 km^2 grid cell and four climate scenarios (2030, 2070; medium- and high-impact scenarios).

3.3.1 BUFFERING

The previous analyses examined environmental change in single 1 km^2 grid cells, but environmental heterogeneity has the potential to effectively reduce the magnitude of environmental change experienced locally by biodiversity, a process known as ecological or landscape buffering. The GDM-based analyses were used to quantify the extent to which environmental heterogeneity in the landscape surrounding each grid cell buffered environmental stress (see Ferrier *et al*. 2012 for details). A typical example of the spatial pattern produced by this type of analysis is presented in Figure 11. This clearly demonstrated significant environmental buffering where there is greater topographic diversity. However, the precise pattern emerging from this analysis is very dependent on the spatial grain at which the analysis is conducted (which links to assumptions about biological dispersal capability when drawing ecological interpretations). Running the analysis at finer spatial grains will always produce more intricate looking maps (see example in Figure 12), but much more work is needed to better understand the ecological relevance, and implications, of such patterns. Further discussion of ecological buffering as a function of environmental variation is provided in Section 3.4.1.

3.3.2 INTERPRETING DIFFERENT APPROACHES WITH DIFFERENT RESULTS

While the ANN and GDM analyses both point to the likelihood of marked spatial variation in environmental stress across the continent, the pattern of this variation is not strongly congruent between the two approaches. Similarly, these analyses differ from previous analyses in the regions that they highlight as likely to experience the highest levels of ecologically significant change. For example, the ANN-based analyses indicate quite complex variation in the levels of change within and between regions; while the GDM-based analyses indicate inland northern Australia, in particular the north-west, as likely to experience faster change than other regions; analyses based on the characteristics of individual species (e.g. shifting bioclimatic habitats;

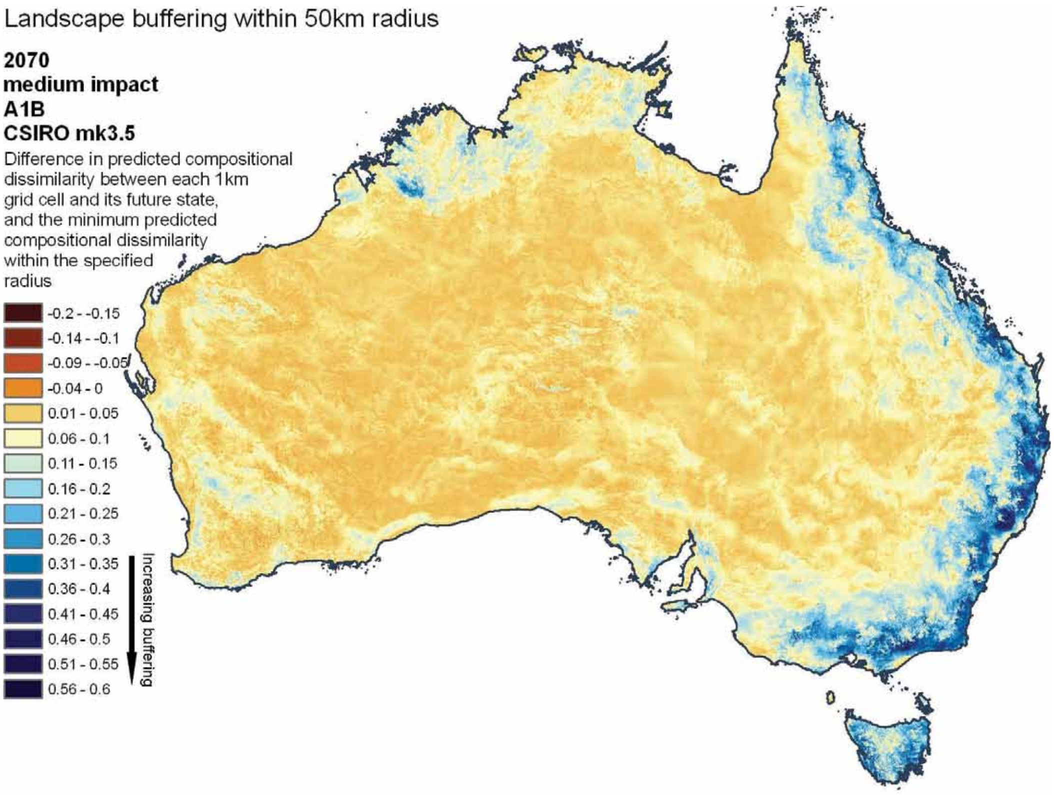


Figure 11. An index of the potential buffering effect of environmental heterogeneity in the landscape surrounding each 1 km^2 grid cell based on GDM analysis of vascular-plant composition. For each cell, this was calculated as the environmental change (stress) of the cell itself, minus the minimum difference (stress) between the current environment of the cell and the future environment of all other cells within a 50 km radius (2070 medium-impact scenario, assuming pre-European vegetation cover, see Section 2.3.2). Higher values (darker blues) indicate areas with higher potential for buffering as a result of environmental heterogeneity. Habitat loss would decrease availability of buffering.

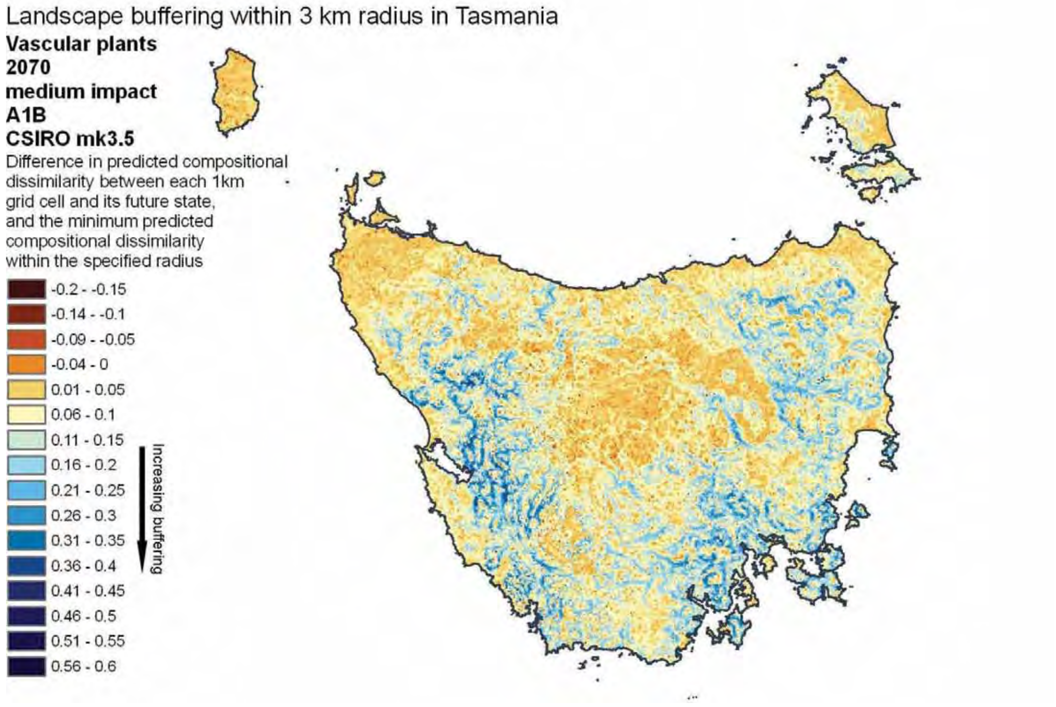


Figure 12. Enlarged Tasmanian example of the index of the potential buffering effect of environmental heterogeneity in the landscape surrounding each 1 km^2 grid cell based on GDM analysis of vascular-plant composition. For each cell, this was calculated as the environmental change (stress) of the cell itself, minus the minimum difference (stress) between the current environment of the cell and the future environment of all other cells within a 3 km radius (2070 medium-impact scenario, assuming pre-European vegetation cover, see Section 2.3.2). Higher values (darker blues) indicate areas with higher potential for buffering as a result of environmental heterogeneity.

IPCC Fourth Assessment Report: Hennessy *et al*. 2007) have identified south-west Western Australia, the mountains of the Wet Tropics and Australian Alps as being particularly ecologically vulnerable; and Dunlop and Brown (2008), assessing potential changes in seasonal productivity, identified two zones in south-eastern Australia as being likely to experience relatively high levels of ecological change. All of these analyses used different biotic patterns or ecological reasoning as the basis for their assessments, so they are potentially reflecting different change phenomena (vegetation structure, changed community composition, shifting distributions, altered ecosystem processes). These different results highlight that more work is needed to better understand how the outputs of different methods might actually relate to future ecological changes, how different types of ecological changes might combine, and how different impacts might vary spatially. This is just one manifestation of a more general challenge confronting the rapidly growing science of modelling climate change impacts on biodiversity. Modelling focused on different biological attributes (corresponding to different types of ecological change) or employing different modelling techniques will often highlight potential impacts in quite different regions. These differences may well be ecologically meaningful—that is, different types of change process could dominate in different places. However, the climate change impacts modelling community is a long way from being able to make such ecologically precise inferences from the results of different methods, or knowing how to integrate them.

3.4 Ecological change

The ecological assessments conducted by this project identified and explored a wide range of possible future impacts on species and ecosystems in four biomes. A number of possible broad trends were identified, but there remains considerable uncertainty about the fine scale details. For example, widespread ecosystem-level thinning of overstorey species is expected in response to drying. However, there are many uncertainties associated with this trend, including the extent to which increased water use efficiency due to elevated CO_2 concentrations will counter the trend or increase shrub layers, whether compositional change might lead or lag structural change, whether co-occurring changes (e.g. altered fire regimes) would accentuate or counter the trend, and the importance of a drying trend versus changes in variability and extremes. In general, the available ecological and quantitative evidence was insufficient to describe specific predictions about the two or three most important changes, vulnerabilities, potential losses in value or actions in each biome. Overall these assessments confirm the key finding of Dunlop and Brown (2008) that:

- many different types of ecological change can be expected
- it is very difficult to anticipate how they may combine or the rates of change
- different phenomena are likely to drive ecological change in different situations.

Below we summarise a range of lessons that emerged from the four biome analyses and the continental modelling. These lessons are drawn from the consultative workshops and the biome and modelling reports (see Appendices 1, 2 and 3).

3.4.1 ENVIRONMENTAL VARIATION

Environmental variation, including fine-scale heterogeneity and coarser topographic and climacteric gradients, contributes significantly to the spatial patterning of biodiversity in all the biomes. This variation was regarded as likely to have a critical mediating impact on the responses of species and ecosystems to climate change. However, the scale and nature of this variation, and its impact on biodiversity, varied among the biomes. This highlights that the spatial scales of biodiversity responses to climate change are likely to vary between regions. For example, the temperate grassy ecosystems and sclerophyll forests biomes have significant macro-scale gradients of temperature and rainfall seasonality (north–south) and water availability (coast to tablelands and inland). But the sclerophyll forests biome has much greater heterogeneity due to high topographic variability (ranges and deep gullies), allowing for much mingling of ecological communities and a high degree of local- and meso-scale buffering. The temperate grassy ecosystems biome has significant environmental buffering, mostly associated with relief at the fringes of the Great Dividing Range. More widespread “biological buffering” was historically provided through high species richness and widespread distributions; however, this is now greatly reduced by habitat fragmentation and degradation. In contrast, the hummock grasslands and savanna biomes have very shallow rainfall and temperature gradients. The savannas include many micro-habitats associated with wetlands, fire-protected pockets and escarpments that provide refuge from annual drought, fire and heat stress both for species restricted to these habitats (including many endemics) and more generalist species in the broader landscape. In the hummock grasslands biome there is some fine-level heterogeneity due to micro-topography, rocky outcrops and ranges, ground water systems and uncoordinated drainage systems. Fine-scale buffering is small in magnitude but very important, as significant macro-scale buffering is restricted to a few regions in the biome.

In each biome there are species that have survived for millennia in restricted, topographically defined micro-habitats that provide more reliable water availability or protection from fire (e.g. gullies, water holes, drainage lines). It was expected that biodiversity in such places might also be less vulnerable to future climate change, and that these places might facilitate the persistence of other species in the wider landscape that are able to access water or shelter in these refuges. In addition, local environmental gradients associated with slope, elevation or geology were expected to provide local buffering against general temperature and rainfall trends. However, it remains uncertain how much buffering might be provided by such local environmental diversity: could such variation enable long-term persistence under high levels of climate change, or merely slow the rate at which species and ecosystems decline in their present regions? Modelling suggested that local environmental variation could provide significant buffering, especially in the medium emissions scenario; but by 2070 and under the high emissions scenario, even though buffering still reduced the levels of biotically scaled environmental stress, the absolute levels of stress were typically very high, indeed higher than previously appreciated. This potentially suggests that limits to widespread buffering through environmental heterogeneity may be exceeded within decades, especially in the savanna and hummock grassland biomes. However, it should be noted that the modelling did not take account of some aspects of the environment, such as surface and ground water and changes in CO_2 concentration, and while it was conducted at a scale finer than most species ranges, it was at a scale much coarser than real-world texturing of species distributions due to local environmental variation. Further analysis, specifically of fine-scale environmental variation in biodiversity patterns, is being undertaken for a number of regions where suitable data are available.

Even if the environments in refuges do change such that the extant biodiversity is not adequately buffered, these places will continue to provide “islands” of different types of habitat that potentially support a range of species and ecosystems that might not exist, in the future, in the wider landscape.

At the other end of the environmental gradient, there were many examples of species existing in isolated dry and exposed micro-habitats (e.g. spinifex on rocky ridges in the savanna). These outlying populations and ecosystems could become important genetic sources in a drying environment: ecologically for local population expansion, and evolutionarily through pollen or seed dispersal, especially where they have been isolated for extended periods and have undergone some local adaptation. Similarly, in regions with increasing rainfall, isolated protected pockets will become biodiversity sources.

3.4.2 VEGETATION STRUCTURAL AND COMPOSITIONAL CHANGE

In each of the biomes, changing moisture availability (mean and variation), increases in CO_2 concentration and fire regimes are likely to lead to changes in vegetation structure (possibly including decrease in tree density in sclerophyll forest, temperate grassy ecosystems and savanna biomes; increased shrub abundance in grassy woodlands). At the same time, it is likely there will be gradual changes in the composition of species along vegetation-structure gradients. However, as noted in Section 2.3.6, it is possible that vegetation structure and composition could change independently of each other. It would also be possible for structure and composition to change at different rates. For example, structure could change much faster than composition, especially where stored water and seasonal drought are important (e.g. savannas biome), or drought exacerbates dieback (e.g. sclerophyll forests biome). Or composition could change faster than structure where elevated temperatures affect some species (possible in all biomes). In grassy woodlands (temperate grassy ecosystems biome), the determinants of structure are complex but thought to be rather finely balanced, with disturbance regimes playing a key role. Thus small changes in productivity and disturbances could lead to rapid changes in structure through changes in relative abundance of trees (with tree decline driven by decreased rainfall) and shrubs (with shrub increases driven by increased moisture stress, less frequent fire, increased CO_2). This has implications, for example, for coastal and tablelands arboreal fauna, which are dependent on large closely spaced eucalypts.

While in many extant ecological communities there are strong associations between species composition and ecosystem structure, it is quite unclear how dependent these relationships are. Similarly, changes in composition and structure may be driven by different climatic trends (e.g. respectively, temperature and moisture), and different factors might drive understorey and overstorey structure (e.g. in sclerophyll forests, respectively fire and rainfall, and drought). However, it is unclear the extent to which some "environmentally expected" changes in ecosystem structure could occur without the establishment of species currently characteristic of the new ecosystem structure. Might unchanging vegetation structure enable the persistence of composition despite high predicted environmental change? These issues have flow-on implications for fauna that may be dependent on particular species or patterns of vegetation structure; for example, fauna dependent on old-growth tall open forests (Mackey *et al*. 2002) and large-canopied trees in woodlands (Prober *et al*. 2012).

3.4.3 COMPOUNDING IMPACTS OF HABITAT LOSS AND DEGRADATION

All of the biomes have been greatly affected by human activities since colonisation by Europeans, including habitat loss and degradation. Extensive modifications have occurred for intensive uses in the temperate grassy ecosystems biome, with very high levels of clearing and fragmentation (for agriculture) and grazing and nutrient enrichment of many remnants. Similarly, in the sclerophyll forest biome, the impacts have been intensive (for agriculture, forestry and urban development) but much more localised, and the impacts are much greater in the north of the biome. Degradation in the hummock grasslands and savannas is mainly driven by extensive grazing (over grazing, trampling by ungulates, alien pasture species, weeds, water points) but includes small areas of agriculture, mining and urban development. Altered fire regimes and invasive species have also had widespread impacts. As well as directly reducing the amount of habitat available for biodiversity, habitat fragmentation reduces the ability of many species to expand their distributions along environmental gradients and exploit local environmental heterogeneity. It also reduces population sizes and genetic diversity, affecting their ability to respond dynamically to climatic variation (e.g. especially in the temperate grassy ecosystems biome), and reducing the ability of species to access variable resources in the landscape, particularly where fertile areas and flood plains have been cleared (e.g. Mac Nally *et al*. 2009). Habitat loss greatly reduces environmental buffering by reducing the local availability of habitat gradients and diversity. In regions particularly affected by past clearing, targeted revegetation might be able to restore some habitat diversity and connectivity. On the other hand, it is likely that further habitat modification, especially land-use intensification as a response to climate change in agricultural and forestry sectors, remains a major threat to biodiversity.

