NCCARF
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National Climate Change Adaptation Research Plan

Terrestrial biodiversity

Update 2017

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NCCARF works to support decision makers throughout Australia as they prepare for and manage the risks of climate change. Hosted by Griffith University on the Gold Coast, NCCARF has a national focus across Australia to build resilience to climate change in government, NGOs and the private sector.

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Executive Summary

In 2011, a National Climate Change Adaptation Research Plan (NARP) was developed for the terrestrial ecosystems and biodiversity theme of climate change adaptation (Terrestrial NARP 2011). The Terrestrial NARP aims to identify priority research questions for climate change adaptation issues relevant to Australia's cities, towns and regions, including coastal communities and regions. This NARP was updated in 2013 (Terrestrial NARP 2013).

The purpose of this document is to review the Terrestrial NARP 2013 and this was done through a series of workshops with key stakeholders in 2015-16. The most important component of the NARPs is to identify and prioritise adaptation research questions that are important, often urgent, and will provide knowledge needed by adaptation stakeholders across Australia.

Based on the stakeholder review, a total of 20 priority research questions (Table 1) are presented in this report within four research themes:

1. Developing conservation goals and implementation strategies aimed at maximising the long-term resilience of biodiversity in a changing climate (five questions)
2. Integrating conservation management and adaptation actions across diverse, multi-use landscapes to support ecosystem resilience and maximise positive biodiversity outcomes in a changing climate (five questions)
3. Managing threats and stressors to maximise ecosystem resilience in a changing climate (seven questions)
4. Managing biodiversity assets (three questions).

This document delivers a resource for research providers to identify critical gaps of information needed by sectoral decision-makers; set research priorities based on these gaps, and identify capacity across the network that could be harnessed to conduct priority research that addresses stakeholders' requirements and involvement. Strategic, cost effective actions are required to maximise potential benefits of management and the knowledge generated by research that addresses the questions described in this report will facilitate informed decisions and appropriate adaptation actions.

Table 1. Priority research questions for the National Climate Change Adaptation Research Plan for Terrestrial Biodiversity 2017.

1. Developing general conservation goals, policy and implementation strategies aimed at maximising the long-term resilience of biodiversity in a changing climate	
1.1	What are the general principles that should guide conservation goals and decisions?
1.2	What are the necessary factors and policies to enable the implementation of these modified principles and goals?
1.3	What are the social and institutional barriers to the implementation of adaptation change and how do we overcome them?
1.4	How should the existing Australian legal, policy and institutional architecture for land management and biodiversity conservation respond to changes in conservation goals and principles?
1.5	How can major socio-economic trends occurring in Australia contribute to effective adaptation responses?
2. Integrating conservation management and adaptation actions across diverse, multi-use, multi-scale landscapes to support ecosystem resilience and maximise positive biodiversity outcomes in a changing climate	
2.1	What principles should guide ecosystem-based adaptation and the design of landscapes?
2.2	How should new protected areas be selected?
2.3	How can management of protected and non-protected areas incorporate and adapt to climate change?
2.4	How can Australia's land-based climate change mitigation initiatives be designed so they also enhance ecosystem services and resilience and deliver biodiversity conservation benefits?
2.5	What conceptual models and long-term observation systems are needed to support the design, analysis and assessment of active adaptive management and policy experiments?
3. Managing threats and stressors to maximise ecosystem resilience in a changing climate	
3.1	Which extreme events and aspects of their regime (frequency, magnitude, duration and the return period) are associated with the vulnerability of biodiversity and how can we adapt to minimise their impacts on natural ecosystems?
3.2	How will climate change interact with habitat change (loss, fragmentation and degradation) and what are the implications for managing ecosystem resilience?
3.3	How will climate change interact with fire and what are the implications for managing ecosystem resilience?
3.4	How will climate change interact with invasive species and what are the implications for managing ecosystem resilience?
3.5	How will climate change interact with salinity and water availability and what are the implications for managing ecosystem resilience?
3.6	How will climate change interact with emerging disease and what are the implications for managing ecosystem resilience?
3.7	How can we assess and quantify the relative impacts and their interactions/synergies of all stressors in a system in order to enable the most effective and balanced adaptation actions?
4. Managing biodiversity assets	
4.1	How do we identify species/communities that should be the focus of investment in climate change adaptation?
4.2	How will climate change affect current management actions for protecting priority species / communities and managing problem species, and what management changes will be required?
4.3	How do we optimise the investment in adaptation actions aimed at protecting biodiversity assets?

1. Introduction

There is now widespread acceptance in Australian society of the need to respond to climate change, with changes in our climate already being observed both in Australia and around the globe. For instance, in 2015 NASA reported that the Earth's surface temperatures were the warmest since modern records began in 1880. In 2016, Arctic winter sea ice reached the lowest maximum extent in the satellite record, replacing 2015's record low. In Australia, Sydney had a record run of 36 days of temperatures above 26°C, breaking the previous record of 19 days set in 2014. And there have been dramatic impacts linked to these weather events: an aerial survey of the northern Great Barrier Reef showed that 95% of reefs were affected by bleaching during the 2016 bleaching event, and mortality is estimated at 22%. The Australian Government has acknowledged the need to respond to climate change by meeting its internationally agreed targets and by supporting an effective international response.

1.1 Global policy context for adaptation

The global policy context is managed through the United Nations Framework Convention on Climate Change (UNFCCC), and sets the scene for Australia's response to climate change. The principle international mechanism for climate change response is the Paris Agreement, which emerged from the UNFCCC Conference of the Parties in December 2015 (COP21). The Agreement covers both adaptation and mitigation efforts, and sets out goals for each.

The Paris Agreement establishes a global goal to significantly strengthen national adaptation efforts

For adaptation, the stated goal in the Agreement is set out in Article 7:

> ***Adaptation*** – *The Paris Agreement establishes a global goal to significantly strengthen national adaptation efforts – enhancing adaptive capacity, strengthening resilience and reduction of vulnerability to climate change – through support and international cooperation. It also recognizes that adaptation is a global challenge faced by all. All Parties should submit and update periodically an adaptation communication on their priorities, implementation and support needs, plans and actions. Developing country Parties will receive enhanced support for adaptation actions.*

Goals for mitigation are set through the Intended Nationally Declared Contributions (INDCs) to global emissions reduction put forward by individual nations. Although the Agreement states that the target is to limit global temperature increase to no more than 2°C above pre-industrial levels, at the present time the sum total of declared INDCs will most likely lead to a rise of around 2.6°C. The agreement came into force on 4 November 2016 once it had been ratified by 55 countries representing at least 55% of global emissions.

Article 13 of the Agreement obliges all countries to have a transparent and robust accounting system that will enable them to report on their actions relating to mitigation, adaptation and support, and that will be subject to international review. Linked to this is a 'global stocktake' that will take place in 2023 and subsequently every five years to assess collective progress in meeting the purpose of the Agreement

The Intergovernmental Panel on Climate Change (IPCC) is responsible for assessment of the scientific knowledge on climate change, as a basis for the negotiations carried out through the UNFCCC. It prepares periodic Assessment Reports, the most recent of which was the Fifth Assessment, published in a number of volumes through 2013 and 2014. The IPCC has embarked on a Sixth Assessment, due to report in time for the 2023 global stocktake.

1.2 National policy context for the National Climate Change Adaptation Research Plans

The Australian Government is committed to undertaking and supporting adaptation to climate change. In this context, the term 'adaptation' refers to the practical actions undertaken by society to reduce the adverse risks of climate change on human and natural systems, as well as to harness any beneficial opportunities that climate change may generate.

The basis for guidance on government action on adaptation in 2016 remains the *National Climate Change Adaptation Framework* (the Adaptation Framework) that was endorsed by the Councils of Australian Governments (COAG) in 2007. The Adaptation Framework identifies possible actions to assist adaptation to climate change by vulnerable sectors and regions, such as water resources, human health, settlements and infrastructure, and coasts. It also identifies actions to enhance the knowledge base that underpins climate change and to improve national coordination of climate change adaptation research. The Adaptation Framework to date has catalysed a broad range of initiatives and institutions, including the establishment of the National Climate Change Adaptation Research Facility (NCCARF) in 2007 followed by further funding for NCCARF in 2014.