3.4.4 FIRE

In each biome fire plays an important role in ecosystem function and in shaping the distributions of many species, and changes to fire frequency, intensity, season or extent would be likely to have significant impacts on composition, structure, habitat heterogeneity and ecosystem processes. Williams *et al*. (2009) reviewed how climate change may affect fire regimes, using Bradstock's (2010) conceptual model that identifies four "switches", any of which may limit the occurrence of fire: (B) biomass (fuel accumulation), (A) availability to burn (fuel dryness), (S) fire spread (fire weather), and (I) ignition. The switches most important in controlling fire regimes vary between regions. Climate change is likely to affect each switch in different ways and variably among regions. In the sclerophyll forest biome the relevant trends include increasing occurrence of fire weather (extreme days and duration of fire season); increased biomass accumulation (longer growing season, possible increased growth due to elevated CO_2 and more C4 grasses; shorter window for hazard-reduction burning), and decreased biomass accumulation in some areas (dryer and shorter growing season); more available litter (faster drying/curing in hotter, drier climate); and possible increase in ignitions (summer storms). Together these are likely to drive increases in fire frequencies, which will lead to changes in vegetation structure and composition, but impacts on fire intensity are less clear. As well as changes to averages, changes to regimes of drought (frequency and severity) and rainfall (seasonality and events) are likely to have significant but even less well-understood impacts.

The temperate grassy ecosystems highlight some of the complexity of litter dynamics, with likely increases in fire weather, decreases in growth of the native herbaceous layer, but invasion of fire-promoting exotic buffel grass (*Pennisetum ciliare*) and possible increases in shrubs. The impact on fire regime is uncertain, but frequent low-intensity fires are a key structuring process for maintaining composition and structure within grasslands, and reductions in frequency and increases in intensity would drive changes in composition and structure. In the savannas fire is very frequent, but fire season is crucial, affecting the intensity of fires: late-season fires are hotter and burn larger areas, reducing the patchiness of landscape and in particular the occurrence of long-unburnt pockets. Reintroduction of patchy, low-intensity, early-season fires, and control of the introduction and spread of high biomass alien grasses (e.g. gamba grass, *Andropogon gayanus*) are conservation management objectives. Fire in the hummock grasslands is limited by fuel availability and connectivity (clump size and intervening vegetation), which is complex and driven by rainfall; time since fire, grazing, wind and temperature are also important. Expansion of high biomass flammable exotic grasses (e.g. buffel grass) could increase the spread, frequency and size of fires.

In summary, while increases in the frequency of severe fire weather across much of Australia are very likely, the responses of vegetation and the dynamics of biomass accumulation and fuel availability are much harder to predict with current knowledge, so predictions about changes in fire frequencies and intensities are uncertain (Bradstock 2010; Williams *et al*. 2009). In all the biomes, fire regimes (frequency, intensity, season), fire patchiness and the presence of long-unburnt patches all affect vegetation demographics, structure and composition, with considerable impacts on fauna in complex ways, including the availability of adequate habitat, cover and food.

3.4.5 INVASIVE SPECIES

Alien invasive species have had and continue to have a dramatic impact on biodiversity in Australia. These impacts reduce the ability of species and ecosystems to respond to climate variability and climate change. For example, in the savannas and hummock grasslands, feral buffalo, donkeys and camels degrade wetlands and refuge sites, and cats and foxes prey on species attracted to the refuges. In the new environments created by climate change, simplification of ecosystems and stress on many species are likely to create additional opportunities for alien species to expand and colonise new regions. The greatest conservation concern is likely to be expansion of species that are capable of altering ecosystem processes and transforming ecosystems (e.g. altered fire regimes due to the expansion of gamba and buffel grass). Grazing by domestic, feral and native species, enabled by permanent water points associated with pastoralism, is also a major source of habitat degradation and alteration. Alien predators and grazing have both been implicated in the ongoing rapid decline in small mammals in the savanna biome (Fitzsimons *et al*. 2010). Temperate grassy ecosystems are particularly vulnerable, as they have high levels of degradation, there are multiple sources of potential for alien species, and there is a high potential for invasive species to significantly affect ecosystem responses to climate change.

The analysis of the impacts of climate change on buffel grass revealed very significant changes in the distribution of suitable environments under climate change (Martin *et* *al*. 2012). The most striking feature was a marked southward and eastward shift in the environments most suitable for buffel grass by 2070, suggesting it may become more of a problem in the south and east, and less of a problem across the north. However, introduction (from naturalised populations or via deliberate introduction for grazing) was identified as a critical factor affecting current and future buffel grass distribution. The current total area of environmentally suitable habitat for buffel grass is markedly larger than the area of *susceptible habitat*, that is, both environmentally suitable and with a *colonisation source nearby*. In many places in southern Australia there is very little overlap between areas currently susceptible and areas that may be suitable in 2070 (high-impact scenario). The predicted decrease in the suitability for buffel grass in the north and increase in the south raises a number of interesting ecological and management issues, which are likely to be important for many other invasive species:

- Despite the prospect of a decline in the future, buffel grass is currently having a negative impact on biodiversity, so future decline does not mean its current presence and expansion in the north and centre will stop being a management concern.
- As suitability declines in the north, will the population distributions and abundance decline, or will buffel grass persist, possibly with local adaptation to the changing environment?
- Even if suitability decreases in the north, the current distribution is much smaller than the area suitable, so there is considerable scope for significant expansion before such time as it is physiologically limited.
- Is there a “window of management opportunity” to slow the spread into currently suitable but unoccupied environments, to avoid new populations in key sites becoming sources for future colonisation as the environmental suitability increases in the south?

3.4.6 SPECIES INTERACTIONS

Changes in the interactions between species are likely to be a major determinant of ecological outcomes under climate change (Dunlop and Brown 2008). Changed interactions have the potential to greatly alter realised niches (i.e. that portion of a species’ fundamental niche it actually occupies), for example, exclusion of species through competition and predation; interruption to pollination and seed dispersal; and loss of cover, habitat and food. These processes could be as important as geographic shifts in fundamental niches (i.e. suitable environment). Such interactions are well illustrated with the impacts of many alien species; but they are harder to characterise and predict among native species. Invasive species also highlight that, as well as species-by-species interactions, one new species can impact on many resident species and transform whole ecosystems. Changes in invertebrate dynamics—affecting pollination, herbivory, nutrient cycling, seed dispersal and food availability—are likely to be particularly important but hard to predict. As well as being affected by trends in climate averages, species interactions could be altered by changes in climate variability, for example, drought incidence increasing the risk of disease in forests (Allen *et al*. 2010).

3.4.7 VARIABILITY, EXTREMES AND THRESHOLDS

Climate change will alter the frequency with which various climatic thresholds are crossed as a result of intra- and inter-annual climatic variability. Variability and extremes were identified as being structuring elements in many of the biomes. The diversity of life-history strategies for coping with extreme heat and aridity and with high rainfall variability make the biodiversity of the hummock grasslands globally significant. Many species in the savanna and hummock grassland biomes are likely to be close to physiological limits and particularly sensitive to increased heat stress; the modelling also suggested very high sensitivity of biodiversity to temperature in these hotter biomes. While the savannas are periodically very wet, water *stress* throughout the long dry season is a critical factor driving tree abundance. In temperate grassy woodlands and sclerophyll forests drought affects vegetation structure directly through water-deficit stress and indirectly through increased fire weather. Ecosystems dominated by fire-killed species (e.g. heathlands, Mountain Ash Forest, Alpine Ash Forests, rainforests) are particularly likely to be affected by changes to fire frequency driven by increased drought in the sclerophyll forest biome. In the hummock grasslands, occasional high rainfall events drive productivity, much population dynamics, and the extent and intensity of subsequent fires. As with species interactions, altered variability is likely to be a key driver of ecological changes, but climate models are highly variable and uncertain when predicting changes in rainfall and its variability, and ecologists are uncertain about ecological responses to variability and in particular about any key thresholds. Observing how biodiversity responds to disturbance and climatic extremes, and assessing how this may have changed in the past, will be an important part of monitoring climate change impacts.

3.4.8 KEY ISSUES EMERGING FROM THE BIOMES

The nature of ecological responses and the extent of subsequent loss will depend on many factors: the amount of environmental change and the sensitivity of biodiversity (the modelling tells us something about this), the characteristics and responses of species, the nature and resilience of ecosystem processes, the environmental gradients and heterogeneity in the landscape, and the degree of degradation of these capacities by alien species and human activities. These factors were assessed for each biome, as much as possible within the parameters of this project. However, the nature of the variability within each biome—multiple environment types and ecosystems within ecosystems—greatly restricts our ability to make generalisations about which biomes may be more vulnerable or subject to additional losses due to climate change, or about biome-specific adaptation priorities. Such assessments may have to be done at fine scales.

Several key questions emerged from the analyses of the biomes:

- To what extent will high levels of environmental change, as predicted for a number of regions, lead to significant ecological change? What other factors affect how predicted environmental change, or ecological change, translates into vulnerability or likelihood of loss in values, and can these factors be assessed at broad scales (e.g. with continental data)?
- To what extent will local- and meso-scale environmental heterogeneity provide ecological buffering from climate change? What other factors might affect this?
- What is the best way to characterise the nature of ecological change, effectiveness of buffering, impact of changed interactions, ability of species to adapt, role of altered ecosystem processes and species impacts? How should the many lines of evidence for different phenomena be integrated and presented, especially in the context of strong uncertainty and points of disagreement among different lines of evidence and different experts?

4. Adapting to climate change

There is increasing recognition that climate change represents a threat to biodiversity that is fundamentally different from other threats, and as a result it needs to be approached differently. For example:

- Climate change will lead to many different types of changes to species and ecosystems; some of those may result in loss, others will not.
- The impacts of climate change will be experienced across all biodiversity and cannot be excluded in the way legal protection can reduce habitat loss or pest exclusion can reduce the impacts of invasive species. (However, loss is likely to be greater where biodiversity is under pressure from fragmentation and invasive species.)
- The rate, scale and geographic extent of climate change and the responses of biodiversity make this a phenomenon of a much greater magnitude than other threats.
- All biodiversity will be affected and change will be ongoing for many decades, if not centuries, requiring a major revision of the objectives of conservation.
- It is likely that systematic management responses are needed, as opposed to addition of climate adaptation bandaids to existing portfolios of conservation strategies.
- There is considerable uncertainty about future environmental change, how biodiversity will respond, where the losses will be and what actions might reduce those losses. And there will be limited opportunity to reduce those uncertainties by learning from locations that experience the impacts first or from early signals, since changes will be occurring everywhere and many changes will be hard to detect against the noise of environmental and ecological variation.
- While much ecological and evolutionary theory is predictive when one or two factors are varying, the circumstances of climate change make accurate prediction from available theories very difficult. For example, contrasting predictions about change and vulnerability can frequently be made from different strands of ecological theory.

Below we outline a range of emerging issues about how to approach adaptation to climate change, and in the following section (5) we focus on their implications for the NRS.

4.1 Mainstreaming climate change adaptation

Our experiences—personally, in the biome expert workshops, and with various agencies—suggest that responding to climate change is not easy. These experiences strongly support the notion of a journey of increasing understanding about climate change and its implications, the responses that might be effective and the information that might be useful. To be effective, and be adopted, adaptation strategies need to fit with local institutional and ecological contexts (Howden *et al.* 2007). Our approach is therefore to support the mainstreaming of climate adaptation: helping individuals and agencies acquire the knowledge and skills to gradually build their own responses to climate change into their core business rather than deliver stand-alone, context-free adaptation actions. Here we outline three steps for developing effective responses to the impacts of climate change (adapted from Van Ittersum 1998).

1. There needs to be awareness and agreement that climate change will affect biodiversity and that something needs to be done about it. For many conservation agencies this step is largely completed due to a wealth of evidence from Australia and overseas studies that have demonstrated that future climate change is likely to have a large impact on biodiversity. However, the relatively near-term and significant nature of the changes emphasised in this report (e.g. Figure 10) is not necessarily appreciated. Also, in regions where biodiversity decline is ongoing and significant due to other pressures (e.g. mammal decline

in northern Australia), adaptation may appear a lower priority. Likewise, it may appear in some regions that biodiversity will be resilient to climatic changes, or that little can be done about it. This step involves recognising that climate change will directly affect important biodiversity values and affect the management of existing pressures.

2. The second step is reassessing the objectives of conservation in light of the likelihood of significant and continual future changes in species and ecosystems. Assessing which conservation aspirations are feasible and which are less so involves understanding how the full spectrum of climate change impacts will affect a wide range of biodiversity values and how it may be possible to reduce future biodiversity losses by managing differently in response to climate change. While the need to reassess objectives is widely acknowledged, in our experience with many managers, actually doing so is a challenging process. In practice it is hard to move substantially beyond identifying additional monitoring and management actions that might help preserve currently threatened species or ecosystems as the climate begins to change. Yet future-oriented conservation strategies really do need to accommodate the likelihood of substantial changes in biodiversity at most locations. While step 1 can focus on one or two types of change and biodiversity values, step 2 must include consideration of a wide range of types of change and values to be effective. Some of the many dimensions of this challenge are discussed in the following subsections.
3. The final step is assessing which conservation strategies will be most effective under climate change. This includes considering the revised conservation objectives, the availability of information, the effectiveness of different options, and the impact of uncertainty on outcomes and effectiveness. These factors have the potential to significantly affect which types of strategies are most suitable, and how species or locations are targeted. With a growing understanding of the rate and impacts of climate change and sense of urgency there is a natural desire to develop and implement adaptation actions rapidly. It is not uncommon for the second step, reassessing objectives, to be bypassed in the haste to implement on ground action.

As new strategies are implemented, and new information about climate change and ecological responses becomes available, including from the results of implementation, returning to step 1 would close the loop on the classic policy adaptive management cycle.

One of the key differences between the steps is the type of information required. For step 1, good evidence (e.g. from theory, observation and modelling) about one or two types of change (e.g. species distributions, phenology) is sufficient. However, steps 2 and 3 require a much more complete understanding of how biodiversity may change (Section 3.1) and understanding of social values associated with biodiversity, even if the evidence for these is less readily available. It is also the case that, while many approaches have been suggested (Dunlop and Brown 2008; Heller and Zavaleta 2009; Mawdsley *et al*. 2009; Steffen *et al*. 2009), given the state of knowledge about the level of environmental change and the future responses of species and ecosystems, there are no best practices or demonstrably most efficient management responses.

4.2 Reassessing conservation objectives

Before concerns about climate change, most conservation objectives were implicitly focused on preserving biodiversity as it is, or restoring it to some prior condition from a current degraded state, or at best allowing some fluctuation within defined bounds. However, climate change will drive continual and directional changes in the genetics, abundance and distribution of many species and in the composition, structure and function of ecosystems. As a result, there will almost certainly be extinctions, losses in ecosystem services and other impacts on values associated with biodiversity. The details of the changes and the rate of change remain uncertain, but the modelling conducted in this study suggests that environmental changes driving biotic change will be substantial within decades. Although most of these changes will be essentially unstoppable, in some situations management may be able to have some influence on how the changes unfold and may be able to reduce some of the losses.

It is now widely acknowledged that there is a need to develop conservation objectives that are consistent with a dynamic biodiversity, but there is little clarity about what this means. It is sometimes expressed as a need for “dynamic conservation objectives”; however, this is quite confusing as “dynamic” should primarily refer to *biodiversity*, not the objectives. Dunlop and Brown (2008) suggest the new conservation task is to “manage the change to minimise the loss”, on the basis that stopping change and stopping loss are both infeasible, and that change in biodiversity is not synonymous with loss in biodiversity values. In many cases, revising objectives will not greatly change the types of actions undertaken (fire management, protecting habitat, revegetation, weed and pest control), although it may alter how they are implemented (where and when); the biggest difference will be in why these actions are undertaken, the outcomes sought and how success might be measured (Biggs and Rogers 2003). Below we discuss various issues associated with change and loss.

4.2.1 PRESERVATION VERSUS FACILITATING CHANGE

There are two main management approaches to minimising loss as changing environmental conditions become less suitable for extant species and ecosystems. The first is *preserving* biodiversity *in situ* and may involve manipulating habitat and local environmental conditions; this is most consistent with traditional species recovery and ecosystem restoration activities and may accompany behavioural, phenotypic and evolutionary changes. The second is *facilitating change* so that species and ecosystems can, in some way, remain in equilibrium with the changing climate. Such outcomes might include biodiversity moving spatially to remain within current bioclimatic niches as they shift.

There are likely to be significant challenges with attempting to both preserve and facilitate change. It may be possible to actively manage species and ecosystems in small areas *against* the tide of environmental change. However, it is unlikely to be efficient or even feasible to intensively manage whole protected areas and landscapes in this way, especially for change corresponding to more than, say, 2°C of global warming. Change can be facilitated by ensuring the availability of habitat for species to establish, assisting dispersal, managing some ecosystem processes such as grazing and fire, potentially managing some keystone species, and creating new ecosystems (Steffen *et al*. 2009). However, it will not be feasible to actively help all species remain in equilibrium with shifts in their bioclimates at regional scales: the rates of shift for the bioclimatic niches of most species are expected to be faster than the species could disperse even with available habitat and connectivity; there will be too many species to translocate, and the environmental niches of many species could disappear completely.