In 2015, the Australian Government developed the *National Climate Resilience and Adaptation Strategy* (the Adaptation Strategy) which outlines the roles of governments including the critical role to ensure the right institutional environment to support and promote action to address climate risks. This includes outlining the role of the Australian Government, which is to ensure the provision of authoritative climate science and information to ensure that those in society can make informed decisions and changes to their behaviour to address climate risks. The Adaptation Strategy specifically 'affirms a set of principles to guide effective adaptation practice and resilience building, looks at leading practice nationally, and considers areas for future review, consultation and action' (p.5). These principles are:

1. Shared responsibility
2. Factoring climate risks into decision making
3. An evidence-based, risk management approach
4. Helping the vulnerable
5. Collaborative, values-based choices
6. Revisiting decisions and outcomes over time.

The National Climate Change Adaptation Research Plans (NARPs) are one important route for developing capacity by articulating the key knowledge gaps for an evidence-based, risk management-based approach for adaptation knowledge and action. Also important is to outline clear direction for investment in science, technology and innovation for adaptation that will help to manage climate risks and emerging opportunities.

1.3 Background to the NARPs

NCCARF was established by the Australian Government in 2007 (and then further funded from 2014 to 2017) to coordinate and lead the Australian research community in generating the biophysical, social and economic information and tools needed to facilitate adaptation to climate change. A key role of NCCARF is to coordinate the development of the National Climate Change Adaptation Research Plans (NARPs) across a range of priority areas. This exercise is led by NCCARF's National Adaptation Networks that, as communities of researchers and practitioners, aim to connect researchers and research users in government, sectors and communities with a view to building and maintaining the capacity to adapt to a changing climate. The current National Adaptation Networks focus on four key challenge areas in adaptation; Natural Ecosystems; Settlements and Infrastructure; Social, Economic and institutional Dimensions; and Vulnerable Communities (for more information www.nccarf.edu.au/content/adaptation-networks).

The NARPs are research plans, addressing specific topics, which aim to identify critical gaps in the information required by governments, industry and the community to develop and implement effective adaptation responses to climate change. The gaps that are identified by research providers, policy makers and practitioners through this process can be used to set research priorities. The NARPs provide an outline for a strategic approach to priority research aimed at informing managers, policy makers and the public in order to facilitate better decisions that help to maximise Australia's potential to adapt to climate change.

The first NARPS were developed during the period 2009-2010 and covered eight priority areas: emergency management, human health, marine biodiversity and resources, primary industries, settlements and infrastructure, terrestrial biodiversity, freshwater biodiversity and social economic and institutional dimensions of adaptation. An Indigenous communities NARP was developed in 2012. Several of the NARPS were revised during 2011- 2013 and now, in 2016, there is another round of NARP revisions. The revisions timetable is outlined in Table 1.

Table 1: Timetable of NARP development and revision.

Original NARPs	Previous revision of NARPs	Current revision of NARPS
Emergency Management (2010)	Revised in 2012	-
Human Health (2009)	Revised in 2012	-
Marine Ecosystems and Biodiversity (2010)	Revised in 2012	Under revision in 2016
Primary Industries (2009)	Revised in 2013	-
Settlements and Infrastructure (2010)	Revised in 2012	Under revision in 2016
Terrestrial Ecosystems and Biodiversity (2011)	Revised in 2013	Under revision in 2016
Freshwater Ecosystems and Biodiversity (2011)	-	Under revision in 2016
Social, Economic and Institutional Dimensions (2011)	-	Under revision in 2016
Indigenous Communities (2012)	-	

1.4 Revision of the NARPs

The revision of the NARPs broadly follows a process of four steps:

1. Appointing a writing team of topic experts
2. Reviewing the scientific literature published since the previous version of the NARP
3. Undertaking consultation workshops with researchers, practitioners and policy makers
4. Collating the material into an annotated list of priorities
5. Subsequently, each of the NARP teams has customised this process to suit their topic and stakeholders.

2. Context and methodological approach

The aim of this National Climate Change Adaptation Research Plan is to identify priority research required to inform policy and management aimed at implementing adaptation actions to protect Australia's biodiversity under a changing climate.

This process helps to identify and prioritise knowledge gaps, suggest research to fill these gaps, strengthen linkages between researchers and stakeholder/end-user groups, reduce duplication of research and maximise return on public investment in research. To assist this process, our analysis provides a significant review and consultation process in order to identify research gaps, stakeholders and research provider needs, and collaborative possibilities and synergies, thereby delivering a valuable resource for terrestrially focused research providers and end-users.

This document delivers a resource for research providers by helping to locate relevant research information more efficiently, and by ensuring that proposed research is strategic and targeted at the needs of the end-users. It provides a resource for end-users by delivering a repository of biodiversity research prioritisation by identifying the areas of research where stakeholder interests overlap. Finally, the report can also be used by funding bodies to help guide the prioritisation of resources into future biodiversity research. To achieve that aim in the second phase of NCCARF, every Network organised a review and writing team to produce a National Adaptation Research Plan 2016. The NARP Terrestrial Biodiversity review and writing team reviewed the previous NARPs (2010 and the update on 2013) and identified research priorities and changes given the progress in knowledge and research since the date of the last NARP.

A literature review was conducted to identify gaps and priorities not addressed since the last NARP. In a similar way the review of the previous research programs funded by NCCARF in phase 1 were evaluated. The outputs from NCCARF phase 1 research programs were considered as how much they addressed the knowledge gaps identified in 2010 and 2013. Once these advances and gaps were identified, the previous priority research questions (PRQs) were updated and restructured. The final draft was submitted for open review and consultation, with different stakeholders, key end-users and wider community providing comments and input to the final NARP.

The approach taken for this NARP revision was as follows.

a. *Revise and update recent literature in the time since the last NARP.* An extensive literature review was done for each priority research question of the previous NARP, where research gaps and priorities have been identified (see Appendix 1).

b. *Identify information and knowledge gaps* to respond to climate change in ways that reduce vulnerability of terrestrial ecosystems.

c. *Evaluate the adaptation research priorities proposed in the previous NARP*. After the identification of research gaps for each priority research question of the previous NARP, we evaluated the priority research questions to be maintained modified or removed in the current plan.

d. *Set adaptation research priority questions based* on the identification of gaps and analysis of the previous research questions of the 2013 Terrestrial NARP.

As with the original Terrestrial Biodiversity NARP (Hughes et al., 2010), five criteria were used to determine the priority of research questions.

Critical
1. **Severity of potential impact or degree of potential benefit**
What is the severity of the potential impact to be addressed or benefit to be gained by the research? Potentially irreversible impacts and those that have a greater severity (in social, economic or environmental terms) will be awarded higher priority.
2. **Immediacy of required intervention or response**
Research will be prioritised according to the timeliness of the response needed. How immediate is the intervention or response needed to address the potential impact or create the benefit? Research that must begin now in order to inform timely responses will receive a higher priority than research that could be conducted at a later date and still enable a timely response.
3. **Need to change intervention or practicality of intervention**
Is there a need to change the intervention used currently to address the potential impact being considered. If yes, what are the alternatives and how practical are these alternate interventions? Does research into the potential impact of the intervention being considered contribute to the knowledge base required to support decisions about these interventions? Research that will contribute to practicable interventions or responses will be prioritised.
Desirable
4. **Potential for co-benefit**
Will the research being considered produce any benefits beyond informing climate adaptation strategies?
5. **Potential to address multiple, including cross-sectoral, issues**
Will the research being considered address more than one issue, including cross-sectoral issues?

Additionally, the criteria established by NCCARF to produce and update the priority research questions for the current NARP 2016 included consideration of the previous NARPs, including:

Criteria NARP Terrestrial Biodiversity 2016
1. **Was it comprehensive and relevant?**
Evaluate the previous PRQs, identify how comprehensive and relevant each questions remains with new knowledge developed in the last three years.
2. **Are the research priorities/questions still relevant given progress in the science and changing needs of end users?**
How much knowledge has been added and research gaps filled since over the last three years? Are there new advances in knowledge and research on the impacts of climate change on terrestrial biodiversity that need to be understood and investigated?

3. Summary of knowledge gaps addressed in NCCARF Phase 1

The original Terrestrial Biodiversity NARP (Hughes et al. 2010) identified research knowledge gaps with respect to helping terrestrial systems adapt to climate change, and developed priority research questions (Appendix 2) to enable researchers to focus their efforts on filling these gaps.

In 2013, the Terrestrial Biodiversity NARP update was revised and re-worded to reflect changing government policies and contemporary knowledge on climate change impacts (Kitching et al. 2013), with the aid of a literature review (Guitart 2012). The 2013 revised priority research questions, under each of four main sub-themes which represent the primary ecological scales of organisation and management, are shown in Table 3.

Table 3: High priority research questions from the Terrestrial Biodiversity NARP Update (Kitching et al. 2013).

5.1 National/continental scale issues	
5.1.1	How will climate change affect existing conservation goals and how should change conservation goals be promoted and achieved?
5.1.2	How can the existing Australian legal, policy and institutional architecture for land management and biodiversity conservation respond to changes in conservation goals caused by climate change?
5.1.3	What conceptual models and long-term observation systems are needed to support the design, analysis and assessment of active adaptive management and policy experiments at regional and national scales under climate change?
5.2 Regional issues	
5.2.1	What principles should guide ecosystem-based adaptation in Australia and the design of landscapes to support ecosystem resilience?
5.2.2	How will climate change interact with other key stressors such as fire, invasive species, salinity, disease, changes to water availability, grazing and clearing, and what are the integrated implications for ecosystem structure and functioning?
5.2.3	How can Australia's land-based carbon mitigation initiatives be designed to enhance ecosystem services, ensure appropriate ecological connectivity, deliver biodiversity conservation benefits and avoid adverse impacts on biodiversity?
5.2.4	How can the major socio-economic trends occurring in many regions of Australia contribute to effective climate change biodiversity adaptation responses?
5.3 Local land management issues	
5.3.1	What are the costs and benefits of different climate change adaptation measures in vulnerable ecological communities and ecosystems?
5.3.2	How should fire management adapt to climate change?
5.3.3	How can management of local protected areas incorporate and adapt to climate change?
5.3.4	How can we better integrate conservation plans and actions across landscapes, incorporating protected area management, off-reserve conservation measures and other land uses, in order to maximise biodiversity conservation benefits / outcomes under a changing climate?
5.4 Managing key species and communities	
5.4.1	How can investment in climate change adaptation measures to conserve species and communities be prioritised?
5.4.2	How will climate change affect current management actions for protecting priority species and communities, and what management changes will be required?
5.4.3	How will climate change affect current or potential problem species and what management responses will be required?

The priority research questions in the original Terrestrial Biodiversity NARP (Hughes et al. 2010) were used to prioritise research funding under NCCARF Phase I. NCCARF funded a number of research projects specifically tasked with addressing these questions (Table 4). The projects were completed after the second revision and update of the NARP in 2013.

The literature review (Appendix 1) for this 2016 NARP revision is structured around each of the previous priority research questions presented above. The aim of the literature review was to review the findings and conclusions of the various NCCARF funded projects, with relevance to specific priority research questions, and also to review any other relevant literature published between 2013 and 2015 (including research published in late 2012 not in the review by Guitart (2012). A particular focus was research and policy undertaken in Australia, but global studies are included when they were considered to be generally relevant to a specific priority research question. In total, this review includes 156 papers, books, book chapters and reports.

Table 4: NCCARF funded projects commissioned to address original priority research questions (Hughes et al. 2010).

Research Project Title	PRQs addressed	Principal Researcher
Contributing to a sustainable future for Australia's biodiversity under climate change: conservation goals for dynamic management of ecosystems.	5.1.1, 5.1.2, 5.4.2	Michael Dunlop - CSIRO
The architecture of resilient landscapes: scenario modelling to reveal best practice design principles for climate adaptation	5.2.1, 5.2.4, 5.3.3, 5.3.4	Veronica Doerr - CSIRO
Optimal habitat protection and restoration for climate adaptation	5.2.4, 5.3.1, 5.3.3, 5.3.4, 5.4.1, 5.4.2	Richard Fuller - UQ
Climate-resilient revegetation of multi-use landscapes: exploiting genetic variability in widespread species	5.3.3, 5.3.4, 5.4.1, 5.4.2,	Margaret Byrne – DEC WA
Adaptation strategies for Australian birds	5.3.3, 5.3.4, 5.4.1, 5.4.2	Stephen Garnett - CDU
Developing management strategies to combat increased co-extinction rates of plant-dwelling insects through global climate change	5.3.3, 5.3.4, 5.4.1, 5.4.2	Melinda Moir - University of Melbourne
Determining high risk vegetation communities and plant species in relation to climate change in the Australian alpine region	5.2.2, 5.3.3, 5.3.4, 5.4.1, 5.4.2, 5.4.3	Catherine Pickering - Griffith University
The role of refugia in ecosystem resilience and maintenance of terrestrial biodiversity in the face of global climate change	5.2.2, 5.3.3, 5.3.4, 5.4.2	Stephen Williams - JCU
Adapted future landscapes - from aspiration to implementation	5.2.1, 5.2.3, 5.2.4, 5.3.4	Wayne Meyer - University of Adelaide
Determining future invasive plant threats under climate change: a decision tool for managers	5.2.2, 5.3.4, 5.4.1, 5.4.2, 5.4.3	Lesley Hughes - Macquarie

This report represents a more substantial revision of the original NARP priority questions as there has now been considerable new research and, importantly, strategically targeted research aimed at addressing the original questions. However, with limited time and budgets, many of the original questions remain unanswered, or partially answered, and much remains to be done. While fundamental knowledge in many areas is still required, most of the research suggested below is focused on the knowledge needed for specific adaptation actions. Collectively, the overall aim of the research questions is to focus research effort on how we can incorporate risk and vulnerability assessment at all levels of environmental management with future climate scenarios, to support informed decisions about the timing and cost/benefit trade-offs of adaptive management options. Based on previous versions of the NARP, new knowledge, perceived changes in policy and management needs and the results of the research supported under NCCARF Phase I, the new priority research questions (20 in total) are presented here within four research themes all aimed at maximising the long-term resilience of biodiversity and natural ecosystem function in a changing climate:

1. Developing conservation goals and implementation strategies (five questions)
2. Integrating conservation management and adaptation actions across diverse, multi-use landscapes (five questions)
3. Managing threats and stressors (seven questions)
4. Managing biodiversity assets (three questions).

These new questions are cross-referenced with research questions identified in previous Terrestrial Biodiversity NARPs in Appendix 2.

4. Priority research questions

The priority research questions are listed in Table 1. In this section, each theme is described in general followed by a more detailed description of the significance, background and aims of each specific priority research question.

Research theme 1: Developing conservation goals and implementation strategies aimed at maximising the long-term resilience of biodiversity in a changing climate

Climate change presents an enormous challenge to conservation, not only because of the biophysical impacts but because it requires a complete re-think of the general principles that underlie our entire approach to conservation of biodiversity and natural ecosystems. We need to develop guiding principles of conservation based on a fundamentally changed conservation paradigm of managing change, rather than maintenance of the status quo. These new principles need to maximise the capacity of natural ecosystems and each species to move, evolve and change in ways that maintain the overall resilience and healthy functioning of Australia's ecosystems while minimising biodiversity loss. Successful implementation of a new, more-dynamic conservation paradigm will require careful consideration and review of existing policy, management, legal and institutional frameworks for conservation.

Changing the fundamental underlying philosophy of a system will require research aimed at providing the knowledge to understand the philosophical, social and economic barriers and challenges associated with implementing these changes. The questions in this section target research on developing the knowledge to bring about a significant change in the existing conservation paradigm, including:

1. General principles of conservation in a changing climate
5. Policy changes necessary to a new conservation paradigm
6. Social and institutional barriers to this change
7. Legal and policy issues necessary to implement new guiding principles
8. The potential for broad social-economic trends to influence successful adaptation actions.

Question 1.1: What are the general principles that should guide conservation goals and decisions in a changing climate?

There has been a general acknowledgement and acceptance that conservation practice needs to become more dynamic and move beyond the earlier paradigm of in-situ preservation. Dunlop et al. (2003) reviewed this issue within an NCCARF-funded study "Climate-ready Conservation Objectives: a scoping study". The study found that, while most conservation documents mention climate change, there was little consistency in how it was treated and little acknowledgment of the potential severity of the impacts. Dunlop et al. (2013) describe the concept as being 'climate-ready' and found that few strategic documents are sufficiently climate-ready. This view has been supported by several other studies on this topic (Stein et al. 2013; Wise et al. 2014) and has subsequently been taken up by regional NRM planning in many regions.

Some themes were identified in the Dunlop et al. (2013) review that were consistently considered to be important to adapting our general conservation goals and principles, including; managing threats, building landscape resilience, maintaining and improving habitat connectivity (when appropriate), protecting species, habitats and ecological processes. The overall goal of conservation in Australia should continue to include traditional conservation practices such as (i) maintenance of well-functioning ecosystems, (ii) protection of a representative array of ecosystems, (iii) removal or reduction of existing stressors, (iv) building and restoration of habitat connectivity, (v) identification and protection of refugia, and (vi) minimising the loss of species. But as the climate changes rapidly, our traditional conservation focus on preventing ecological change needs to shift toward the management of change to minimise loss of biodiversity and maintain evolutionary processes and ecosystem functions.