For most species, survival may be a combination of both changing and persisting. This could happen in a number of ways, including local-scale dispersal into different environments within existing distributions (local habitat buffering); gradual expansions of species distributions but into areas of sub-optimal environment; or some species may persist in their current distributions and expand into completely new regions. While local persistence is likely to be significant for many species through local buffering and adaptation, it is unclear if or when the magnitude of environmental change might exceed that persistence capacity.

Some management actions are likely to assist both persistence and facilitation of change, for example, protection and restoration of a diversity of habitat and reduction of other threats. However, there are also likely to be situations where the two objectives come into conflict (e.g. fire regimes, habitat restoration, managing invasive native species), and it may be necessary for managers to identify when they are seeking to preserve versus facilitate change (Dunlop and Brown 2008).

4.2.2 MULTIPLE VALUES

While extinction is frequently listed as the headline indicator of biodiversity decline, there are many ecosystem services and other aspects of biodiversity that are valued by society (Millennium Ecosystem Assessment 2005a). If the environment is essentially static, then many of these biodiversity values are likely to be highly correlated, and a focus on protecting a few “biodiversity surrogates”, such as threatened species, is likely to lead to protection of a wider set of values. As a result, there is currently little articulation of the full range of societal values in the objectives of legislation, policy or management programs. Indeed, many programs focus on preservation of ecological communities, giving priority to threatened ecological communities. The logic is that if communities are protected then their constituent species will be, as will the ecosystem functions they perform. However, even in a static world, a singular focus on threatened species or types of communities can lead to significant trade-offs. For example, values associated with tracts of vegetation being large and intact, important for biodiversity in a regional context, or being part of an urban landscape, might not be reflected by the threat status of the species that are present.

With a growing understanding of the impacts of climate change it is even clearer that many biodiversity values are not correlated, and managing for one may not benefit others. It is therefore necessary to unpack the different types of values associated with biodiversity, and assess which ones are more feasible to protect, possibly which ones are higher values, or in some way more fundamental. This is an emerging area of research, and as values are socially constructed they can be expected to evolve over time (Prober and Dunlop 2011). Through our attempts to help people think about different values in this project and in many other interactions with conservation stakeholders, we have identified a range of different types of properties of biodiversity that may give rise to values, and we have categorised them into different dimensions of biodiversity and how persistent they might be under climate change (Table 3). This typology suggests which attributes might be more feasible to protect; other research will be required to assess how much they might be valued by society. The table focuses on assessing different aspects of biodiversity as potential normative ends of policy; design of management to implement such policy would require identification of means and indicators for each of these ends.

In the table, the first column categorises biodiversity into different dimensions or entities. While similar to the traditional genes-species-ecosystems categorisation of biodiversity, this is intended to reflect the entities that people might experience and value in various ways. The top three rows reflect, for example, what someone might experience, respectively, when bird watching, on a stroll through the bush, and looking out from a hilltop. These dimensions are quite different ecologically from each other and, we suggest, readily recognised as being valued by the person in the

Table 3. Attributes of biodiversity associated with different dimensions of biodiversity that might be experienced and valued by people in different ways (adapted from Dunlop and Brown 2008). Static attributes are those that could be conserved with an unchanging biodiversity; dynamic attributes are those that might be conserved as biodiversity changes in response to climate change. This is presented not as a definitive statement but to aid debate about biodiversity values and changing objectives.

	STATIC ATTRIBUTES	DYNAMIC ATTRIBUTES
DIMENSION OF BIODIVERSITY	CURRENT OBJECTIVES	FUTURE OBJECTIVES
Individual species and genes (fundamental units of biodiversity, including ecological communities)	Abundance, distribution and cooccurrence	Existence of a species (surviving and evolving somewhere
Ecosystem (quality, ecosystem processes; from the scale of a patch on the ground to the scale of key ecological processes)	Ecosystem type (composition, structure and function; condition relative to type)	Ecosystem health (key ecological processes underpinning the cycling of water, carbon and nutrients, soil formation, primary productivity, and species diversity)
Land/seascapes (social-ecological system; degree of human domination; many ecosystem services; surrounds to continent)	Mixture of the types of human uses and natural ecosystems	The balance of uses (quantity of native ecosystems in the social-ecological system)
Biological diversity (genetic, α, β, γ)	Change in species and ecosystems identity across space	Patterns of diversity and potential for evolution

street. While species and their collectives (ecological communities) dominate official expressions of biodiversity value, there are examples of values associated with the other dimensions being recognised in programs, for example, habitat degradation (ecosystem dimension), and wilderness or paddock trees (landscape dimension). The goal of a "healthy working river" for the Murray-Darling system was a very explicit landscape objective seeking to balance river flows between human uses and maintaining ecological processes (COAG 2004). The fourth row, biological diversity, is perhaps a more technical and hidden dimension, but it represents the all-important variation at multiple scales within the totality of genes, species and ecosystems that is valued in its own right and because it gives rise to and maintains the other three dimensions.

The second and third columns include various attributes of the biodiversity dimensions that give rise to values. The second column includes those attributes that are associated with biodiversity in largely unchanging environments, whereas the third column seeks to identify attributes of biodiversity that might persist and continue to provide value as the attributes in the second column change. The attributes in the second column are, coincidently, exactly the types of attributes that might be recorded in contemporary assessments of the state of biodiversity, and change in these attributes is typically (sometimes legislatively) regarded as decline or potential loss. The coincidence of these attributes as normative expressions of biodiversity and as attributes facing inevitable change will eventually become a problem for conservation policy as the climate changes.

The challenge is to develop a robust set of attributes for the third column, translate them into climate change resilient conservation objectives, and transition the focus of conservation programs to those objectives. Doing this will necessitate giving more explicit attention to aspects of biodiversity other than species (i.e. the ecosystem, landscape and biological diversity dimensions in the second, third and fourth rows of Table 3). Ensuring the existence of species—that is, "minimize native species loss at the national scale" (Prober and Dunlop2011)—is a relatively straightforward aspiration. However, the dynamic attributes for ecosystems, landscapes and biological diversity are currently much more contestable scientifically. For example, ecosystems, despite having clear emergent properties, are almost always described in terms of their constituent species, yet it may become necessary to define policy objectives for ecosystem health in terms of levels of biological productivity; storage and cycling of carbon, nutrients and water; formation of soils; species richness; trophic structures; and demographic and structural diversity. This is further complicated as the environmental potentials for these parameters, against which management success could be measured, would also be expected to change with climate change. Landscape objectives might be defined in terms of the balance between natural and human-dominated land uses, or the partitioning of primary productivity. By explicitly combining potentially conflicting biodiversity and production outcomes, landscape objectives are very likely to be socially as well as scientifically contestable (e.g. debates about water allocations in the Murray-Darling system). Objectives for biological diversity might be described in terms of the richness and spatial structuring of variation at different levels, or as maintaining the "evolutionary character of the Australian biota" (Prober and Dunlop 2011).

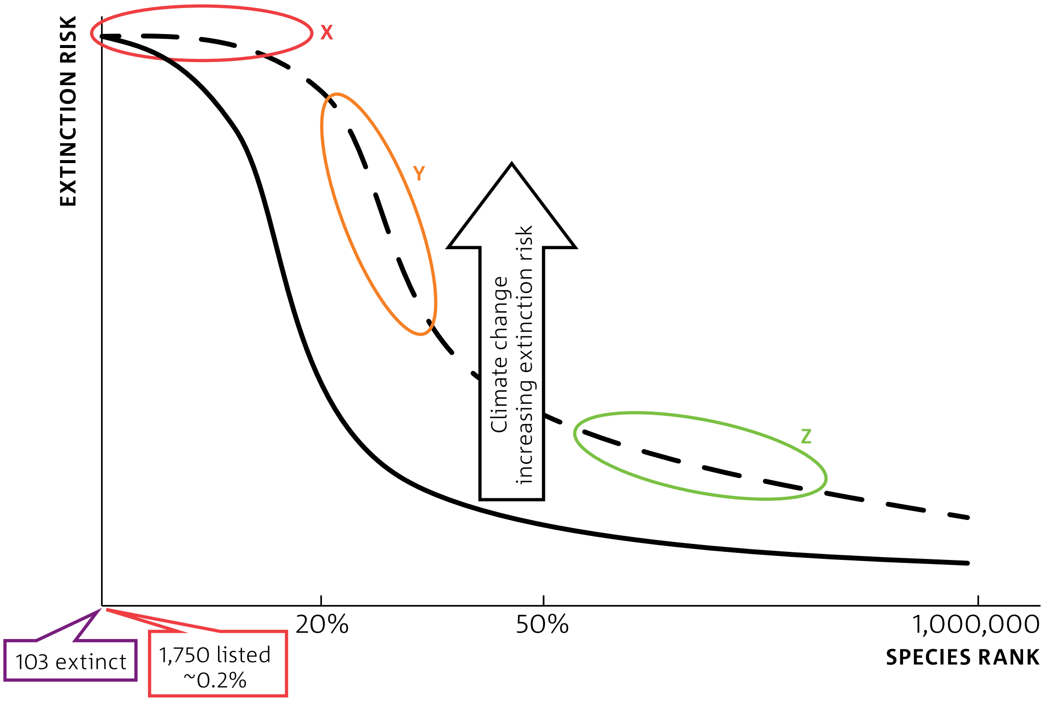
Characterising these various attributes of biodiversity, how they relate to values and developing institutionally workable definitions, indicators and objectives is one of the science–policy challenges of the decade (e.g. to be delivered in time for the next 10-year review of the EPBC Act, or its successor). The sister science–management challenge is to develop conservation actions and programs that effectively reduce loss in values associated with the attributes in the third column, while allowing or even facilitating change in the attributes in the second column.

4.3 Priorities and triage

In addition to shifting focus from static to dynamic attributes (moving from the second to third column in Table 3) and giving more attention to the "other" dimensions of biodiversity (bottom three rows in Table 3), there is a need to start considering how we might distribute conservation investment, or prioritise, *within* each of the things listed in the third column: which species, which aspects of ecosystem health, which properties of landscapes, what biodiversity patterns. Each of these decisions (between columns, between rows, within cells) will affect the assessment of which places might be of higher conservation priority. Currently a significant proportion of conservation effort is prioritised on the most threatened elements of biodiversity: protecting and restoring threatened species and ecological communities. However, there is growing recognition that some species might be beyond recovery, and it may be more appropriate to "take a more holistic and strategic approach, building the fence at the top of the hill rather than staffing the ambulance at the bottom" (Garrett 2009), adopting a triage approach to conservation (Bottrill *et al*. 2008; Hobbs and Kristjanson 2003). An alternative is to increase the *efficiency* of limited conservation resources by focusing investment on those places or species where the greatest "marginal loss avoided" might occur (e.g. Pressey *et al*. 2004). With sufficient knowledge it may be possible to mathematically implement this aspiration (Possingham *et al*. 2001). Climate change has implications for both of these methods of choosing priorities.

While the number is unknowable, it is very likely that under climate change the rate of species extinction will be much higher than at present (Millennium Ecosystem Assessment 2005b; Thomas *et al*. 2004). If it were feasible to rate the probability of extinction of all species as a result of climate change (and other pressures), then a plot of the species ranked from most vulnerable to least might look something like Figure 13.[1] Using a vulnerability approach: if a small number of species were expected to go extinct then it might be sensible to focus on those near extinction (X), but if, say, 20% or 50% of species were likely to go extinct then effort focused on the most vulnerable would be wasted and it might be better to invest effort in reducing the risk for species at relatively lower risk (in zone Y or Z).

Figure 13. Hypothetical "rank-extinction risk" curve for Australian species ordered from most to least vulnerable on the horizontal axis. There are about one million species in Australia; 1 750 are nationally listed as threatened or endangered, and 103 are known to have gone extinct. Under climate change the risk of extinction for most species would be expected to increase (curve shifting up/right), the shape of the curve may change, and the actual ranking of species might also change. The shape of the curve, now and under climate change, is quite unknown.



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[1] As far as we know, such a curve has never been produced analytically for any region of the world, and we doubt a remotely accurate one could be produced. All we actually know about the shape of such a curve is that there are some species that are much more likely to go extinct (or are even "destined for extinction"), and others that are probably at very low risk of extinction, and the curve is probably smooth; but it may be somewhat symmetrical as shown, or skewed with relatively few species vulnerable or most species vulnerable.

It may be much easier to reduce the risk of extinction for some species than for others; an efficiency approach might assess, for example, the relative merit of reducing by a small amount the extinction risk of highly vulnerable species compared to reducing by a larger amount the risk to species that are moderately vulnerable. Unfortunately, actual extinction risks for individual species will depend on a wide range of factors, some of which are currently unknown (from future greenhouse gas emissions right through to changes in interactions between species), and the effectiveness of management at reducing risk for individual species under climate change is likely to be even more unknown.

So, from an efficiency perspective, in many situations it will definitely be sensible to avoid concentrating management effort on the most vulnerable species. However, from a technical perspective, the more efficient alternatives are probably difficult to actually identify and implement due to the precision required of the information needed to make those decisions. In addition, there are significant social considerations about reducing conservation effort on the most vulnerable species, especially once they have been identified. There may, however, be other ways to achieve a similar "more efficient" outcome without having to accurately rate the vulnerability of individual species. This is another climate-adaptation science frontier. One approach might be to try to characterise and manage the ecological factors that most limit the survival prospects of species in different parts of the curve (e.g. competitors, predators, habitat, connectivity, ecological flows), without having to actually identify and rate all those species.

Where it is difficult to accurately select the most efficient target species or locations for management, there is a risk that an optimisation process may lead to resources being actively concentrated in a less efficient manner. This highlights that some attempts to prioritise effort might *decrease* the ability of management to reduce biodiversity losses (Walker and Salt 2006). It might therefore be sensible to ensure effort is not being concentrated in any one group, especially the most vulnerable or the least vulnerable. Alternatively, management actions that benefit a larger number of species, across the vulnerability spectrum, might be more effective even if they benefit individual species less than more targeted management. For example, developing continuous habitat corridors might be beneficial to those species in need of contiguous habitat (quite possibly the most vulnerable), but many more-mobile species will be able to use stepping stones and biodiversity-friendly matrices to colonise distant patches of suitable habitat. Similarly, reducing threats from exotic species and habitat degradation, or managing a few ecologically important species, may be beneficial to many species. As well as the vulnerability of species to extinction, such analyses could also be applied to other valued aspects of biodiversity (Section 4.2.2).

Rather than rate the vulnerability of species, it might be possible to rate locations, as done using the biotically scaled environmental stress metrics in this project. These metrics do not directly equate to vulnerability, or probability of loss, as they do not take account of the ability of species and ecosystems to respond without loss of values. However, it may still be effective for managers to vary the focus of management, depending on stress levels (see Section 5).

In summary, in recognition that some losses of biodiversity values are inevitable, there is potentially merit in reducing the management focus on the most vulnerable parts of biodiversity. Such a move would have technical, administrative and social implications. Attempting to do this species-by-species would require considerable amounts of information. An alternative might be to use management approaches that can be demonstrated to be effective for many species, if not the most vulnerable, without necessarily needing to assess the vulnerability and management needs of individual species. Such approaches might focus on ecological processes, locations, biodiversity patterns, ecosystems and landscapes more than on individual species (Prober and Dunlop 2011).

4.4 Types of adaptation strategies

Various approaches to adaptation are possible, with their suitability depending on the nature of the future changes, knowledge of the systems, the availability of information about how they might change, the resources available and other institutional factors.

Where change is expected to be small and knowledge and capacity high, it might be feasible to manage towards a desired state of biodiversity (specific community or ecosystem, or locations for species). Managing to achieve a very specific outcome is always an attractive prospect, especially for people with intimate familiarity with particular ecosystems and who might be less willing to countenance marked change in the system. However, in the majority of situations knowledge of the dynamics of the species and ecosystems are relatively low and the ability to predict future dynamics even lower. Furthermore, the modelling in this study highlights that the expected level of change is very high, hence a wide range of ecological outcomes could occur through a combination of multiple types of change, which in turn is likely to necessitate significant reassessment of objectives. We suggest these factors (uncertainty, multiple changes and new objectives) are framing conditions, and we provide a template for choosing management approaches.

4.4.1 TARGETED VERSUS BROADLY APPLICABLE STRATEGIES

Adaptation strategies can be broadly grouped into two categories (Table 4). In general, for relatively low levels of change and where resources and available knowledge are high, characteristics on the left may be appropriate, but in the face of high levels of environmental change such characteristics in management are likely to become less effective. This has implications for the setting of conservation targets and monitoring and evaluation, which is likely to be more complicated for strategies with a wider focus.

In many ways the NRS, as a conservation strategy, sits in the right column, with its focus on representativeness and low levels of intervention. In contrast, threatened species management sits in the left. The institutional context of management

Table 4. Characteristics of contrasting strategies for managing biodiversity under climate change.

	INTENSITY OF MANAGEMENT	
	HIGH	LOW
Focus	Highly targeted	Broadly applicable
Outcome	Seeking prescribed change	Facilitating natural change
Control of biodiversity	Active	Passive
Management detail	Species- or location-specific blueprint	Rule-of-thumb
Level of intervention	More	Less
Information requirement	High (requiring information about the dynamics of the specific species or locations and scenario)	Low, since applicable to many species, locations and scenarios
Planning	Species-by-species, need to decide which species to target for management	Many species as possible, but not necessarily identified species
Resource allocation	Optimised: effort concentrated on species or locations where the greatest marginal loss avoided can be achieved	Robust/Resilient: effort distributed to achieve outcomes under many contingencies (Walker and Salt 2006)
Monitoring and evaluation	Measure targeted species	Measure a wide range of values, as expect many species, but not all, to decline
Species affected	Few targeted	Many less targeted
Impact per species	High	Low
Applicable	Low environmental change	High environmental change

strategies is likely to shape its characteristics; for example, where threatened species or communities are the key institutional driver, strategies may be more likely to have characteristics from the left hand column, even where the intended conservation outcomes are much broader, for example, managing change in whole landscapes. It may be appropriate to use a mixture of types of strategies, for example, using relatively passive management of large areas of intact habitat, and more active management in the intervening matrix where threats are greater and maintenance or creation of additional habitat is more an issue.