These principles are inherent in a number of the other priority research question in this NARP and need to be considered in a dynamic framework rather than a traditional static approach. An important aspect of this question remains the development of general, dynamic conservation principles and the subsequent communication and implementation of these fundamental changes to the conservation management and policy stakeholders.

Question 1.2: What are the necessary policies and resources required to enable the implementation of these modified principles and goals?

Conservation policies have traditionally focused on land with specific tenure or zoning for conservation (i.e. national parks, State forests, reserves etc.), individual plant and animal species with particular conservation status (e.g. endangered) or ecosystems (again with a particular conservation status). Climate change presents new challenges to these location- and status-based classifications and policies. The risk, therefore, is that the underlying approaches of existing policy will limit our ability to implement new and modified approaches to conservation.

While existing research findings and knowledge provide an initial basis for considering climate change adaptation and land management, new information must be considered in all relevant policy. This new information should not only include impacts of climate change on individual species or ecosystems, but key biological and ecological factors such as species interactions, dispersal, phenological changes, hysteresis, evolution and sampling of species niches as well as extinction and future species range. To this end, new conceptual models are likely to help support adaptation planning and policies. Dynamic species distribution models integrate factors such as disturbance, dynamic population processes, species interactions and transient climates (Reside et al. 2010). Emphasis on mechanistic models reflects an increasing understanding that underlying ecological processes are as important as the impacts of climate change. Generalised dissimilarity modelling provides spatial information on the potential effects of climate change on key groups of organisms, such as plants or mammals, at the community level, enabling a 'whole of biodiversity' perspective in planning (Williams et al. 2014). Supporting modelling approaches is access to data and monitoring of ecosystem responses. While there is already a significant body of information and data that can support development of policy, it is often disparate and disconnected. Development of integrated data management systems will improve access and analysis of information to support policy analysis. Existing efforts include Australia's Terrestrial Ecosystem Research Network (TERN) established in 2010. Within TERN is a Long Term Ecological Research Network for Australia (LTERN) based on a network of long term monitoring plots as well as a network of subcontinental bioclimatic transects (Australian Transect Network) using the space-for-time approach to understand likely evolutionary and biogeographical responses in ecological communities under different climate futures.

Decision makers will need to have a broader understanding of how biodiversity will function in the broader landscape including identifying climate refugia (Reside et al. 2013) and also an understanding the changing threats of invasive species including the increased and decreased invasiveness of different species (Scott et al. 2014).

Monitoring indicators of climate change impacts, adaptation of species and ecosystems and management interventions will be necessary to test policy appropriateness and effectiveness.

In the absence of long-term data sets, surrogates such as botanical records and museum records can help build baseline data to measure change against. Examples of this include bird movement or breeding patterns (Chambers & Keatley 2010).

Ongoing investment in developing and testing new predictive ecological models, data management and monitoring, as well as testing new modelling approaches to support policy development will provide for more informed prioritisation and efficient allocation of resources.

Question 1.3: What are the social and institutional barriers to the implementation of adaptation change and how do we overcome them?

Adaptation to climate change is a social phenomenon requiring social research for resolution (Van Vugt 2009). While conservation actors almost universally agree that active management will be required to conserve biodiversity, very few are willing to countenance many of the more interventionist approaches, preferring instead to augment existing approaches (Hagerman & Satterfield 2013). This is a different problem to denial of climate change and appears to be largely a response to uncertainty of all kinds. Of these, epistemological uncertainty about how organisms may respond under climate change has received most research effort (Kujala et al. 2013) and has highlighted the pervasiveness of climate change as a problem for biodiversity. However other forms of uncertainty contribute to a reluctance to take action. For instance, linguistic uncertainty can lead to misunderstandings that can inhibit action.

Thus a finding that widespread acceptance of a need for action (Hagerman et al. 2010) was interpreted as there being an acceptance of a need to abandon climate-challenged species (Tingley et al. 2013), a far more challenging prospect. This plays on ontological uncertainty that arises from differences in world view (Lane & Maxfield 2005). This means that an active response to climate change is asking people to change long-standing core values about biodiversity (Hagerman & Satterfield 2014). Just as a strong attachment to place can inhibit adaptation (Marshall et al. 2012), so too can a strong association of biodiversity with place. Understanding what may be needed to persuade people to alter such values, and accept a need for active management, represents an essential area of social research, and begs questions about legitimacy of competing world views; i.e. that some extinction of species from climate change may be offset by advantages to which they give greater value.

There are many parallels with research on climate change denial which is similarly threatening to deeply held beliefs (Dickinson 2009). Although there has been much research on mitigation, there has been relatively little psychological research on the adoption of adaptation measures (Clayton et al. 2015). In particular, research is needed on positive adaptations and ways to encourage them (De Young 2014). However, the psychological research is only just beginning on 'individual capabilities, cognitive processes, biases, values, beliefs, norms, identities, and social relationships' that are needed to communicate effectively about risk and to support behavioural change for adaptation to climate change (Clayton et al. 2015).

Question 1.4: How should the existing Australian legal, policy and institutional architecture for land management and biodiversity conservation respond to changes in conservation goals caused by climate change?

Australia already supports an extensive network of reserve areas and environmental management legislative and policy instruments legislative and policy. Much of this has been predicated on the notion of preserving ecosystems in a pre-European state and maximising biodiversity. While many of the provisions in existing instruments contribute to the new and modified principles of conserving biodiversity (e.g. reducing disturbance, controlling weeds, managing fire risks) there are a number of challenges associated with climate change that are not well addressed (e.g. species movement beyond reserves, new disturbance threats such as saline inundation of freshwater systems, limits to adaptation for some species). If governance arrangements and strategic planning approaches do not review their approaches, there is a risk of maladaptive practices that put biodiversity at greater risk under climate change.

Policy options are likely to include economic instruments that allow for co-benefits of productivity and biodiversity (Ring et al. 2010; Van Oosterzee 2012), reviewing existing land management plans to incorporate adaptation (e.g. Rissik et al. 2014), and assessment of biodiversity at a national level (e.g. Groves et al. 2012). Conservation approaches will need to consider landscapes as a whole and will demand greater cross-jurisdictional cooperation and coordination.

To meet biodiversity outcomes, in a policy setting of competing interests, it will be critical to embed or mainstream biodiversity into policy across sectors. Outcomes that address social, economic and biodiversity outcomes should be at the heart of best practice adaptation planning.

Policy, legislation and the underlying regulatory frameworks will need to allow for greater flexibility and identify low regrets options as discussed in McDonald et al. (2016). Policy will need to balance ideal solutions (i.e. best conservation outcomes) with practical solutions that take account of social considerations. A worst-case scenario may require a triage approach in which resources are focussed on ecosystems that are most likely to survive through the effects of climate. Research will be needed to develop and test these new policy approaches.

Question 1.5: How can major socio-economic trends occurring in Australia contribute to effective climate change biodiversity adaptation responses?

Adaptation for biodiversity conservation under climate change is embedded within the wider context of ongoing social trends. Only some of these trends are likely to be influenced by climate change in the short-medium term and therefore climate change adaptation planning needs to incorporate different socioeconomic pathways (Kriegler et al. 2012; O'Neill et al. 2014). Significant trends can be identified through horizon scanning (Sutherland & Woodroof 2009). To date such exercises have tended to emphasise threats (e.g. Stanley et al. 2015) and barriers to adaptation (i.e. Keys et al. 2014; Roiko et al. 2012), However some potential threats can be reframed into opportunities for conservation, or some national trends can be used to identify benefits for biodiversity.

Investment of sufficient funds is a critical element of any adaptation strategy. Ongoing wealth generation needs to underpin investment in biodiversity conservation in general and climate change adaptation for terrestrial biodiversity in particular. While this economic growth is currently driving climate change, there is potential to break this link through decreasing carbon intensity of production and expansion of a knowledge-based economy. Average wealth in Australia has increased by 40% in the last decade, much of it going into savings, and the country is ideally placed to increase the utilisation of renewable energy sources and to expand trade in resources, manufactured goods and services into the expanding Asian market. Thus funds should not be limiting if biodiversity continues to be valued by the community.

Demographic change is the most obvious social trend that could lead to opportunities for adaptation to conserve terrestrial biodiversity. Potential options for biodiversity conservation include carbon sequestration, tourism, urban redevelopment, low density peri-urban development, retiree interest in Landcare, greater management and use of traditional knowledge, and private organisation conservation investments (Steffen et al. 2009). For example, land management practices that involve re-establishment of habitat could use climate change projections to guide assisted colonisation to guide species selection (Lunt et al. 2013), timing (McDonald-Madden et al. 2011) and location (Harris et al. 2013). Even in urban areas, the surge in support for community gardens could provide refuge and habitat for native wildlife, offer other ecosystem services, and offset disadvantages of industrial agricultural practices, by decreasing food miles, improving food security, reducing environmental costs and promoting agro-biodiversity (i.e. Guitart 2011). The IPCC (2014b) also note that some options for reducing energy and water consumption in urban areas, such as greening cities/roofs and recycling water, can have co-benefits for biodiversity and climate change adaptation.

More generally, integrated response packages—in terms of governance, education, investment sources and action plans for biodiversity conservation and potential for carbon and biodiversity offsets— can be tailored to the demographic, land use, climatic and socio-economic trajectories of specific regions around the country. These response packages will need to account for potential population shifts driven by land use changes resulting from the impacts of climate change, especially in coastal regions.

Socio-economic trends also include a re-evaluation, both in Australia and internationally, of ecosystem services (i.e. carbon, water, biodiversity) with consequent changes in practice, policy and legislation (Boulter 2012); including expansion of both the private and public protected area estate. Mechanisms to promote synergies between increased landscape carbon and biodiversity values through Australia's Carbon Farming Initiative are a further recent impetus for adaptation in some regions. Water property rights, such as those being implemented through the Murray Darling Basin Plan (MDBA 2012), also provide conservation management opportunities for improved aquatic and riparian ecosystems.

Adaptation opportunities arising from socio-economic trends are likely to be regionally-specific; regional land use patterns are likely to respond to challenges and (arising from long term climate change impacts) changes in the valuations of ecosystem services, commercial and other lands uses and economic and demographic trends (Mansergh 2010). Increased resources and an expanded role for natural resource management planning are becoming available through the Clean Energy Future package and the associated increased involvement of NRM bodies in regional environmental planning, delivering planning that is resilient to political change. These opportunities would benefit from priority-setting and cross agency decision-support tools; especially those that could inform resilience analysis.

Some current socio-economic trends could contribute to effective climate change adaptation for terrestrial biodiversity. However, there are no published examples and little current research making this a priority for future focus. Most analyses have focused on threats and socioeconomic trends as a barrier to adaptation actions rather than opportunities arising from trends. Many of these opportunities are likely to be spatially specific (for example, savanna fire in northern Australia) meaning managers need to identify potential opportunities in their region as they arise; even if the driving force behind trends is at a larger scale.

Research theme 2: Integrating conservation management and adaptation actions across diverse, multi-use landscapes to support ecosystem resilience and maximise positive biodiversity outcomes in a changing climate

It is becoming increasingly recognised that biodiversity conservation cannot rely solely on protected areas and that the management of natural ecosystems is best achieved by an integrated land management approach that incorporates activities such as biodiversity conservation, carbon storage/mitigation, agriculture and forestry. Changing landscape management objectives from maximising production to developing landscapes that are resilient and productive over long time scales will become increasingly important in stabilising ecosystems and production capacity. An integrated approach should provide the highest likelihood of positive benefits, and reduce the potential for perverse negative impacts arising from conflicting land-use goals, for both natural ecosystems and the provision of resources and ecosystem services to people. Significant opportunities exist in multi-use landscapes with demonstrable benefits to both the resilience of farming enterprises (particularly during drought) and nature conservation. There is an urgent need for increased understanding of how landscape configuration could be modified and managed to optimise biodiversity conservation and promote productivity in other land uses such as agriculture. Are there particular designs, or sets of design principles, that can be applied to groups of landscapes across Australia that maximise resilience for biodiversity?

Steffen et al. (2009) proposed five broad approaches for climate change adaptation, to protect biodiversity:

1. Enhance resilience of ecological systems
2. Create landscapes that maximise adaptation opportunities
3. Expand and augment the reserve system
4. Undertake specific in situ conservation actions
5. Undertake ex situ conservation actions where appropriate.

There is a need to develop general principles of landscape design applicable across diverse ecosystems and spatial scales. These principles need to consider the factors that promote, and detract, from landscape resilience including protected and non-protected areas, production areas, habitat connectivity, biodiversity refugia at a variety of spatial scales and mitigation initiatives.

The role, and cost-benefit trade-off, of biodiversity refuges needs to be considered at multiple spatial and temporal scales and across a wide spectrum of interacting disturbance types, from pristine ecosystems to highly fragmented production landscapes. It will be invaluable to develop generalised approaches for identifying refuges within landscapes, estimating their spatial and temporal buffering capacity to the most significant impacts, incorporating interactive influences of other stressors and planning protective management for multiple species.

The concept of 'appropriate connectivity' is also important in a climate change context. Enhancing connectivity has become conventional wisdom for supporting biodiversity adaptation to climate change, and is frequently linked to other benefits such as carbon sequestration, salinity reduction, water provision and biomass production. While connectivity between habitats can allow adaptive movement of native species, it may also facilitate the spread of weeds, disease and fire. Decision-makers therefore need a more nuanced understanding of the potential benefits and problems likely to result from changes to connectivity, since this varies greatly amongst species and ecological communities at local and landscape scales. A key task is to determine what types of landscape connectivity will have positive impacts for biodiversity conservation by facilitating adaptive capacity, while minimising the risks (such as enhanced disease, weed or fire impacts).

The questions in this section attempt to focus on research that develops general principles of integrated landscape design and provide stakeholders with a synthesis of the available tools and frameworks that facilitate policy and decisions about landscape management at any given spatial scale. Specific questions focus on:

2.1. General principles for landscape design that balances biodiversity conservation, natural and human disturbances such as fire and other land uses while maintaining important ecosystem services

2.2. Selecting new protected areas

2.3. Managing landscapes for resilience and maintenance of biodiversity

2.4. Ensuring biodiversity adaptation and mitigation initiatives are co-ordinated and value-add to each other

2.5. Long term monitoring and observation systems to provide baseline data and knowledge for adaptive management.

Question 2.1: What principles should guide ecosystem-based adaptation and the design of landscapes?

When climates change, either naturally or anthropogenically, there is almost always an impact on the species exposed to that change. Most frequently, species distributions and abundance patterns will shift along climatic gradients to places which better match their preferences and tolerances (Parmesan 2006; Pecl et al. 2017). This depends on the existence of landscape connections between source and sink locations. Even in natural landscapes such movement may not be feasible with transit areas presenting, potentially, inimical barriers to movement. The vulnerability of any given species will be mediated by the biological traits of the species, the specific landscape context, other existing stressors and the potential for adaptation management (Williams et al. 2008; Pacifici et al. 2015).

Since the 2013 NARP revision, several reports have addressed the general principles of landscape design under various scenarios of climate change. Under direct NCCARF funding Doerr et al. (2013) used a modelling approach to examine the effectiveness of different landscape designs for climate change adaptation while Meyer et al. (2013) developed an online tool to guide decision making. Doerr et al. (2013) found only one scenario – vegetation restoration to 30% cover – improved future landscapes in terms of their resilience to climate change. They identified four areas requiring further exploration, viz.:

- greater spatial targeting with a stepwise approach to population restoration
- defining priority areas based on likely future distributions
- designing land-uses to maximise incidental biodiversity benefits
- restoring native vegetation at the whole property scale.

The Meyer et al. (2013) on-line tool emphasised the need to bridge the science/decision making gap, noting that 'one size doesn't fit all' and that there was a further gap between landscape planning and implementation. They also made the useful observation that the widely touted adaptive management approach often led to uncomfortable intermediate outcomes and must be allowed time to work.

Work outside NCCARF funding, such as Lavorel et al. (2015), contributes the idea of 'climate adaptation services' to the lexicon. They see these services as reflecting vegetation structural diversity, the actions of keystone species, landscape connectivity and the capacity for community re-assembly (and re-assortment) under severe climate change.

Based on these and earlier works (see the reference section of the 2013 NARP) we can restate the basic principles underpinning adaptation management of terrestrial ecosystems to climate change, as follows.