This table combines level of change and intensity of management. In theory these could be separated, and there is debate about management approaches in relation to these factors. For example, should management focus on high-intensity (information expensive) management targeted at avoiding loss under a small amount of change (2°C), or low-intensity management (with low information need) targeting higher levels of change (4–6°C)? In reality, even for a small degree of warming (2°C) there will be a considerable amount of unavoidable loss of biodiversity values; thus all future management will be *managing the change to minimise loss*, with the choice being between *preserving in situ* and *facilitating change* (Dunlop and Brown 2008). Furthermore, there is very little prospect of stopping at minimal change; 4°C is quite likely, with greater increases possible in the next century, if not sooner. (The global temperature range for the A1FI scenario, which we are currently tracking above, is about 4 ±2°C by 2100; IPCC 2007; Rahmstorf *et al*. 2007; Solomon *et al*. 2007.) Furthermore, it is likely that many management strategies designed for higher levels of change will be effective at lower levels of change, but the converse is not likely to be true.

4.4.2 PROACTIVE, REACTIVE AND ROBUST STRATEGIES

It is useful to think about three broad types of strategies for managing biodiversity under climate change.

Proactive strategies involve predicting how particular species or ecosystems will change and implementing targeted management in anticipation of the changes, to decrease the losses for those species or ecosystems. In many situations early management may be the most effective or only way to minimise or avoid some losses. However, such strategies may require a high degree of prediction about ecological change and the future effectiveness of management, which is unlikely to be available in most situations. Preventative actions may also be harder to develop in risk-averse agencies that are more predisposed towards dealing with immediate and observable threats of loss.

Reactive strategies rely on observing changes then implementing management interventions targeted at actual or imminent losses. Much current conservation is reactive: intervening when a threat or decline is detected. These strategies have the distinct advantage of requiring little or no predictive ability, and they involve very low risk of investing in a threat that does not materialise. However, empirically, it is very difficult to detect environmental or ecological trends, especially in the context of a highly variable climate. For example, the step change in winter rainfall in south-western Western Australia took two decades to detect, despite very good records of rainfall and stream flows. This is likely to be even more the case for ecological changes that might be hard to observe, l*et al*one detect trends in, and where there are multiple types of change occurring; for example, changes in fire regimes in the savannas may take 50 years to be reflected in age structure (Liedloff and Cook 2007). In many situations adopting reactive strategies may lead to implementation of management interventions well after they might have been most effective, especially if the management itself has a long lead time (e.g. habitat restoration).

Robust strategies, coming from scenario planning, involve designing management that is likely to be effective under a wide range of future magnitudes and types of change, and for a wide range of species. Such strategies could be designed using detailed information and knowledge from case studies, but their implementation more broadly will require less information than targeted management. Robust strategies are, in a sense, a variant on proactive strategies. As discussed above, these approaches are likely to be effective for some species but not for others.

Proactive and reactive strategies can be combined within a scenario planning context. Different ecological scenarios can be developed and explored using modelling, and a monitoring program initiated focusing on testing hypotheses about which scenario will unfold. Management could then be implemented with greater surety at the first signs of impending losses. However, this itself is an intensive planning activity and is very unlikely to be feasible for the majority of protected areas or regions. Where predictive capacity exists, it can be used to help design targeted and robust strategies and test their effectiveness against a range of change scenarios. It can similarly be used to identify the particular situations where a robust strategy may not be effective. This would enable robust strategies to become the dominant management approach, complemented in very specific situations (e.g. highly valued species) by more targeted strategies.

4.4.3 ADAPTIVE MANAGEMENT

Adaptive management is widely regarded as best practice in conservation (if not widely practiced), and is frequently promoted for addressing climate change impacts (Heller and Zavaleta 2009). However, it needs to be noted that *adaptive* management and *adapting* to climate change are not synonymous. Adaptive management is a type of reactive strategy, or if implemented “actively” it has proactive elements (testing different strategies); either way, a primary component is waiting and monitoring ecological change, then altering management in response. Thus, due to the protracted feedback and difficulty of detecting the impacts of management or climate change in a timely manner amid much variability, it is likely that adaptive management may not be effective for directly addressing climate change impacts in many situations. It may be better to think of adaptive management as a framework within which climate adaptation might be implemented (and improved) rather than regarding it as a solution to climate change in itself.

4.4.4 ADAPTATION PATHWAYS

“Adaptation pathways” is a term that is being used to describe staged implementation of a series of planned adaptation decisions (management changes) as information becomes available. Adaptation pathways can be used to work towards more transformational changes that might be required to address high levels of climate change (e.g. 4–6°C) and plan management actions that need to be implemented proactively if they are to be effective, and at the same time accommodate current uncertainty and institutional caution (Stafford Smith *et al*. 2011). Frequently the transformation management actions that might be required to address high levels of future change will be too risky to implement in the near-term due to uncertainty about climate change or ecological responses. However, it may be possible to strategically use lower-cost, incremental decisions as stepping stones towards larger changes, maintaining the proactive element of management but permitting larger management changes to be delayed until risks are lower due to newly available information. In particular, this style of planning can be used to avoid maladaptations—management decisions that may seem attractive in the face of small levels of change, but that may be ineffective at higher levels or actually reduce the capacity to adapt to higher levels of change. For example, efforts to artificially maintain historic levels of water availability to a wetland may be effective for small levels of drying but could become ineffective or impractical for higher levels of drying; and as a result more rapid adaptation to very dry conditions would be required once the initial management approach fails or is withdrawn. Similarly, focusing on long-term climate change in revegetation may ensure species are chosen that lead to a higher chance of establishing populations and ecosystems that can thrive for many decades, and provide hollows and old-growth habitat in the future (Steffen *et al*. 2009; Vesk and Mac Nally 2006).

4.5 Managing species, ecosystems and ecological processes

There is an increasing aspiration in Australia to move beyond a focus on conserving individual species with more conservation programs (e.g. submissions to reviews of both the National Biodiversity Strategy (DSEWPaC n.d.) and the EPBC Act (Hawke 2009)); and the need for this is highlighted by the challenge of conserving biodiversity in the face of climate change. This trend has various drivers, including recognition that biodiversity has many values in addition to those associated with species; the species-by-species approach is likely to become more difficult to manage with a dramatic increase in the number of species vulnerable to extinction; and species persistence is underpinned by environmental resources and ecosystem processes and it may be more effective to focus on preserving those foundations ("conserve the stage not the actors"; Beier and Brost 2010; Hunter *et al*. 1988). The framework used to develop the NRS in Australia, with its bioregional approach and comprehensiveness principles (National Reserve System Task Group 2009) certainly has a focus beyond individual species, and it is to some extent pre-adapted to dealing with climate change (Dunlop and Brown 2008). However, the spatial extent of the NRS as currently implemented is limited, and as a conservation tool it has restricted application to whole landscapes.

This expanded scope for conservation is often referred to as the ecosystem approach, landscape approach or connectivity conservation. The science-policy knowledge base for shifting the focus of conservation is growing, but there are significant uncertainties; for example, what is the relative importance of knowing about the characteristics of genes, species, ecosystems, landscapes or ecological processes, or about environmental and biotic change at local or landscape scales? It is also unclear how different ecosystem-based conservation programs might actually be from species-based ones. One potential key advance is a focus on ecological processes as opposed to the state of biodiversity, in particular the processes that give rise to persistence of biodiversity in the face of environmental change and other pressures (Prober and Dunlop 2011). The utility of such an approach is highlighted by comparing the sclerophyll forests biome and adjacent temperate grassy ecosystems. No forests are undisturbed by human activities or invasive species; however, there are many large areas of relatively intact forest ecosystems, and they typically include much biotic variability and have a high level of functioning of ecological processes. As a direct result they can be expected to undergo a considerable amount of natural adaptation to climate change. In contrast, the grassy woodlands have been highly fragmented and many remnants are degraded, greatly impeding the ecological processes that underpin their natural responsiveness to variability and disturbance. These ecosystems are far less likely to be able to adapt naturally to climate change without significant restoration of landscape-scale ecological processes.

Various ideas were put forward in the workshops to enable this broader approach:

- identifying and preserving key landscape characteristics: environmental gradients and variability, topographic variability, pockets of high productivity and refuges
- protecting remnants and less disturbed areas such as travelling stock reserves and cemeteries as sources of native species and as sites more likely to assemble healthy native ecosystems rather than exotic-dominated communities
- "softening the matrix" by protecting and facilitating the recruitment of native vegetation between fragments (e.g. paddock trees)
- restoring degraded or cleared land to increase three key process factors: the area available to native biodiversity, the diversity of environment types available, and the movement of individuals (and species) through landscapes
- recognising the potential value of cleared areas of higher productivity land in the vicinity of remnant native vegetation, which if restored could provide significant resources for biodiversity in the remnants, especially during drought
- starting to experiment with landscape-scale climate-resilient restoration in the temperate grassy ecosystems as the need is high and there is lower risk of adversely interfering with natural ecological processes; this could include ensuring restoration

undertaken for other reasons (e.g. watertable control, carbon sequestration) facilitates adaptation.

There needs to be further development of the knowledge base required for refocusing conservation objectives and management on ecosystems and landscapes. Developing this knowledge base needs both clearer articulation of biodiversity values and a good ecological understanding of how specific landscapes work. Prober *et al*. (2012) present a framework that integrates the state of biodiversity at multiple scales, and the processes acting on it, in particular highlighting the processes that enable biodiversity to persist (through resistance and resilience) in the face of disturbance and variation (Figure 14). Table 5 is an application of Figure 14, and lists key persistence processes identified for the temperate grassy ecosystems. This framework can be used either conceptually, or can be populated for a specific region, to help characterise different management opportunities (e.g. for the Great Western Woodlands in south-west Western Australia; Prober *et al*. 2012). It is also useful for enabling a shift in focus from the state of biodiversity to the processes and structures that give rise to persistence of biodiversity at various scales.

Figure 14. A framework for integrating the state of biodiversity and the process driving change and persistence (after Prober et al. 2012).

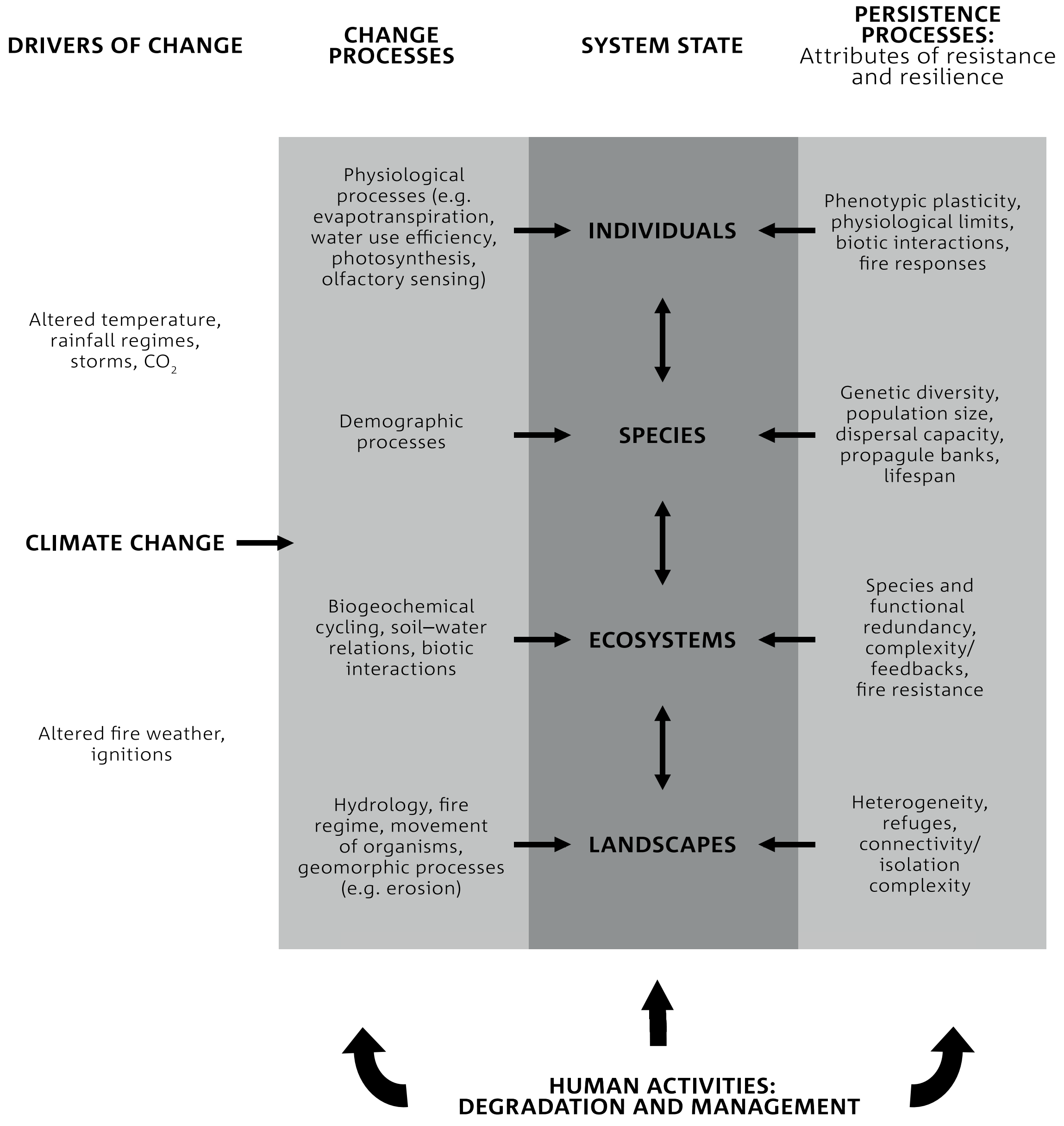


Table 5. Key attributes enabling the persistence of biodiversity, through resistance or resilience, in the temperate grassy ecosystems biome. In the current state of the biome, many of these attributes have been compromised by fragmentation and degradation, hence restoration of these attributes could facilitate adaptation.

SCALE	KEY ATTRIBUTES INFLUENCING PERSISTENCE OF BIODIVERSITY IN THE BIOME
Individuals/Species	Many widespread species with likely wide physiological limits within individuals
	High genetic diversity and large population sizes facilitate adaptation in widespread species
	Relatively short generation times in herbaceous species facilitate adaptation through selection
	Limited seed banks reduce resilience
	Variable fire resilience
Ecosystems	Moderate functional diversity facilitates adaptation to change in climate and fire regime: C3/C4 and annual/perennial mixes; variety of fire responses
	High native species richness (redundancy) facilitates functional replacements
Landscapes	High connectivity except in isolates facilitates migration
	Moderate landscape heterogeneity facilitates local shifts in distributions
	Refuges

5. Adaptation issues for the NRS

In previous sections we presented results on environmental change (in terms of biotically scaled environmental stress) and ecological change, and discussed key issues for adaptation, particularly around objectives, vulnerability and priorities. These issues raise a range of questions for the NRS. For example: should protected areas in regions facing higher and lower levels of biotically scaled environmental stress be managed differently? Should a manager (or the NRS) place a higher or lower priority on a region facing higher biotically scaled environmental stress? How should a manager vary management conservation objectives between areas of high and low stress? These issues were discussed in various ways at several workshops during the project. It was clear these questions are critical, and the level of future environmental change has the potential to affect management choices. However, it also became clear that there is no objective scientific prescription for how the magnitude of environmental change should affect issues such as which objectives, how much management, and which types of strategies. In the end, regional and institutional contexts will affect the choices of managers and policymakers about the appropriateness of different responses. Below we discuss some of the issues that might be relevant to consider when assessing how to respond to spatial predictions of environment stress.

5.1 Biotically scaled environmental stress and the NRS

Multiple factors determine how biotically scaled environmental stress may translate into potential loss of biodiversity values. First, the sensitivities of individual species and local- and landscape-scale ecological processes will determine ecological responses. Any concomitant losses will be a function of the socially constructed values associated with the multiple dimensions of biodiversity and how they are variously affected by ecological change. Issues associated with setting priorities and management strategies are discussed in Sections 4.3 and 4.4 respectively. On average, higher biotically scaled environmental stress will *probably* lead to greater ecological change which will *probably* lead to greater loss in biodiversity values. However, it is quite feasible that there will be large and systematic differences between biomes, regions, ecosystems and species groups, especially in the specific climatic drivers of change, types of ecological changes that predominate (e.g. Figure 5) and how they interact with other pressures (again regionally variable); and the construction of what is valued socially also varies regionally, institutionally, among taxa and over time. Thus any presumed relationship between predicted stress and ecological change or loss, used to set management priorities, should be regarded as a hypothesis and be subject to monitoring, further analysis and active adaptive management. Some possible strategic management responses to predicted environmental stress include:

- For the NRS as a whole, if the objective is to have protected areas that maintain the highest levels of biodiversity values, then it may be sensible to target sites that have low levels of predicted stress.
- In contrast, if the objective is to protect the biodiversity of the continent as effectively as possible, then it may be more effective to target the places in greatest need of conservation management (or the next greatest need, Section 4.3). Not only do these issues affect strategy and planning, they also have a great bearing on monitoring and evaluation.
- It could be argued that a passive management approach (reducing broad threats but just letting biodiversity do its own thing, possibly in large protected areas) might be appropriate for areas with lower levels of stress; and a more interventionist approach might be applicable in areas of higher levels of stress.
- In areas of lower stress it may be suitable to focus on persistence of biodiversity, and in areas of higher stress focus on facilitation of natural adaptation, given that persistence is less likely to be feasible. Given that the modelling suggests average levels of stress will be high, it might be more important to actively protect the

relatively few refuges facing less change where biodiversity might be more likely to persist.