Key landscape components. In considering species and communities, ecological landscapes comprise *patches of suitable habitat* within which sustainable populations of species and the communities within which they occur can persist. These habitat patches are surrounded by *a matrix* of less suitable or even hostile environments within which the species and communities cannot persist (although some species may be able to traverse these areas seeking new suitable habitat patches). Imposed upon the landscape pattern of these components are existing land tenures and uses: reserves, roads, urban and industrial areas.

Properties of the species. Three features in particular will contribute to the ability of species to adapt regardless of the landscapes in which they occur: generation time, plasticity (behavioural, ecological, physiological) and vagility (i.e. their pre-adapted capabilities of movement). These will determine, respectively, the likelihood of a species being able to adapt successfully to change in using evolutionary, behavioural or biogeographical mechanisms.

Minimising other stressors. Anthropogenic climate change imposes an additional stress on a biota already being impacted by other forces including land-use change (reducing the size of existing patches of suitable habitat), non-native predators, diseases and weeds, changed fire regimes, changed soil qualities, changed water regimes and, so on. To maximise the chances of self-adaptation to climate change these other stressors need to be minimised.

Management interventions. Under anthropogenic climate change, without active and adaptive management, there is a potentially dire threat to species and communities. Interventions including habitat restoration and rehabilitation, establishment of movement corridors, proper planning of agricultural and horticultural activities, and, as indicated, the minimisation of other stresses. More substantial interventions—including translocation of species and *ex-situ* maintenance—may well also have a role depending on the magnitude of the impact and the species/communities concerned.

Successful strategies for landscape/ecosystem management and design need to incorporate a consideration of all of the above factors especially shifts in the spatial patterns of distribution and abundance, the specific landscape context, species biological traits, other existing stressors and how all of these factors may interact under changing climates. Research on each of these aspects, and their interactions, is fundamental to designing landscape/ecosystem-level management actions that will be effective.

Question 2.2: How should new protected areas be selected?

Strategically, increasing the extent and scope of protected areas is one of the most important adaptation actions required to maintain the resilience of our natural ecosystems (Dunlop et al. 2012; Dunlop et al. 2013; Steffen et al. 2009). Considerable research has already focused on this question and significant positive outcomes have been achieved as a direct result of NCCARF research. However, the question is far from answered. There is great complexity across natural ecosystems with compounding layers of complexity based on; climatic modelling, understanding the natural resilience of systems and species, the diverse aims and expectations of stakeholder groups, and the many different reasons and strategies behind selecting a new area to formally protect.

Various types of climatic refugia are widely considered to be an important factor in prioritising new protected areas (Keppel et al. 2012; Schut et al. 2014; Shoo et al. 2013; Shoo et al. 2010). A number of NCCARF projects addressed various aspects of this question. In particular Maggini et al. (2013) and Reside et al. (2013) modelled the exact specific locations for locating new protected areas (including refugia) to maximise resilience to climate change impacts. Reside et al. (2013) suggest a cost-effective solution is to identify and protect the places in the landscape that will harbour many species from the worst impacts of climate change. Approaches developed in this project have already produced significant on-the-ground outcomes with the Queensland Government selecting and acquiring more than five new national parks aimed at maximising resilience under a changing climate (Vanderwal et al. 2015; Williams & Falconi 2015). A number of studies have emphasised the problems associated with movement across an often fragmented landscape and highlighted the importance connectivity and the need for an integrated network of protected areas that will facilitate the general movement of biodiversity into refugial areas or to simply track their preferred climate (Lukasiewicz et al. 2013; Maggini et al. 2013; Reside et al. 2013). Other research projects have highlighted the need to consider expansion of the network, prioritise more-stable areas, bigger areas and those closer to existing areas (Brodie et al., 2012; Dunlop et al., 2013; Ervin, 2011; Gillson et al., 2013; Lukasiewicz et al., 2013; Maggini et al., 2013; Reside et al., 2013).

Identification of the most effective additions to the protected area network needs to consider the relative natural resilience of ecosystems/species, species/habitat irreplaceability and complementarity, exposure to future climatic change based on species and ecosystem bioclimatic modelling, dispersal scenarios, landscape structure, habitat connectivity, refugial areas, areas of ongoing evolution, management goals and the feasibility of possible adaptation strategies. All of this should be done within a spatially-explicit systematic conservation planning framework that overtly considers different future scenarios, and their relative certainty, to inform managers and policy makers; this would enable the most effective strategies to be designed that provide the best return from available resources.

Question 2.3: How can management of protected and non-protected areas incorporate and adapt to climate change?

Shifts in both the mean and extreme values of climatic variables are resulting in changes to ecological communities. These changes range from the barely detectable to drastic depending on the resilience of the community. From an individual perspective, this resilience may be in the form of inherent plasticity or an acclimation response, where for example physiological, metabolic, behavioural or phenotypic changes enable the individual to withstand the environmental change. Once resilience thresholds are exceeded, then there are likely to be shifts in species distributions and community structure and composition and processes such as migration, extinction and the disruption of symbioses may lead to novel community assemblages and changes to ecosystem processes. These shifts are unavoidable under climate change and management of protected and non-protected areas must deal with transformations of ecosystems and communities whilst minimising overall loss of biodiversity and ecosystem functioning.

Attempts to maintain a status quo of ecosystem form, function and location in protected and non-protected areas under the pressures of climate change are unlikely to be successful; this means management strategies must adjust to take account of the community shifts and ecosystem changes. There needs to be baseline observations of current community distributions and assemblages in order to better monitor where and when the effects of climate change are being realised. Such observations may come from traditional survey methods, but there needs to be novel and potentially more rapid methods and techniques (such as DNA metabarcoding of environmental samples, including soil microbes), and use of large-scale bioclimatic gradient analysis; these should be explored for their utility in tracking ecosystem and community change and informing management practice. With the expected changes in ecosystem and community assemblage, management practices need to consider how best to deal with the fact that many native and introduced species will be moving across the landscape, exploiting previously inhospitable or inaccessible areas or niches. Whereas previously species migrating into new areas may have been considered as invasive, under climate change whole scale shifts in species distributions may become commonplace and management practice must best reflect and deal with this. Declines in species distributions will also be a major concern and ongoing monitoring of threatened species should inform management practices. It will also be important to understand the contribution of climate change to observed changes in ecosystems in order to avoid prematurely accepting transformative changes that may be driven primarily by other factors.

Question 2.4: How can Australia's land-based climate change mitigation initiatives be designed so they also enhance ecosystem services and resilience and deliver biodiversity conservation benefits?

Mitigation is the most important aspect of dealing with the climate change challenge. Mitigation actions aim to reduce the concentration of greenhouse gases in the atmosphere via either emission reduction (e.g. from emission sources as energy, industry, transport agriculture, forestry, land use change, deforestation) or the prevention of emissions by actions such as reducing deforestation, promoting carbon sequestration and storage, alternative energy etc. Many strategies and initiatives have been proposed, designed and implemented globally as mitigation actions and measures, however, not all consider the potential negative impacts on biodiversity and ecosystem services or the potential gains possible if a balanced and thoughtful approach was used (IPCC 2014b).

This question is aimed at obtaining knowledge that promotes a balanced approach that can attempt to maximise both the mitigation and biodiversity benefits of any adaptation/mitigation actions.

Land-based climate change mitigation initiatives—such as carbon sequestration and carbon storage in biomass— can contribute to the conservation of biodiversity under climate change (Thomas et al. 2013). A system of market-based instruments and other incentive approaches (such as biodiversity credits, carbon trading and offset schemes in landscape) should ensure biodiversity adapts to climate change rather than be adversely affected by mitigation activities (Evans et al. 2015). Research into the design of such instruments is urgently required, as well as the creation of a measuring, reporting and verification system to assess performance and impacts on biodiversity from mitigation and adaptation implemented actions.

Furthermore, it is crucial to ensure that such projects maximise biodiversity benefits and do not result in excess perverse outcomes— such as weed invasion, increased fire risks or loss of high value vegetation— depending on the degree to which biodiversity conservation and adaptation issues are explicitly considered in the design of the sequestration scheme. Additional research is needed to increase the potential synergies between biodiversity resilience and sustainable use with climate change mitigation activities.