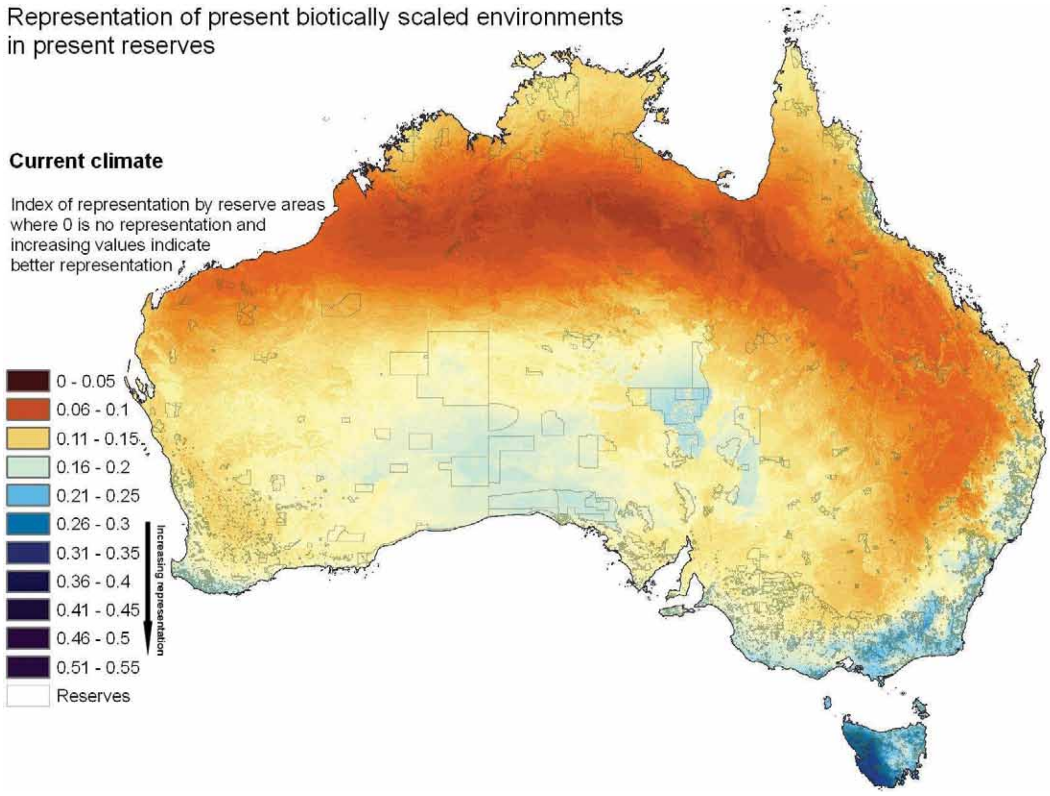
We make these points to highlight that, in general, it is not immediately obvious what the most appropriate management response should be to a given prediction about future environmental stress or ecological change in a region or protected area. There are good theoretical arguments for making it a higher *and* lower conservation priority, adopting more *and* less active management, and seeking to preserve existing biodiversity *and* facilitating change, and so on. The choice will depend on ecological and social contexts of specific regions and protected areas. Therefore it may be appropriate to work towards addressing questions about management responses to predictions of stress in plans of managements for individual protected areas (see also Section 5.4).

5.2 Representativeness

Traditional analyses of the representativeness of the NRS have been based largely on discrete classes such as bioregions and vegetation types (Sattler and Glanznig 2006; National Reserve System Task Group 2009). In those analyses each location (grid cell) is a member of a particular class (e.g. a bioregion or a vegetation type), and all cells in a given class are therefore viewed as having the same level of proportional representation in reserves. Couching this traditional approach in terms of the language of this report, cells occurring within the same class are treated as having a compositional dissimilarity of 0 (i.e. they are identical biologically), while cells in different classes are treated as having a dissimilarity of 1 (i.e. they are totally distinct biologically). In the GDM-based approach to assessing representativeness adopted in this project the dissimilarity between pairs of cells is allowed to vary continuously across the landscape and the estimation of proportional representation in reserves has therefore here been adapted to enable mapping of representativeness as a continuous variable.

In a separate Caring for Our Country project conducted for DSEWPaC (then DEWHA) (Williams *et al.* 2010) this GDM-based approach has been used to assess the

Figure 15. Present proportional representation of biotically scaled environments within the NRS (CAPAD 2006 version; DEWHA 2009), based on vascular-plant GDM modelling (dark blue = high proportional representation, through to dark brown = low proportional representation).



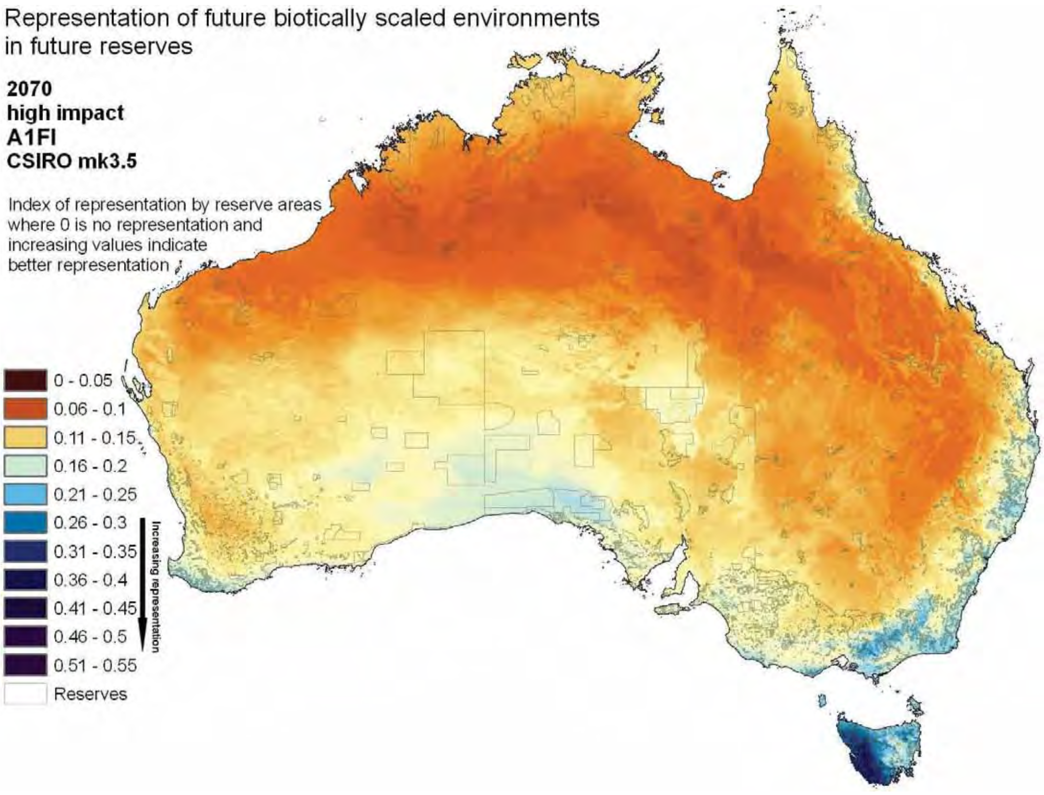
representativeness of the NRS under current climatic conditions. This assessment was based on NRS-boundary data from the Collaborative Australia Protected Area Database (CAPAD), version 2006 (DEWHA 2009). An example of results obtained using the vascular-plant GDM model is presented in Figure 15. This highlights that many environments, especially in northern Australia, are currently not well represented in the NRS.

This approach to assessing and mapping representativeness of reserves has never before been extended to consider the potential effects of climate change. As part of the current project we therefore experimented with two variations of the original analysis to account for potential climate-change effects on the representativeness of the NRS. In the first of these variations the analysis is repeated using the existing NRS boundaries, but replacing all present climate surfaces with projected surfaces under a given climate scenario (non-climatic environmental attributes relating to terrain and soils are assumed to remain constant). This analysis therefore estimates the proportional representation of *future* biotically scaled environments or 'habitats' within existing NRS boundaries (see example in Figure 16). Comparing Figure 15 with Figure 16 reveals very little change in the extent and spatial pattern of representativeness of environments as a result of climate change.

This result suggests that the degree to which the NRS is representative of the continent's habitats "of the day" changes very little, even following very significant environmental change. In other words, climate change does not notably alter the environmental representativeness of the reserve system. Dunlop and Brown (2008) argued that *the framework* for the NRS, effectively targeting representativeness at three different scales, was likely to lead to a highly robust conservation strategy in the face of climate change *when implemented*. This analysis demonstrates that with the current level of implementation, the NRS retains very similar overall levels and patterns of environmental representativeness (including significant gaps), supporting the proposition that representative reserve networks in general, and the NRS in particular, are a highly robust conservation strategy in the face of climate change.

However, in the second variation of this analysis, we found very low levels of proportional representation of *present* environments (habitats) by the *future*

Figure 16. Proportional representation of *future* biotically scaled environments (under 2070 high-impact scenario) within the NRS (assuming existing boundaries, CAPAD 2006 version; DEWHA 2009).



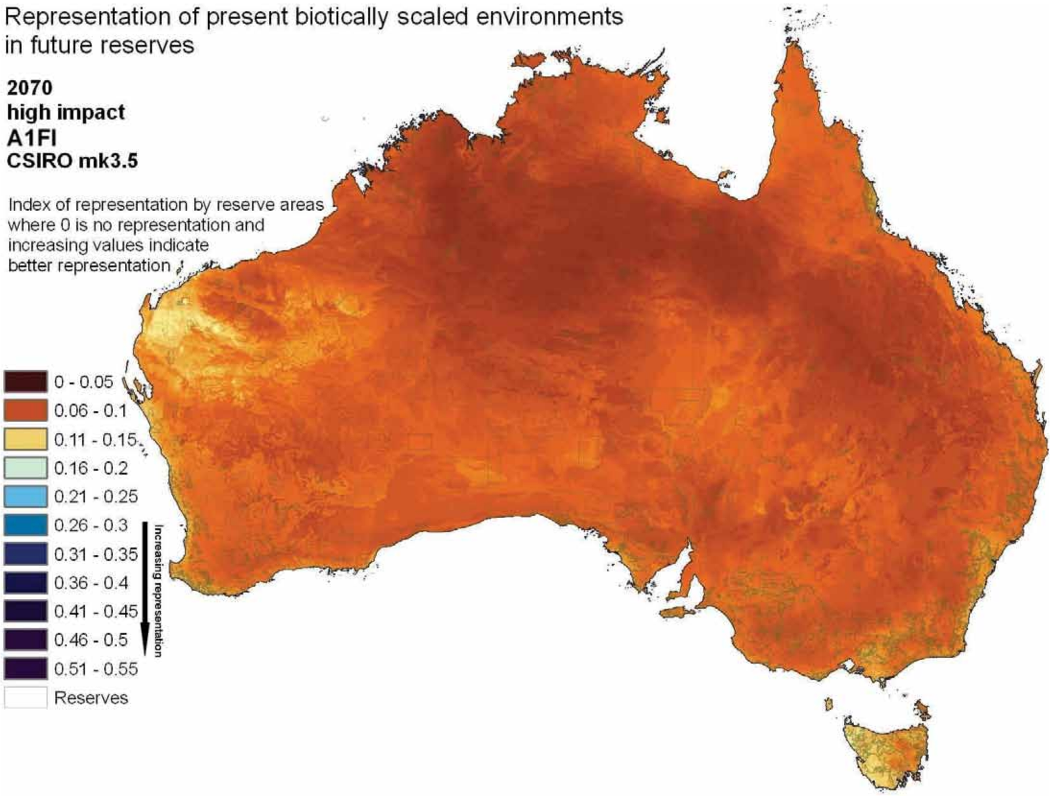


Figure 17. Proportional representation of *present* biotically scaled environments by *future* environments (2070 high-impact scenario) predicted to occur within the NRS (assuming existing boundaries, CAPAD 2006 version; DEWHA 2009).

environments (habitats) predicted to occur within the whole NRS (based on existing boundaries) (Figure 17; see Ferrier *et al*. 2012 for details). This largely reflects the nature of climate change leading to many novel and disappearing environments (Figure 7).

While the implications of this particular analysis require much more thought and exploration, this preliminary result hints at the possibility that expansion of the NRS may help manage the change transition to representation of a new configuration of habitats (biotically scaled environments) across the continent (as depicted in Figure 16). But while this analysis perhaps points to the need for additional reserves to help manage the transition, it does not answer the question of where these additional reserves should be located. Addressing this question will require a whole new form of analysis that has not yet been attempted. In addition, this analysis does not suggest that the current reserve system will lose its value or that individual reserves need to be moved to maintain their value within the system.

Effective progress will also require rigorous debate, and achievement of broad consensus, around fundamental conservation objectives, and therefore the role of reserve systems, in the face of climate change.

5.3 A landscape focus

With climate change, the role of habitat and its management across whole landscapes becomes more important: the biodiversity in protected areas will be more affected by what happens in the broader landscape, and vice versa, in addition to increased movement of biodiversity across the landscape through habitat both in and outside the Protected Areas. Total availability of habitat, the diversity of habitats, including a distribution of disturbance histories, environmental buffering, access to particular habitat features such as refuges and high productivity areas, and outlying populations are all key landscape-scale phenomena. The NRS can play a key role in protecting these features. In addition, the conservation value of a protected area may be enhanced by protecting or maintaining these features where they occur off-reserve in the broader landscape; these factors could be considered in the design of the system. In some situations these features may be ecologically important but may not necessarily represent good quality habitat or they may not be available to the NRS; thus management of these features may be best done through a mixture of programs operating together across landscapes.

Protected areas in some jurisdictions are built up over many decades, with gradual additions to a core node. This approach could be used to help build the effectiveness of the NRS in several ways:

- While this is traditionally done to build up the size and contiguity of a protected area, this approach could also be used to add environmental heterogeneity, or target specific landscape processes, such as moister and more productive sites offering resources in drought and refuge from fire, if not high quality habitat.
- Larger areas and a greater diversity of habitat in the landscape might be kept available for biodiversity by protecting additional areas near but not necessarily adjacent to existing ones.
- Overall representation could be increased and large distances between protected areas reduced (total connectivity increased) if more emphasis were placed on establishing new nodes, rather than adding to existing protected areas. This may come at a management cost and could mean smaller protected areas that may individually be less viable, especially under climate change.
- The selection of future nodes could also consider broad-scale environmental change, and landscape processes and patterns. This could be done, for example, by targeting inland rivers and wetlands as breeding grounds, staging posts and critical ecological sources for biodiversity in times of drought and flood; selecting areas of high environmental diversity, such as the Great Eastern Ranges; or choosing biologically productive areas that have been heavily cleared but could be augmented in the future through large-scale habitat restoration activities (e.g. via biodiversity offset and carbon mitigation programs).

The size of individual areas of protected habitat does, however, remain important, possibly even more important than in the absence of climate change. The question of size is related to the adequacy of individual protected areas, and it is challenging in the face of climate-driven changes in species abundance, community composition and landscape context.

5.4 Management of protected areas

Climate change will begin to affect the management of individual protected areas in various ways. Management objectives may change to accommodate changing biodiversity. Managers may need to address changing threats, including threats that may interact with climate change, and those with social drivers that may conflict with conservation objectives: for example, the management of “wicked threats” of altered fire regimes, new native and exotic species, changing land use, and altered hydrology (Dunlop and Brown 2008). There may be changes in the impact of climatic events and disturbances, including more (or less) frequent crossing of key thresholds. It is likely that much climate change–driven ecological change will happen after disturbance, so biodiversity may respond differently to disturbance at different parts of climate cycles and as the climate changes. Changing objectives and threats may have impacts on future management costs. Some protected areas may lose biodiversity or strategic conservation value (although this should be assessed in the context of revised conservation objectives and the contribution of an individual protected area to the landscape or reserve system as a whole). Managers will also be confronted with increasing uncertainty (concerning values, the biodiversity in protected areas, and the effectiveness of management) and the possible need for more frequent review of management strategies as appropriate information becomes available.

One effective way for managers to prepare for high levels of future environmental and ecological change might be implement changes in management strategies incrementally, starting with no regrets strategies and increasing capacity, them moving to more significant changes as more knowledge becomes available. For example, this could be done over a series of plans of management, aiming to mainstream climate change into management planning, rather than treating it as an additional threat to be managed separately. Three phases or increments of planning could sequentially address increasing the understanding of future changes and their implications; revising conservation objectives and management approaches; and revising management strategies and actions (Section 4.1). The first phase would focus on building an understanding of the different types of ecological changes that might occur, beginning to test for sensitivities to climate in past records and observations, adding climate *variability* and extremes to the list of threats, starting to assess the impacts of future changes on objectives and the consequences of possible new objectives for management, assessing how biodiversity responds after disturbance, experimenting with management of disturbances, and so on. The second phase would focus on conservation objectives. Some ecological changes may have few implications for management; however, choosing between conservation objectives and management approaches—whether or when it is most suitable to *encourage* change, *manage* change, passively *allow* change, or actively *minimise* change—is potentially a *threshold issue* for some protected areas, and could lead to significant shifting of management resources among different species, ecosystems, ecosystem services and protected areas and regions, as well as leading to quite different conservation outcomes. The third phase, by now very well informed, involves revising or developing and implementing new management strategies or adaptation pathways, again across a series of plans of management. Such adaptation pathways could ensure near-term actions were effective stepping stones toward more transformational changes that might be required to accommodate a high magnitude of future ecological change, and help managers avoid resistive actions that might seem reasonable in the short term but actually reduce future management options.

6. Acquiring information about ecological and environmental change for adaptation

While it is certain that climate is changing rapidly, that biodiversity is already being affected and that projections of the future are dire, there are many uncertainties and unknowns in both the science and the management spheres. The science of biodiversity impacts is developing rapidly in Australia and internationally, but there remain considerable gaps in basic information and, consequently, little process or mechanistic understanding of how biodiversity (genes to ecosystems) will respond to climate change. Policymakers and managers are faced with the question of how to respond now to what appears to be a very significant challenge but where there is limited and patchy information.

This project has made a significant step toward a broad understanding of the climate change threat to biodiversity by producing the first continental, model-based assessments and applying them, along with regional expert knowledge, to four major biomes. But these results also highlight numerous uncertainties and data needs. For example, we have identified regions where ecological stress may be the greatest due to future climate change. But predicting how this stress will translate into ecological change, let alone loss of values, in a mechanistic way is limited by many uncertainties. These uncertainties include the direct effects of increased concentration atmospheric CO_2; the relative importance of species' direct responses to climate and complex community-level interactions; the importance of changes in ecosystem processes such as primary production and nutrient cycling; and how species, community or ecosystem changes feed back and interact with disturbance regimes, especially fire.

There is a wide range of ecological techniques that can be applied to investigate each of these issues; from work to date it is clear that different methods do not necessarily give similar results. Some methods or research outputs may seem more relevant than others; for example, coloured maps have wide appeal and connote high authority (Monmonier 1996). Different methods also have vastly different levels of assumptions about how biodiversity will respond. In this report we pioneered an approach of presenting some of the modelling results as being about *environmental change* (entirely free from any assumption about future biodiversity responses), whereas these could have been presented as measures of biodiversity impact, laden with assumptions. As the field grows rapidly, users of research outputs need to be aware of the caveats and diversity of implications associated with different methods and interpretations. It could be very ineffective to prioritise effort on the basis of the precision of a single analytical technique without considering its limitations, assumptions and inherent biases. Similarly, it is important to appreciate that different types of information will be more useful at different phases of the adaptation learning journey (Section 4.1) and for planning and implementing different types of strategies. With time and observation of the changing world, more clarity will emerge about how best to integrate the wide range of methods for predicting ecological change, including expert knowledge, species habitat modelling using a variety of methods, combined habitat and population viability analyses, modelling of productivity, and analyses of community patterns or vegetation-structure (Kuhnert *et al*. 2010).

Uncertainty can be paralysing; but while there is uncertainty about details of future change, there is high confidence about many of the implications of climate change. Many options can be chosen that are robust to the uncertainties (e.g. clearly worth doing irrespective of the details of future change), or increasingly relevant under increasing levels of change. Decisions with different levels of risk can be staged into adaptation pathways, along with research and monitoring, to reduce sensitivity to uncertainty.

6.2 Monitoring

A properly designed and coordinated monitoring program can both track ecological change and provide considerable insight into the processes and mechanisms of change, thus enabling better prediction. This understanding can then inform policy and management. Monitoring is also an essential component of the adaptive management framework of assessing the impact of management actions to inform design and selection of future management options.

However, monitoring is expensive, takes time to yield information, and may not be relevant to management even if scientifically useful. If it is to be an effective management tool, then monitoring should be designed around key hypotheses of change that have implications for management (Biggs and Rogers 2003). Variables to be monitored and the methodology used should be selected so that changes that are detected indicate explicitly that different management is needed. There are frequently calls for more monitoring, but these rarely result in long-term commitments of resources due to cost constraints; monitoring needs to be focused to be useful (McDonald-Madden *et al*. 2010). This need for a well-thought-out monitoring strategy would still hold even if resources increased greatly. This is especially true of monitoring to support climate change adaptation, where different variables may need to be measured, and perhaps in new ways.

To plan effective monitoring that is tightly aligned with policy and management, we suggest that it is necessary to consider:

- What environmental and ecological changes might occur?
- How would these affect management objectives, noting that these may themselves be revised?
- What management options are available (e.g. using scenario planning)?
- What information would be needed to choose between management actions?
- Can monitoring provide that information in a cost-effective manner and relevant time frame?
- What information is needed to design and implement the actions?
- Is that information available now or in the future?
- If required information is not likely to be available then the desired management option, or even the objective, may not be feasible. Can more robust and general strategies be developed and used instead?

This report describes considerable environmental change, driven by climate change, which will eventually translate into biogeographic and ecological change. So, ideally, monitoring should attempt to measure environmental changes as well as ecological changes in, for example, communities, vegetation structure, species interaction and ecosystem processes. Some further conceptual development maybe required for some attributes of interest, such as to be able to assess ecological health in a way that is independent from changes in composition and structure.

As discussed in Section 4.4, the nature of climate change—its timing, multiple types of change, variation and noise—mean that many important signals of ecological change will be hard to detect, and possibly not until it is too late to adequately respond. One way to increase the effectiveness of monitoring might be to use scenario planning to identify key uncertainties about environmental or ecological change and then develop and explore various management options for each scenario. Where the differences between scenarios are critical for management, hypotheses can be developed that distinguish between the scenarios, and research and monitoring can be designed to test the hypotheses and provide rapid guidance about future change and which management actions to implement.

6.3 Key knowledge gaps

From the consultations and deliberations in this project a number of key information gaps were identified:

- More work is required in the emerging discipline of climate change biogeography to understand how high levels of environmental change, as predicted for much of the continent, will translate into ecological change, vulnerability and the likelihood of loss in values. One of the challenges includes effectively integrating and presenting information about different types of changes, especially in the context of persistent uncertainty and points of disagreement among different lines of evidence and experts.

- To help policymakers and managers respond to climate change, debate is needed in science, policy and public domains about suitable objectives for conservation in the face of climate change—how to effectively minimise loss while accommodating substantial ecological change. This needs to be informed by an understanding of the many different attributes of species, ecosystems, landscapes and patterns in diversity, how they may change, and the social values associated with them.
- Understanding the implications of climate change at regional scales and reassessing objectives will require good information about future changes at appropriately fine scales. This can come from a combination of collating existing information (e.g. the continental analyses of this project, and many reviews of ecological impacts), existing regionally specific ecological knowledge and the results of monitoring and new research. Site-specific collaboration between researchers and managers may help address this. Our buffel grass analyses highlighted a method for effectively combining expert knowledge and existing data to explore future changes.
- More information is required about landscape processes and features that might give rise to persistence and adaptability of biodiversity at various scales. Relevant ecological factors may include interactions between species, climatic variability, extreme events, disturbances, connectivity, environmental buffering, refuges, access to variable ecological resources and the value of restored habitat.
- A richer body of science-policy knowledge is required to enable managers to determine and seek the information that will be useful to them, and to help researchers develop more useful analysis tools and monitoring. This needs to incorporate social and institutional factors such as biodiversity values, information availability and resources. For example, more debate and analysis is required, in specific regional contexts, about how to allocate resources or alter management in response to predictions about different levels of future environmental change, and potential loss, that is, if and how to implement triage strategies in the face of significant loss and uncertainty.
- Similarly, climate change logically increases the demand for protection of habitat (larger area and greater diversity); protection of key locations and landscape features (refuges, resources, diversity, connectivity); and management of threats (reducing other pressures, increased movement of alien species in and outside reserves). However, more work is required to be able to assess which of these might be a higher priority in a given region.
- There is a need for more understanding about and better use of simple tools for helping planners and managers deal with uncertainty, for example, effective use of multiple scenarios where uncertainties are significant, as opposed to picking a supposed “most likely” scenario or generating probabilities or probability distributions that are often appealing but very hard to interpret correctly.

Efforts to address these knowledge gaps would be enhanced by establishing new alliances between science and conservation agencies. Such alliances could ensure that research is focused on priority policy and management knowledge gaps, and help facilitate a rapid flow of information into conservation agencies’ decision making.

7. Conclusions and implications for the NRS

1. Climate change is likely to lead to very significant and widespread ecological impacts

Over most of the continent climate change will lead to a significant mismatch between local biodiversity, as it is distributed today, and future environments. This mismatch is substantial in the 2030 scenarios, indicating that managing the impacts of climate change is a near-term challenge—within the time span of protected area and conservation planning. Inland northern Australia, particularly in the west and centre, and some areas along the east and west coast are likely to be affected first. By 2070 the mismatch will be widespread and extreme.

Since the distribution of species and ecosystems is largely, although not solely, controlled by climate, this will result in high *environmental stress*, or force driving change in biodiversity. In response, species and ecosystems will change in many ways. Our modelling results do not, by themselves, predict the resulting ecological changes, although they do suggest some broad directions of change. Their importance is in providing new information for local to national impact assessments, management and policy, drawing on the full range of available ecological and conservation expertise and data. Rather than relying on maps of variables from climate models, our maps of biotically scaled environmental stress provide insights into climate change as it may be "perceived" by ecosystems and their biota.

The modelling indicates that the future environments on much of the continent, when biotically scaled, may be quite unlike those currently occurring anywhere in Australia. This result suggests that the ecological impact of climate change will be much more than simply a reshuffling of habitats and communities.

2. Spatial environmental heterogeneity may help buffer the impact for some species

Ecological analysis and modelling indicate that the ecological impacts of climate change at any given location may potentially be reduced by local and regional-scale environmental heterogeneity, including the presence of refuges, and that this buffering is likely to be widespread. However, the level of buffering afforded by such heterogeneity will vary substantially between regions, depending especially on topographic relief and elevation gradients.

The modelling suggests that, in many areas, it is possible that the capacity for local buffering may be swamped by the overall magnitude of environmental change. However, analysis with finer-scaled biotic and environmental information is required before conclusions can confidently be drawn about future local and regional environmental buffering and refuges. Even where the magnitude of change does exceed buffering for current species, environmental variability will still provide critical habitat heterogeneity and buffering (from temporal variability) for new species, thereby contributing to future landscape-level species richness.

Some broad trends in the different biomes are clear. In the sclerophyll forest biome there is much complex environmental variability, a high degree of buffering and much intact and connected habitat, potentially leading to a relatively higher natural ability to cope. The savannas and hummock grassland biomes are largely intact (although not undisturbed), but they may face a higher magnitude of future biotically scaled environmental change, have very shallow rainfall and temperature gradients and less natural buffering (less widespread meso-scale topography). The temperate grassy ecosystems biome historically had high natural ecological capacity to respond to climate variability, which may have conferred an ability to adapt to climate change, but much of this has been lost through widespread habitat fragmentation and degradation. However, despite any broad trends, within each biome there is substantial ecological heterogeneity, variation in interacting threats and many counter-examples. Therefore, any assessment of the ability of biodiversity to adapt may need to incorporate more fine-scaled ecological information and assessment of threats.

3. Many threats to biodiversity will increase as a result of climate change

Without careful planning, adaptation to climate change in other sectors—including grazing, cropping, forestry, water supply and settlements—is potentially a significant threat to biodiversity, and could readily affect protected areas by changing the landscape context, including broad ecological processes.

Threats from alien species are likely to change regionally, as demonstrated by the very significant continental-scale shifts (southwards and eastwards) in the regions environmentally suitable for the establishment of buffel grass. While predicted suitability may eventually decline in some regions (e.g. the north), buffel grass will remain an ongoing threat with significant potential to continue expanding within existing areas for decades.

While fire *per se* is not a threat to most Australian biodiversity, altered fire regimes are likely to be a significant driver of ecological change and a potentially driver of additional human impact. Drying is likely to lead to longer fire seasons and more weather capable of supporting intense fires across much of Australia. However, changes in the dynamics of vegetation, litter and fuel are complicated and much harder to predict—drying could decrease fire incidence in some regions. In addition, any changes in climatic variability (both rainfall events and drought) could significantly affect fire regimes in many regions.

4. Climate change will affect how we conserve biodiversity

The magnitude and pervasive extent of future climate change means that the NRS and other conservation programs are facing much greater levels of ecological change and losses in species and other biodiversity values than previously anticipated. This suggests significant changes to current conservation strategies may be required. These should be underpinned by a good appreciation of the ecological impacts of climate change, including the multiple types of change.

New objectives for conservation need to be developed that seek to minimise loss while accommodating significant ecological change. This requires consideration of many different attributes of species, ecosystems, landscapes, and patterns in diversity; how they may change; and how they are valued by society. Approaches to conservation that accommodate some losses (i.e. some form of triage) and that are effective under considerable uncertainty (i.e. robust strategies) will need to be developed and implemented. It may also be more effective to place increased focus on the ecological processes that give rise to the adaptability and persistence of biodiversity in landscapes, as opposed to individual habitat patches, species or ecosystems. The NRS is well suited to these challenges.

5. Interpreting predictions of environmental change is not straightforward

This project presented two new methods for assessing future environmental change quantified on a biologically meaningful scale. However, while knowledge is increasing rapidly about ecological responses to climate change, as yet there is no biogeography theory of rapid climate change to adequately integrate the many different types of change phenomena and to enable accurate predictions of ecological change, vulnerability or loss.

Future environmental change could have significant implications for the management of protected areas, for example, in deciding how to allocate management effort, how to revise management objectives, and how to prioritise when selecting new protected areas. However, the nature of these decisions is such that the project was unable to develop any general prescriptions for responding to predictions of higher or lower levels of change. These questions need to be addressed within regional and institutional contexts, considering conservation objectives, landscape factors, local ecological factors, available information and resources.

6. Developing a representative reserve system: protecting habitat diversity

The availability and diversity of habitat is likely to be increasingly important for conservation of biodiversity under climate change. Therefore there is potentially an increasing role for protected areas and other programs that manage habitat.

Modelling undertaken in this project suggests that climate change is unlikely to significantly change the degree to which the NRS is representative of the continual diversity of environments of the day. This reinforces the proposition that habitat or environmental representativeness is a robust approach for addressing climate change. However, the nature of change is such that the set of environments represented in the NRS in the future may be very different from those represented now. Given this, more consideration needs to be given to the role that protected areas could play in managing major ecological transitions under climate change, perhaps by placing more emphasis on establishing new nodes of protected areas, or adding new protected areas near, but not adjacent to existing nodes. This will decrease the distance between protected areas, increase the availability of protected habitat for a wider range of species at the landscape scale, and potentially increase the diversity of environments and habitat protected. However, the size of areas of protected habitat remains important, possibly even more important than in the absence of climate change. Protected areas can also play a key role in securing landscape processes by targeting areas of high environmental diversity or productivity, such as inland wetlands and flood plains.

7. Adapting the management of protected areas and landscapes

The capacity to respond to climate change in protected areas can be built up iteratively, potentially through a sequence of plans of management. Three key steps are understanding the possible future ecological changes and their implications; reassessing conservation objectives and overall management approaches; then revising or developing and implementing new management strategies.

Many of the key challenges of responding to climate change—deciding how to respond to different levels of change, developing new objectives, and managing changing threats—are affected by local and regional context and might best be dealt with at the protected area or regional level. An increased emphasis on broadly focused management and ecological processes, rather than on individual species or habitat patches, is likely to be effective for facilitating the persistence and adaptability of species and ecosystems, dealing with increasing uncertainties, and, in effect, implementing triage outcomes without needing species-by-species assessments.

The risks associated with uncertainty, the possible need for transformative change in the longer term, and the need for proactive management can be mitigated by developing adaptation pathways—strategically staged series of decisions and monitoring—incorporating elements of adaptive management.

8. Key knowledge gaps

Key knowledge gaps identified in the project include:

- a new discipline of climate change biogeography that attempts to integrate the disparate approaches and information about responses of species and ecosystems to climate change
- debate in science, policy and public domains about suitable objectives for conservation in the face of climate change, informed by an understanding of social values associated with biodiversity
- regionally specific information about impacts and their implications, combining local ecological expertise with modelling and published information
- information about landscape processes and features that might give rise to persistence and adaptability of biodiversity
- a richer body of science-policy knowledge to enable managers to determine and seek the information that will be useful to them, and to help researchers develop analysis tools and monitoring
- knowledge and tools to help managers balance worthy but competing demands, such as the protection of habitat and management of threats
- more understanding and better use of tools to deal with uncertainty.

Establishing new alliances between science and conservation agencies would ensure research was focused on priority policy and management knowledge gaps, and help facilitate rapid flow of information into conservation agencies' decision making.

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Appendix 1: Summary of consultative workshops

Eight workshops organised by the project provided important scientific and policy advice that is included in this and other project reports. Workshops were held for each of the four focal biomes; one workshop elucidated expert opinion for use in the modelling of buffel grass, and a workshop for policymakers was held near the end of the project in Canberra. During external review and finalisation of the report further technical and policy workshops were held with representatives from Australian government and state agencies. This appendix briefly outlines the objectives of the workshops, where and when they were held and lists the participants. We invited participants who had the appropriate expertise, and we attempted to achieve representation of as many stakeholders as possible, including CLAN representatives. In some instances we obtained advice following the workshops to include input from individuals who were invited but could not participate directly.