A number of authors highlight the potential to tailor the spatial arrangement across the landscape of climate mitigation activities to coincide with biodiversity priorities such as expanding corridors, building appropriate connectivity, providing habitat refugia, landscape resilience and maintain and restore degraded ecological processes, ecosystems and their services (Bryan et al. 2014; Budiharta et al. 2014; Jantz et al. 2015; Thomas et al. 2013). Many biodiversity adaptation actions involve extensive revegetation, reforestation, afforestation and/or restoration, which produce mitigation-adaptation co-benefits through carbon sequestration and can simultaneously enhance biodiversity resilience to climate change. It is important to characterise and quantify the carbon storage potential of newer adaptation efforts for biodiversity, including protection and restoration of climate refugia, and to better understand the costs and benefits of replanting for different outcomes (Evans et al. 2015). It is also important to quantify the cost- financial benefits of carbon credits schemes for protecting biodiversity.

Significant changes have occurred in Australia's approach to carbon mitigation through land management initiatives and associated measures to protect or enhance biodiversity since the last NARP update in 2013. Since then, there have not been funding rounds of initiatives such as the Biodiversity Fund and the future of the Emission Reduction Fund is currently uncertain. Nevertheless, private mitigation initiatives have been implemented in carbon offsets scheme programs around Australia with some of these initiatives also considering biodiversity benefits. However, at the last Conference of the Parties (COP 21) for the United Nations Framework on Climate Change Conference held in Paris in 2015, Australia committed to reduce emissions by 26–28% below 2005 levels by 2030 as part of their intended nationally determined contributions. This will require new changes in the current national policy in terms of Australia's mitigation initiatives program, and a great opportunity to establish synergies and co-benefits to enhance biodiversity resilience to climate change. Finally, in the same context, it is important to increase the research on the impacts on biodiversity from the implementation of mitigation actions in different sectors as energy, biofuels, agriculture, infrastructure, etc.

Question 2.5: What conceptual models and long-term observation systems are needed to support the design, analysis and assessment of active adaptive management and policy experiments?

The complexity of climate change, and the uncertainty of its interactions with human activity and ecosystems, makes it difficult to predict and plan for future outcomes. As such, adaptive management and policy experiments designed to mitigate climate change outcomes will be most effective if informed by conceptual models and ongoing and longer-term monitoring. Research can provide clarity to researchers, decision-makers, policy analysts, land managers and other stakeholders as to which conceptual models will underpin large-scale adaptive experiments, and how they should be designed in order to help identify alternative management options.

The development of practical strategies that increase the resilience of terrestrial ecosystems and maximise their adaptive potential under climate change will rely upon observational data and monitoring. For example, the use of large-scale transects positioned along climate gradients to monitor population and community changes over space and time can inform on species-level changes, such as genotypic and phenotypic turnover, as well as the resilience of whole ecological communities to climate change. Such monitoring can help to determine the adaptive drivers and limits of species and ecosystems, as well as allowing for more accurate forecasting of the effects of climate change.

The Terrestrial Ecosystem Research Network[1] (TERN) has a range of ecosystem monitoring infrastructure, but of most relevance to assessing species and adaptation responses to climate change is the Australian Transect Network[2] (ATN). The ATN comprises seven large-scale transects distributed across the continent designed to collect species and community-level data to investigate the impacts of and adaptation to climatic variation. Outcomes from this network are already being used to inform and support management and policy planning and monitoring. Further research is required to better understand which species, habitats, environmental gradients, refugia, and ecosystem and evolutionary processes are suitable and worthwhile candidates for observation and management.

A number of initiatives that collate and store observational and monitoring data are already well established, such as TERN, particularly its AEKOS portal[3]. Distributional data for species derived from curated specimens and simple distribution modeling tools are also available through the Atlas of Living Australia[4] (ALA). These resources are being used to inform the adaptive management of ecosystems. Analysis of these resources can help to assess the rate at which species, ecological communities, ecosystems and landscapes are responding, and to detect trends or thresholds that will trigger policy and management actions. Options should also be explored for stakeholder contributions to observation systems, for example through citizen science projects and programs.

Research theme 3: Managing threats and stressors to maximise ecosystem resilience in a changing climate

Potentially the most important threat to global biodiversity is the synergistic interactions between climate change and other human pressures (Asner et al. 2010; Brodie et al. 2012; Brook et al. 2008; Martin et al. 2013). Most studies reporting effects of climate change (Root et al. 2003; Thomas & Williamson 2012; Thuiller 2004; Williams et al. 2003) or land cover change, habitat loss, habitat fragmentation and disease on biodiversity (Yamaura et al. 2009) studied each stressor in isolation. However, a single stressor perspective is inadequate when ecosystems and species are threatened by multiple, cumulative stressors (Brook et al. 2008).

Understanding the integrated implications of such impacts across scales will assist in allocating resources between mitigating existing stressors and implementing new adaptive strategies that specifically incorporate climate change as a factor. Therefore, evaluating the synergistic impacts of multiple drivers such as climate change, extreme event, land cover change, fire, invasive species, water availability and changing disease dynamics on ecosystems is becoming increasingly important. However, synergistic impacts are also particularly challenging in ecology and conservation and will require multidisciplinary research that includes bot biophysical and socio-political issues and sophisticated analytical approaches that integrate the variable contributions of stressors and their socio-ecological interactions. It will be necessary to analyse these threats in a way that identifies a balanced, parsimonious solution that simultaneously attempts to find the best solution across the multiple stressors. The best solution may not be the best solution for any individual stressor but will be one that provides a best-possible solution that is a cost/benefit balance across multiple stressors.

These questions were identified in previous NARPs under a single question but have been separated here since the research to address each stressor is different. These stressors and their interactions continue to be a high priority.

[1] www.tern.org.au
[2] www.tern.org.au/Australian-Transect-Network-pg22748.html
[3] www.tern.org.au/Eco-informatics-pg17733.html
[4] www.ala.org.au

Question 3.1: Which extreme events and aspects of their regime (frequency, magnitude, duration and the return period) are associated with the vulnerability of biodiversity and how can we adapt to minimise the impacts on natural ecosystems?

It is now widely acknowledged that generally thresholds and extreme events may be much more important than gradual increases in climatic means in influencing the patterns and processes of natural ecosystems. The limits of species distributions, and their population sizes, are frequently limited by climatic extremes, yet most research on determinants of distributions and abundance focusses on climatic averages rather than climatic extremes. Since all species have variable tolerances and resilience to the different aspects of the regime of any given extreme event, it can be expected that shifts in the regimes of climatic extremes will change both biotic and abiotic species interactions, further influencing their distributions and population dynamics.

Future climate projections suggest that we will be exposed to significant changes in the regimes of extreme climate events including the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, resulting in unprecedented extreme weather and climate events (IPCC 2014a; Murray & Ebi 2012). Changes in the regimes of extreme climatic events can be due to shifts in the mean, variance, or shape of probability distributions in any given climate/weather variable. The report defines an extreme event as:

> ***Climate extreme (extreme weather or climate event):*** *The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as 'climate extremes.'*

The relative impact of increased extreme events will vary across both temporal and spatial scales and depend on the relative vulnerability of the species, communities or processes being considered. Impacts on natural ecosystems are highly likely to be influenced by, not only the biological vulnerability, but the relevant social and economic factors determining human impacts (see other PRQs in this section). It is 'virtually certain' that there will be increases in the frequency and magnitude of high temperature extremes and decreases in cold extremes, and 'likely' there will be increased heavy precipitation events. There is 'medium confidence' that droughts will intensify due to increasing evapotranspiration and/or decreased precipitation and it is 'very likely' that rising sea levels will exacerbate coastal high-water extremes. Fire regimes are already changing and will continue to change (see Question 3.3). The IPPC report (2012) states with 'high confidence' that there will be increases in heat waves, glacial retreat and permafrost degradation resulting in many changes to soil/slope stability, flood damage and impacts on biodiversity. There will be high spatial and temporal variability in the shifts in regimes of extreme event.

Future research needs to focus on shifts in the spatial and temporal regimes of extreme events (heat waves, fire, floods, drought, cyclones, storm surges) and how these events affect species distributions and abundance, community dynamics and ecosystem structure and function. The importance of biotic interactions in determining species distributions and what characteristics can indicate susceptibility to impacts due to change in these interactions will continue to be an important research topic. Research needs to examine the temporal and spatial dynamics of how extreme events influence both exposure and vulnerability and give careful consideration to ensuring that adaptation actions aimed at reducing short-term exposure and risk do not unduly increase vulnerability over the longer term.

Given the high spatial and temporal variability of these events, combined with the highly variable impacts on species and community vulnerability, it is highly recommended that research takes a multi-hazard risk management approach to reduce complexity and identify those aspects of extreme events where there is solid evidence to identify and support low-regret adaptation options and strategies.

Question 3.2: How will climate change interact with habitat change (loss, fragmentation and degradation) and what are the implications for managing ecosystem resilience?