Biome workshops

Full reports have been provided to DSEWPaC for each biome and should be consulted for their results (Appendix 2). The following is intended to indicate how advice was elicited and the extent of consultation undertaken. Excluding project staff, 56 individuals, from over 30 organisations participated in one or more of the workshops. The organisations represented in these workshops are listed below (by their names at the time of each workshop).

Arthur Rylah Institute for Environmental Research (in DSE, Vic)
Australian Bush Heritage
Australian Government Department of Climate Change (now DCCEE), ACT
Australian Government Department of the Environment, Water, Heritage and the Arts (now DSEWPaC), ACT and NT
Australian National University
Charles Sturt University
CSIRO
Datastaticians
Department of Environment and Climate Change, NSW
Department of Environment and Conservation, WA
Department of Environment and Heritage, SA
Department of Environment and Resource Management, Qld
Department of Natural Resources, Environment, the Arts and Sport, NT
Department of Primary Industries and Water, Tasmania
Department of Territory and Municipal Services, ACT
Department of Sustainability and Environment, Victoria
Envisage Environmental Services
Forest Practices Authority, Tasmania
James Cook University, Townsville
Macquarie University
National Parks and Wildlife Service, NSW
Nature Conservation Society, SA
NT Environment Centre, Darwin
SA Native Vegetation Council
University of Adelaide
University of Sydney
University of Western Australia
University of Melbourne
University of Wollongong

The primary aims of these workshops were to:

1. identify the environmental and ecological characteristics that make each biome distinctive
2. share understanding of the types of changes likely to affect the biome, its biota and socio-economic characteristics
3. discuss options for modelling and detecting proposed changes, with information on what is needed to do it and how best to progress it
4. discuss the implications of different kinds of changes for biodiversity, habitat protection and NRS
5. consider how the NRS, in a whole-landscape context, could be managed differently under climate change and the information that might be required.

Prior to the workshop, invitees were asked to provide:

1. a biography and summary of their interest/experience in this biome and how this might relate to climate change
2. a summary of their organisation's/State's response to climate change and reserve design/management
3. a few lines on what they thought the big issues are with respect to the relevant biome and climate change.

These responses were collated and used to provide background for the facilitator to use in directing discussion. Participants were also asked to speak briefly to these points at the start of the workshops.

HUMMOCK GRASSLANDS BIOME

This workshop was held at the University of Adelaide, on 5–6 March 2009.

The participants were:

Justin Billings	Department of the Environment, Water, Heritage and the Arts
Tim Bond	Department of the Environment, Water, Heritage and the Arts
Robert Brandle	Department of Environment and Heritage, SA
Jane Brim Box	Department of Natural Resources, Environment, the Arts and Sport, NT
Graham Carpenter	SA Native Vegetation Council and Private Consultant
Sue Carthew	University of Adelaide
Peter Copley	Department of Environment and Heritage, SA
Angus Duguid	Department of Natural Resources, Environment, the Arts and Sport, NT
Michael Dunlop	CSIRO Sustainable Ecosystems, ACT
Simon Ferrier	CSIRO Entomology, ACT
Jeff Foulkes	Department of Environment and Heritage, SA
Pauline Grierson	University of Western Australia
Graham Griffin	Datastaticians
Nerissa Haby	University of Adelaide
Rohan Hamden	Department of Environment and Heritage, SA
Angas Hopkins	Australian Government Department of Climate Change
Peter Kendrick	Department of Environment and Conservation, WA
Stephen van Leeuwen	Department of Environment and Conservation, WA
Adrian Pinder	Department of Environment and Conservation, WA
Jolene Scoble	University of Adelaide
Rick Southgate	Envisage Environmental Services
Anita Smyth	CSIRO Sustainable Ecosystems, SA
Glenda Wardle	University of Sydney

TROPICAL SAVANNA WOODLANDS AND GRASSLANDS BIOME

This workshop was held at CSIRO Sustainable Ecosystems, Darwin, NT on 23–24 April 2009.

The participants were:

Stuart Blanch	NT Environment Centre
Tim Bond	Australian Government Department of the Environment, Water, Heritage and the Arts
Melanie Bradley	NT Environment Centre
Tracy Dawes	CSIRO Sustainable Ecosystems
Liz Dovey	Department of Climate Change
Michael Dunlop	CSIRO Sustainable Ecosystems
Simon Ferrier	CSIRO Entomology
David Hilbert	CSIRO Sustainable Ecosystems
Alex Kutt	CSIRO Sustainable Ecosystems
Adam Liedloff	CSIRO Sustainable Ecosystems
Ian Radford	Department of Environment and Conservation, WA
Dick Williams	CSIRO Sustainable Ecosystems
Stephen Williams	James Cook University
Steve Winderlich	Australian Government Department of the Environment, Water, Heritage and the Arts (Kakadu, NT)

Further input was obtained from John Woinarski (NT Government Biodiversity Unit, Darwin).

TEMPERATE GRASSLANDS AND GRASSY WOODLANDS BIOME

This workshop was held at CSIRO's Gungahlin site, Crace ACT, on 28–29 April 2009.

The participants were:

Greg Baines	Department of Territory and Municipal Services, ACT
Justin Billings	Australian Government Department of the Environment, Water, Heritage and the Arts
Ross Bradstock	University of Wollongong
Kerry Bridle	CSIRO Sustainable Ecosystems/ACIAR
Sue Briggs	Department of Environment and Climate Change, NSW
Don Butler	Macquarie University, Environment Protection Authority, Qld
Oberon Carter	Department of Primary Industries and Water, Tas.
Saul Cunningham	CSIRO Entomology
Liz Dovey	Australian Government Department of Climate Change
Angela Duffy	Department of Environment and Heritage, SA
Michael Dunlop	CSIRO Sustainable Ecosystems
Simon Ferrier	CSIRO Entomology
Louise Gilfedder	Department of Primary Industries and Water, Tas.
David Keith	Department of Environment and Climate Change, NSW
Ian Lunt	Charles Sturt University
Sue McIntyre	CSIRO Sustainable Ecosystems
Tim Milne	Nature Conservation Society, SA
Karel Mokany	CSIRO Entomology
Suzanne Prober	CSIRO Sustainable Ecosystems
Jim Radford	Australian Bush Heritage
Rainer Rehwinkel	National Parks and Wildlife Service, NSW
Vivienne Turner	Arthur Rylah Institute for Environmental Research
Kristen Williams	CSIRO Sustainable Ecosystems

SCLEROPHYLL FORESTS OF SOUTH-EASTERN AUSTRALIA BIOME

This workshop was held at CSIRO Sustainable Ecosystems, Crace, ACT, on 6–7 May 2009.

The participants were:

Mike Austin	CSIRO Sustainable Ecosystems
Justin Billing	Australian Government Department of the Environment, Water, Heritage and Arts
Ross Bradstock	University of Wollongong
Geoff Cary	Australian National University
Liz Dovey	Australian Government Department of Climate Change
Fred Duncan	Forest Practices Authority, Tas.
Michael Doherty	CSIRO Sustainable Ecosystems
Mike Dunlop	CSIRO Sustainable Ecosystems
Teresa Eyre	Department of Environment and Resource Management, Qld
Helen Federoff	Department of Sustainability and Environment, Vic.
Simon Ferrier	CSIRO Entomology
Louise Gilfedder	Department Primary Industries, Water and Environment, Tas.
David Hilbert	CSIRO Sustainable Ecosystems
Alan House	CSIRO Sustainable Ecosystems
Gary Howell	Department of Sustainability and Environment, Vic.
David Keith	Department of Environment and Climate Change, NSW
Graeme Newell	Department of Sustainability and Environment, Vic.
Elizabeth Oliver	Department of the Environment, Water, Heritage and Arts
Ross Peacock	Department of Environment and Climate Change, NSW
Alan York	University of Melbourne

Buffel grass workshop

The buffel grass Bayesian Belief Network (BBN) workshop was held in Darwin on April 20–24 2009. The purpose of the workshop was to bring together experts in buffel grass ecology and management to build an influence diagram to underpin the structure of the BBN. As well as attending the workshop (as indicated), experts in the lists below were consulted multiple times throughout the development of the BBN. Those annotated ** provided elicited probability tables for key variables.

The workshop participants were:

Kerrie Bennison	NCR Planning Manager, Uluru
John Clarkson	Queensland Parks and Wildlife Service
Keith Ferdinands	Department of Natural Resources, Environment, the Arts and Sport, NT
Margaret Friedel	CSIRO Sustainable Ecosystems
Tony Grice	CSIRO Sustainable Ecosystems
Neil Macleod	CSIRO Sustainable Ecosystems
Samantha Setterfield	Charles Darwin University
Anita Smyth	CSIRO Sustainable Ecosystems
Rieks Van Klinken**	CSIRO Entomology
Steven Van Leeuwen	Department of Environment and Conservation, WA
Wayne Vogler	Invasive Pests and Plant Biosecurity Science, Biosecurity Qld
Dick Williams	CSIRO Sustainable Ecosystems

Additional consultants included:

Garry Cook	CSIRO Sustainable Ecosystems
Rod Fensham**	Queensland Herbarium
John McIvor**	CSIRO Sustainable Ecosystems

Policy implications workshop

This workshop was convened at CSIRO's Gungahlin site, Crace ACT on 20 May 2010 to inform and obtain feedback from stakeholders after the biome reports were completed but before overall synthesis of the project's findings had occurred.

The participants were:

Mike Dunlop	CSIRO Sustainable Ecosystems
David Hilbert	CSIRO Sustainable Ecosystems
Simon Ferrier	CSIRO Entomology
Adam Liedloff	CSIRO Sustainable Ecosystems
Anita Smyth	CSIRO Sustainable Ecosystems
Clair Harris	CSIRO Sustainable Ecosystems
Justin Billing	Department of the Environment, Water, Heritage and the Arts
Tim Bond	Department of the Environment, Water, Heritage and the Arts
Angas Hopkins	Australian Government Department of Climate Change
Louise Gilfedder	Department of Primary Industries, Water and Environment, Tas.
Jeremy Reiger	Department of Sustainability and Environment, Vic.
Gary Saunders	Department of Environment, Climate Change and Water, NSW
Debbie Worner	Parks, Conservation and Lands, ACT
Annette Stewart	Australian Bush Heritage
Martin Taylor	World Wildlife Fund

Technical workshop

This workshop was held at the Australian Government Department of Climate Change and Energy Efficiency on 25 July 2011. This workshop provided representatives from Australian Government and state agencies and the external reviewers the opportunity to ask questions and provide feedback on the novel continental modelling work.

Policy workshop

This workshop was held at the National Portrait Gallery on 5–6 December 2011, and involved representatives from Australian Government and the state biodiversity, NRM and climate change policy agencies. The findings of the project were presented and discussed, and key issues for current and future conservation policy were identified. These formed the basis for a standalone *Implications for Policymakers* document.

Appendix 2: Project reports

Summary reports

Dunlop M., Hilbert D.W., Ferrier S., House A., Liedloff A., Prober S.M., Smyth A.,. Martin T.G., Harwood T., Williams K.J., Fletcher C. & Murphy H. (2012) *The Implications of climate change for biodiversity conservation and the National Reserve System: final synthesis*. A report prepared for the Department of Sustainability Environment, Water, Population and Communities, and the Department of Climate Change and Energy Efficiency. CSIRO Climate Adaptation Flagship, Canberra. [This report]

Dunlop M., Hilbert D.W., Stafford Smith M., Davies R., James, C.D., Ferrier S., House A., Liedloff A., Prober S.M., Smyth A.,. Martin T.G., Harwood T., Williams K.J., Fletcher C. & Murphy H. *2012 Implications for policymakers: climate change, biodiversity conservation and the National Reserve System*. CSIRO Climate Adaptation Flagship, Canberra.

Biome reports

House A., Hilbert D., Ferrier S., Martin T., Dunlop M., Harwood T., Williams K. J., Fletcher C. S., Murphy H. & Gobbett D. (2012) *The implications of climate change for biodiversity conservation and the National Reserve System: sclerophyll forests of south-eastern Australia*. CSIRO Climate Adaptation Flagship Working Paper No. 13A. http://www.csiro.au/en/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers.aspx

Liedloff A. C., Williams R. J., Hilbert D. W., Ferrier S., Dunlop M., Harwood T., Williams K. J. & Fletcher C. S. (2012) *The implications of climate change for biodiversity conservation and the National Reserve System: the tropical savanna woodlands and grasslands*. CSIRO Climate Adaptation Flagship Working Paper No. 13B. http://www.csiro.au/en/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers.asp

Prober S., Hilbert D. W., Ferrier S., Dunlop M., Harwood T., Williams K. J., Fletcher C. S. & Gobbett D. (2012) *The implications of climate change for biodiversity conservation and the National Reserve System: temperate grasslands and grassy woodlands*. CSIRO Climate Adaptation Flagship Working Paper No. 13C. http://www.csiro.au/en/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers.aspx

Smyth A. K., Hilbert D. W., Ferrier S., Dunlop M., Harwood T., Williams K. J., Fletcher C. S. & Gobbett D. (2012) *The implications of climate change for biodiversity conservation and the National Reserve System: hummock grasslands biome*. CSIRO Climate Adaptation Flagship Working Paper No. 13D. http://www.csiro.au/en/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers.aspx

Modelling technical reports

Ferrier S., Harwood T. & Williams K. J. (2012) *Using Generalised Dissimilarity Modelling to assess potential impacts of climate change on biodiversity composition in Australia, and on the representativeness of the National Reserve System*. CSIRO Climate Adaptation Flagship Working Paper No. 13E. http://www.csiro.au/en/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers.aspx

Harwood, T., Williams, K. J., & Ferrier, S. (2012) *Generation of spatially downscaled climate change predictions for Australia*. CSIRO Climate Adaptation Flagship Working Paper No. 13F. http://www.csiro.au/en/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers.aspx

Hilbert D. W. & Fletcher C. S. (2012) *Using artificial neural networks to assess the impacts of future climate change on ecoregions and major vegetation groups in Australia*. CSIRO Climate Adaptation Flagship Working Paper No. 13H. http://www.csiro.au/en/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers.aspx

Martin T., Murphy H. & Liedloff A. (2012) *Invasive species and climate change: a framework for predicting species distribution when data are scarce*. CSIRO Climate Adaptation Flagship Working Paper No. 13G. http://www.csiro.au/en/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers.aspx

Appendix 3: Biome summaries

This appendix includes brief summaries of the four biomes and relevant climate change issues. They have been compiled from the four biome synthesis reports (listed in Appendix 2), which were based on literature reviews, expert workshops, environmental modelling and ecological analyses. Maps of the biomes are included in Figure 1.

Hummock Grasslands

DESCRIPTION

- Dominated by globally unique hummock-forming perennial grass (*Triodia* spp. – spinifex), with overstorey in some places
- Additionally globally significant for its uniquely extreme environment, endemic species, and high arid lizard fauna
- Arid, semi-arid interior of Australia, and extending to the coast in WA and SA
- Covers about 50% of the continent, in WA, SA, NT, Qld, NSW and a small part of Victoria
- Hot and dry, with variable rainfall
- Remote, intact, extensive, with outstanding natural and culturally significant places
- Lots of micro-topographic (dunes and swales) and fire-history patchiness; many rocky ranges, paleo channels at larger scales
- Poor baseline biotic information in some parts
- Pressures: Fire, weeds (especially buffel grass, *Pennisetum ciliare*), introduced predators (22 mammals extinct), grazing (water points: stock, ferals, kangaroos), groundwater extraction

HOW IT WORKS

- Hot (heat stress), with shallow temperature gradients
- Unpredictable and low average rainfall with significant rainfall events (e.g. cyclonic depressions); frequency over years very important
- Burst of growth and reproduction after rain
- Many groundwater-dependent ecosystems
- Fire big, patchy, structuring: many influences on it
- Low nutrients, litter-nutrient dynamics, micro-topography important
- Many rocky ranges – refuges from past fluctuations and still important
- Many strategies for tolerating the extremes

EXPECTED CHANGE

- Temperature increase 3–7°C by 2070, especially in summer, and an increase in the number of extreme temperature days within the year
- Will remain arid with very variable rainfall
- Increased aridity likely; changes in rainfall patterns possible (intensity, frequency and geographic distribution) which could be significant
- Increased rainfall in the north-west; decreased elsewhere, especially the southern winter growing season
- Saltwater inundation in the Pilbara region in Western Australia due to rising sea levels
- High levels of biotically scaled environmental stress ANN (>0.7), GDM (plants 0.8, reptiles 0.6).
- Starting in 2030, especially in north, and second highest biome stress in 2070
- Changes in the seasonality variables dominate stress measures
- Increased suitability for buffel grass, especially in south
- C3–C4 balance important and, under contrasting drivers of change, complicated
- Changes in fire regimes possible but affected by litter accumulations (growth due to rainfall) and ignitions (storms, people) both of which could change but unpredictable

DISAPPEARING ENVIRONMENTS

There are few options for hummock grasslands biota outside the biome as it is already at the extreme end of temperature and rainfall gradients. Modelling suggests many environments disappearing in the biome and not found elsewhere, and many novel environments.

BUFFERING

There is some fine-level heterogeneity due to micro-topography, ranges, ground water systems and ephemeral river systems. Macro-scale variability, providing significant buffering, is only present in a few regions.

ISSUES

- While it will get hotter, the changes to the biome will be more than just to a more extreme version its current hot, dry state
- Altered rainfall patterns, and fire (litter accumulation, poorly understood), flow-on impacts to woody components and weed invasion
- Change is at scale much bigger than NRS protected areas
- Increasing aridity and variability putting more species over the edge, and more stress on wetter parts of the landscape
- Very high levels of biotic change expected; dispersal may be critical
- Many micro-environments with outlying populations, could become critical sources of ecological and evolutionary radiation, or refuges, but hard to predict dynamics. Many refuges and possible sources of diversification are already in the NRS. Includes diversification from arid features (ranges, outcrops, etc.) in more mesic south
- Different trend at north and south of the biome. Large-scale shift in many components possible
- Variable between biota, interactions unknown
- Woody thickening and weeds, especially buffel grass, predicted sweeping changes in suitability across the centre
- Plant nutrition for herbivores and their predators
- Clearing of mallee vegetation has greatly reduced natural buffering in parts of the biome
- Hummock grassland biome includes various different systems, and needs to be segmented for planning
- Focus management on fire-free refuges within patchy matrix

Tropical Savanna Woodlands and Grasslands (Savannas)

DESCRIPTION

- The savannas cover the vast north Australian landscapes that include the tropical eucalypt woodlands and grasslands with a range of other embedded habitats from northern Western Australia to central Queensland. This biome blends into the arid interior and closed forests and rainforests nearer the eastern coastline.
- The savannas occupy 25% of the Australian continent and cross two states and the Northern Territory.
- They contain a range of important ecosystems within the savanna matrix (e.g. monsoon vine forests, sandstone escarpment, springs, riparian zones, coastal freshwater wetlands and gorges). These habitats offer refuges and are often isolated, fire sensitive and contain diverse flora and fauna.
- The savannas have experienced limited disturbance relative to southern Australia and to savannas globally, and stable ancient topography and reliability in northern weather patterns have resulted in considerable stability in the tropical savannas over long periods of time, as well as to the somewhat misconstrued view that the savannas are wilderness, pristine, remote, intact and resilient to change
- The savannas contain many globally significant national biodiversity icons and assets (e.g. Kakadu National Park, Einasleigh and Desert Uplands, Kimberley).

HOW IT WORKS

- The savanna biome is strongly influenced by the summer rainfall–dominated monsoon and El Niño (north Queensland) weather patterns. Most areas receive high rainfall but are also periodically water stressed due to a prolonged dry season (or drought in north Queensland).

- There are very shallow temperature gradients and stronger but still weak rainfall gradients (e.g. approximately 1 mm change in rainfall per kilometre travelled along the North Australian Tropical Transect).
- The savannas offer little fixed meso-heterogeneity from topography (except for wetlands, pockets of fire-protected areas and escarpment country). Rather, a patchwork of habitats with various times-since-last-fire exists. Recent fire management may be reducing this heterogeneity with increasing frequency, intensity and extent of savanna fires.
- The fauna and flora of the savannas respond to the spatial, intra-annual and inter-annual variation in rainfall and repeated exposure to fire. A range of adaptations from nomadic populations tracking available resources to re-sprouting ability in many plants after fire are common in the savannas.
- The Australian tropical savannas are the most cyclone-prone savannas on earth and the frequency and intensity of tropical storms and cyclones influence the flora and fauna.
- Many of the iconic species of this biome are now recognised as being under considerable stress and vulnerable to extinction. (e.g. critical weight range mammals and endangered granivorous birds).
- This biome is currently under pressure from altered fire regimes, invasive weeds (e.g. African grasses such as Mission and Gamba grass), feral animals (e.g. cats and cane toads) and broad-scale land management (e.g. grazing and agriculture).

EXPECTED CHANGE

- A predicted increase in temperature by 2–4°C by 2070, with greater increases inland and an increase in the number of extreme temperature days within the year.
- Rainfall seasonality is likely to be unchanged. A less certain prediction relates to fine-scale change such as the length and onset of the dry season. Changes relating to variation in the dry season could be very significant, but this factor is currently variable or unknown in climate projections.
- High levels of stress are predicted from the modelling performed in this report: ANN (0.5–0.85), GDM (plants >0.8; mammals, reptiles, snails ~0.7; birds 0.3; frogs 0.4). Environments in the savanna biome will be among the first to experience high levels of stress (by 2030) and among the most stressed in 2070.
- While the majority of the savannas are currently at the northern extent of buffel grass suitability and distribution, there is currently significant scope for buffel grass to expand before there is a possible decrease in the suitability for buffel grass due to climate change.
- Fire is currently extremely frequent in much of the savanna biome and is an important landscape process. Changes in fire weather, plant growth (fuel) and fire ignitions as well as management may alter future fire frequency and extent. Current management such as pastoralism and Indigenous land management are able to reduce extensive wildfire. The ability to continue managing fire in the future may depend on altered weather conditions. Fire currently increases in extent/intensity in the north of the biome where fuel is available and decreases in frequency in the east and south where active pastoral fire management and declining fuel loads reduce fire frequency.

DISAPPEARING ENVIRONMENTS

- The majority of Australia’s major vegetation groups (MVGs) are represented in the region defined as the savannas. While some of the smaller embedded MVGs are predicted to decline, these environments are frequently found outside the savannas. The MVG environments unique to savannas are expected to expand and no savanna MVGs disappear continentally.
- In contrast, the GDM modelling, oriented more towards composition than vegetation structure, indicates a degree of change corresponding to a very high level of disappearing current environments and novel future environments. This may be due to very shallow temperature and rainfall gradients.

BUFFERING

The modelling work was not able to easily track meso-gradients, but did show finer heterogeneity in the landscape.

The GDM modelling revealed limited effective buffering at the 1 km scale, but some good buffering in some regions at the 100 km scale. There is clearly better buffering in some parts of the region and this needs to be further explored for conservation management. It seems that areas offering greater variation in elevation (e.g. gorges, river systems and escarpments) provide the best buffering to change. This needs further investigation, particularly focusing on the critical areas and changes across multiple scales.

It is unclear the extent to which habitat heterogeneity due to variation in time-since-fire might effectively provide some form of environmental buffering.

ISSUES

- Some experts expected minimal climate change impacts in the savannas as the system has evolved with wide climatic tolerances, adaption to high temperatures and drought and topographic refuges. It is sometimes hard to imagine anything other than current savanna systems occupying northern Australia. However, other threats (late-season fires, weeds, buffalo, feral cats, cane toads) do show dramatic impacts on the savannas, exemplified by very dramatic declines in small mammals.
- In contrast, the modelling and climate change experts suggested a high level of biotic sensitivity and ecological change in the savannas:
  - Empirical results suggest species are near thermal limits and therefore are more sensitive and vulnerable due to shallow temperature gradients.
  - Change is expected across the whole savanna, and the savannas are the first part of Australia predicted to experience this change.
  - Additional data and information are required to inform the savanna experts, allowing for adjusted forecasts. This requires a much better understanding of the physiology of the system (e.g. thermal tolerances), focused monitoring and better predictions of critical factors likely to change and have the greatest impacts (e.g. rainfall variability and not just annual/monthly rainfall change)
- The savannas are currently considered one broad class in this report, but may be better described divided into a series of distinct climatically differentiated classes.
- It is difficult to predict structural versus compositional changes at present. Understanding such changes is required before more accurate assessment of change in the biota can be made.
- More work is required to assess the impacts on hydrological dynamics. This report did not involve experts in aquatic systems and only touched on the impact of climate change on riparian and wetland ecosystems through management.
- Macro-scale dispersal will possibly be critical for savanna species. This is being addressed by ensuring connected protected areas are available across gradients, but there is also a dynamic heterogeneity due to fire to be considered.
- Impact on demographic processes may be critical in variable landscape (tree death and escaping fire). These are complex systems with emergent outcomes often only known once they occur.
- There is a lot unknown about the savannas. There is currently a pressing need for detailed monitoring and focused research. A better understanding of the current level of stress the savanna biota experiences, thermal tolerances, and critical tipping points is required to make predictions of future change and inform conservation and land managers.

Temperate Grasslands and Grassy Woodlands (Temperate Grassy Ecosystems, TGE)

DESCRIPTION

- Grassy eucalypt woodlands and treeless grasslands of temperate south-eastern Australia
- Characterised by a diverse herbaceous ground-layer (forbs and perennial tussock grasses) with sparse shrubs, with or without overstorey of well-spaced eucalypts

- Widespread (occupying c. 38M ha) in the transitional zone between forests of Australia's wetter margins and shrub woodlands, shrublands and hummock grasslands of the drier interior
- Cold winters and mild to hot summers
- Moderate annual rainfall (400–800+ mm) ranging from cool-season to warm-season dominant, with frequent drought cycles
- Soils generally deep with high clay content, but low in available nitrogen and phosphorus
- Highly suitable for agriculture, especially with fertilisation
- Now highly fragmented (<10% remaining in some areas) and degraded owing to impacts of cropping, grazing and other development
- One of the most threatened ecological communities in Australia (2.2% reserved in NRS), and includes many declining native plant and animal species

HOW IT WORKS

- Moderate climate and deep soils support tall woodland trees, except in some environments (e.g. heavy clays, cold, elevated areas) that support grassland
- Continuity of the herbaceous ground layer and Aboriginal burning promoted frequent light fire in pre-European TGE, in turn maintaining their open, grassy structure
- Fire and marsupial grazing important for maintaining diversity in productive TGE
- Fauna assemblages strongly associated with climate and vegetation structure, including many species that rely on large-crowned eucalypts or tussock grasses
- Mild climate and year-round food supply make TGE an important destination for migratory birds
- Cycles of moderate inter-annual rainfall variability contribute to patterns of plant mortality and recruitment
- Major patterns of biotic variation related to north–south gradients in temperature and rainfall seasonality, and coast–inland rainfall gradients
- Soil nutrient enrichment (particularly available nitrogen and phosphorus) and livestock grazing has led to widespread degradation of the herbaceous ground layer (weed invasion, loss of plant diversity)
- Widespread clearing and fragmentation limits viability of many woodland fauna

EXPECTED CHANGE

CSIRO climate change scenarios suggested that by 2070, the biome would experience:

- General warming in all seasons by 1–6˚C (mid-point 1.5–2.5 ˚C)
- Rainfall change ranging from -40% to +10% annually (mid-point -20% to -5%)
- Potential reductions of up to 60% in winter and spring rainfall, and potential change of -40% to +40% in summer and autumn
- High levels of stress predicted for TGE communities under medium and high 2070 scenarios: ANN (0.75–0.95); however, interpretation of these results should be tempered by the moderate stress (0.45–0.62) estimated even for the current climate
- High stress for plants, reptiles and birds predicted by GDM (~0.7 for 2070 high), although less stress predicted for birds, mammals and frogs (~0.4)
- Stress levels dramatically increase if habitat clearing is accounted for in models
- Increased suitability for buffel grass (*Pennisetum ciliare*)
- Expected change in fire regime uncertain, likely decreased frequency and increased intensity due to potentially sparser and more woody ground layer components

DISAPPEARING ENVIRONMENTS

There are likely to be significant continental reductions to the distribution of environments now occupied TGE:

- Under 2070 medium scenarios, areas with moderate to high similarity to TGE in parts of central Victoria, Tasmania and northern New South Wales may persist somewhere within Australia.
- Under 2070 high scenarios, few even moderately similar environments are predicted except for Tasmanian TGE.

- Minimal areas of additional eucalypt woodland environment are predicted by ANN to develop within south-eastern Australia outside current TGE extent.
- Environments favouring grasslands may increase.

BUFFERING/RESILIENCE

In the natural system at least (prior to habitat degradation and clearing) a range of TGE characteristics offered mechanisms for effective resistance or adaptation to environmental change:

- Widespread distributions across broad climatic gradients promote species persistence (consistent with GDM predictions of less point-scale compositional change in cooler areas, but poor evidence for greater compositional similarity in moister zones).
- Large population sizes and associated high genetic diversity promote persistence and adaptability.
- Climatic gradients and topographic heterogeneity provide moderate buffering (little at 1 km scale, moderate at 25–100 km scale).
- Buffering is most apparent in zones with greater relief, particularly the fringes of the Great Dividing Range in New South Wales and Victoria, and in Tasmania.
- High species richness buffers ecological functioning by offering replacement species.

Buffering and capacity to adapt has been dramatically compromised by fragmentation and degradation in TGE, including:

- reduced population sizes, genetic diversity and alpha diversity
- compromised functioning, for example, compaction and reduced soil-water infiltration
- invasions of alien species
- few potential refuge areas remaining robust when clearing accounted for.

ISSUES

- dramatic loss of resilience due to degradation and fragmentation
- likely structural change including declining tree cover and altered shrub–grass balance
- shifts in the functional composition of the herbaceous ground layer such as changed C3/C4 and perennial/annual ratios
- predominance of exotic species such as buffel grass in novel communities
- altered fire frequency, increased intensity and spread
- cascading changes in ecological interactions

POLICY/MANAGEMENT IMPLICATIONS

- Continue to conserve suites of native species in fragmented TGE landscapes through appropriate management and protection of a diversity of sites, representing natural environments and processes across the biome. Under climate change a range of priorities become increasingly relevant; in particular, sites with natural (non-enriched) soil environments and areas are predicted to experience lower biotically scaled stress (refuges).
- Tailor current restoration efforts and carbon plantings towards climate resilient outcomes: diverse plantings, augment genetic diversity, vary connectivity, restore degraded soils.
- Favour land use changes with potential for positive rather than negative biodiversity outcomes, for example, low input native pastures and carbon sequestration initiatives rather than agricultural intensification (e.g. irrigation).
- Manage non-Australian exotics at a range of levels to promote re-assembly by native species.
- Manage disturbance, particularly fire, to maintain open grassy ecosystems at selected locations.

Sclerophyll Forests of South-eastern Australia

DESCRIPTION

- Open and tall open eucalypt-dominated forests of south-eastern Australia
- Rainfall reasonably high (generally over 600 mm) and reliable

- Occupies dissected topographies in close relationship with rainforests and open woodlands
- Fine-scale distributions of forest types based on elevation, aspect, slope and latitude
- Fire and drought adapted

HOW IT WORKS

- Strong temperature gradients, especially in south (coast to sub-alpine)
- Shift in rainfall pattern from winter dominant in south to summer dominant in north
- Fire a dominate process, but regimes varying: low frequency, high intensity fires in the south through to high frequency, low intensity fires in the north
- Sites sheltered from fire and desiccation (e.g. by topography) allow rainforest development
- Rapid switches from open to closed understoreys based on rainfall cycles (droughts) plus fire

EXPECTED CHANGE

- Increase of 3–4°C by 2070, higher inland; lower increases in Tasmania
- Incidence of extreme high temperature days increases, extreme cold days decreases
- Modest but complex changes in total rainfall expected, but big shifts in seasonality: increases of 10–20% in summer rainfall in New South Wales, decreases in southern Victoria and Tasmania. Winter rainfall declines by 20–30%, except Tasmania where it increases by 5–10%
- Increased suitability for buffel grass (*Pennisetum ciliare*), especially on western edge of biome
- Stress modest under both 2030 scenarios; high in north and moderate in south under 2070 medium impact scenario, and high (>0.7) throughout under 2070 high impact scenario. Impacts greater in north, least in Tasmania
- Fire story complex: increased fire weather, altered and variable biomass accumulation (less where dryer and shorter growing season, more where longer growing season; increased growth due to elevated CO_2 and more C4 grasses), more available litter (faster drying/curing in hotter, drier climate). Likely increase in fire frequencies in tall forests, but feedback to size and intensity less clear. Significant but uncertain impact of drought severity and frequency, and rainfall patterns (seasonality and events)
- General replacement of tall open forests by open forests, especially on western margins of biome; rainforest environments also threatened by increasing aridity and fire frequencies
- Heat stress and increased fire in high altitude forests may lead to dieback and replacement by sclerophyll types, for example, in Tasmania

DISAPPEARING ENVIRONMENTS

- Replacement of tall open forests by open forests, especially in south
- Loss of rainforest understoreys and rainforest environments, especially in Queensland/northern New South Wales – overall 68% MVG1 environment disappears under 2070 high impact scenario
- Loss of high altitude coniferous forests in Tasmania
- Most of biome environments in New South Wales and Queensland are likely to disappear entirely under 2070 high impact scenario; central Victoria and Tasmania are less affected

BUFFERING

- Local scale (1 km) buffering poor throughout biome but reasonably good at larger scales (100 km) in coastal Queensland/New South Wales, Victoria and Tasmania
- Local landscape heterogeneity imparted by topography an asset to biome

ISSUES

- Structural change: replacement of tall forests and loss of shrubby and rainforest understoreys will alter habitat conditions for a range of biota
- Narrow endemics likely to be most affected, as are critical parts of the NRS in the biome (Border Ranges, Kosciusko National Park and Tasmania)

- Fire likely to play critical role in shaping new forest environments, but complex relationships with climate
- Invasive species could alter fuel and ecological dynamics, for example, buffel and other C4 grasses, southwards spread of lantana; but others may decline (e.g. blackberry, gorse)
- Impacts on refuges critical in the biome – diversity partly due to spatially restricted “special” habitats (e.g. fire-protected rainforests, rocky outcrops, steep gradients due to terrain)
- Important to retain the reasonably good connectivity in the biome, both across the large latitudinal range and locally from coast to Dividing Range

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