The loss, fragmentation and degradation of natural habitats has, without doubt, been the most important environmental stressor of the 20th century, and continues to be a grave threat to the future sustainability of global biodiversity. The combined impact on natural ecosystems driven by the continued non-sustainable use of natural resources by developed countries and the recent rapid economic development of developing countries (e.g. China, Brazil, India and Indonesia) are continuing to drive large-scale habitat loss and degradation, particularly in tropical forests. Negative impacts on global biodiversity resulting from these large-scale changes in land use and destruction of natural habitat will be further magnified as a result of the synergistic interactions between climate change and habitat (Asner et al. 2010; Brodie et al. 2012; Brook et al. 2008; Martin et al. 2013; Travis 2003).

Habitat loss, degradation and fragmentation resulting from human practices have resulted in reduced sizes and increased spatial isolation of populations. Climate change is expected to further exacerbate these effects. For example, future climate projections lead to predictions that areas of Mediterranean climate in Australia will contract to 77-49% of their current extent. Of the area likely to remain stable under climate change, 64% is not protected and has already undergone conversion, further restricting the availability of climatically-suitable areas for Mediterranean climate-adapted species (Klausmeyer & Shaw 2009).

Reduced population sizes and increased spatial isolation resulting from habitat loss and fragmentation can lead to greater genetic drift and decreased genetic diversity within populations, reducing their adaptive potential. Climate change is likely to place fragmented populations under further pressure as the ability to respond to changing climate in situ is constrained by reduced gene flow and lower genetic diversity, whilst migration across the landscape to more climatically suitable areas is constrained by a reduction in migration pathways (Christmas et al. 2015). Further research is required to better understand the negative effects of the synergies between climate and habitat change as well as the adaptive potential of populations to withstand these pressures.

Landscape restoration and the connection of fragmented populations should be a key priority in order to manage and improve ecosystem resilience to climate change. For example, predicted widespread extinctions in drought-sensitive butterfly populations by 2050 under a 'business as usual' carbon emission scenario could be curtailed by up to 42% through the restoration of semi-natural landscapes to reduce habitat fragmentation (Oliver et al. 2015). Land management practices should focus on connecting up remnant habitat through, for example, the establishment of corridors across the landscape, as well as active management of existing habitat to enhance habitat quality and increase its resilience to future change. These, and other management responses, will be better focused once the condition of Australia's ecosystems has been assessed more thoroughly and the utility and potential success of conservation and restoration approaches have been tested and evaluated.

Question 3.3: How will climate change interact with fire regimes and what are the implications for managing ecosystem resilience?

Changing climate is certain to have dramatic consequences for fire regimes and thus biodiversity, ecosystem services and enhanced forcing of greenhouse gases. The effect of climate on fire regimes is both direct and indirect, and these influences have been well summarised by the 'four switch' (Bradstock 2010) and the 'interval squeeze' models.

The **four-switch model** show how four major climate switches control the risk of landscape fires. The first switch that operates over decade to century scales is the mass of biomass, which is controlled by the productivity of a site and influenced by climate cycles such as El Niño–Southern Oscillation (ENSO). The second switch is the availability of biomass to burn, which is affected in a given fire season by recent weather patterns at the scale of weeks to days. The third switch is the capacity of a fire to spread across the landscape and is influenced by meteorological conditions operating at a daily to hourly scale and the specific landscape context. The final switch involves the types and probability of different ignition sources, for example from dry lightning storms. The predictive capacity of each switch is variable, and it is currently practically impossible, given uncertainties and computational constraints, to combine all these switches to predict future fire regimes. Nonetheless, numerous studies analysing historical meteorological data, past fire events and down-scaled climate models all point to worsening fire weather, particularly more extreme events and prolonged fire seasons, across Australia.

The **interval squeeze model** shows how the increasing occurrence of fires driven by climate change can affect plant species persistence via reduced growth rate and slower maturity, reduced fecundity and seedling establishment. There is a threshold where fire frequency causes the demographic collapse of plant species leading to a shift in species composition and increased flammability resulting in a self-reinforcing feedback. This model suggests that further research on this topic is a critical element of informing fire management in Australia under a changing climate.

Fire management has always been a vexed issue given difficulties in stakeholder agreement on aims, strategies and priorities; often the result is conflict between biodiversity asset management and fuel management that relies on frequent burning. Under climate change, planned burning is becoming much harder to implement because of the shrinking window of opportunity to implement planned burns, and greater risk of fires escaping control.

An additional problem is that planned burning causes air pollution that is harmful to human health. Controlling wildfires, which are becoming more frequent and intense due to climate change, demands fresh thinking about fire management and may include novel approaches including the use of mechanical thinning or mowing vegetation, targeted grazing and browsing, restoration programs to rehabilitate severely burnt areas, including the assisted migration of taxa driven locally extinct by severe fires. In the most extreme cases, some taxa will probably need to be saved in artificial habitats using irrigation and careful fuel management. There is need to reduce destructive wildfires because there is a risk that they will become a potent feedback driving climate change through the release of large quantities of carbon currently stored in living biomass and in dead biomass including organic matter in soils.

Question 3.4: How will climate change interact with invasive species and what are the implications for managing ecosystem resilience?

Invasive species are species that have spread into an area where they are not native and are often associated with negative impacts on ecology, human economy or human health. This traditional definition of invasive species generally has been used to describe species introduced to areas far removed from their native ranges and recent introductions have been largely mediated by human activities (e.g. trade and shipping). Under climate change however, our definition of invasive species may need readjustment. As climate patterns change and average conditions shift across the landscape, migrations to track these changes may result in species distribution patterns looking vastly different compared to those of today, where species occupy new, previously uninhabited areas (Kumschick & Richardson 2013; Pecl et al. 2017). Some species, previously restricted in their distribution, may expand their range and become invasive, outcompeting local species and impacting ecosystem services. Management of ecosystems and communities under climate change therefore will need to track changes of both native and introduced species distributions and measure and control impacts of those species expanding into novel areas (Lodge et al. 2006).

The invasiveness of introduced species may also change under climate change; some species are likely to be well suited to the novel climate conditions, expanding in range and causing more damage in the future, whereas others may decline in distribution and have less negative impacts than they do today (Lodge et al. 2006). Invasive species may also bring about positive impacts under climate change, providing ecosystem services and potentially replacing the roles of other species displaced due to climate change. Management strategies therefore will need to take careful consideration of these changes in community assemblage and risk assessments of the impacts of current and future invasives will need to be undertaken.

The characteristics of newly introduced species, and what makes a species likely to become invasive, needs to be better understood in order to more effectively plan for and manage invasive species impacts and improve ecosystem resilience under climate change (Kumschick & Richardson 2013). Particular ecosystems or regions of the landscape may also be more susceptible to invasion and so identifying these 'invasive hotspots' where intensive management may be applied to increase their resilience to invasive species will also be important.

Question 3.5: How will climate change interact with water availability and salinity and what are the implications for managing ecosystem resilience?

Clearly changes in water availability and salinity will impact directly on almost every natural and human-use ecosystem in Australia. The adaptation actions necessary to face this challenge are largely dealt with under the Freshwater Biodiversity and Ecosystems NARP (Capon et al. 2017), however, here we need to consider the specific interactions between impacts and adaptation in the water sector and adaptation actions to maintain the resilience of terrestrial biodiversity.

Although predictions of changes to future rainfall regimes in Australia are more complex than those for temperature or sea-level rise, most recent models indicate rainfall decreases in the south-west, south-east and temperate east of the continent. These drying trends are predicted with greatest confidence in the extreme south-west and south-east. In contrast there are less confident predictions of higher rainfall in the far north and north-west. Changes in seasonal distribution and rainfall event severity are also predicted (Cheng et al. 2014; Islam et al. 2014; Kumar et al. 2014).

Almost all ecosystems (and therefore the biota they contain) reflect the regime of available water within which they exist. In the arid and semi-arid regions, which comprise most of Australia, the dominant terrestrial flora is dry-adapted to a greater or lesser extent. Nevertheless, the tolerance windows are probably small and changes in the water regime, principally imposed to date by human use or modification, can lead to major degradation or even local extinction (Chen et al. 2014).

In extreme cases land may become sterilised by the deposition of salt on the soil surface forming more or less extensive saline pans. This can be the result of a rising water table following over-clearing of vegetation or over-grazing ('dryland salinity') or through over-irrigation using partly saline groundwater ('irrigation salinity')(Briggs & Taws 2003). Salinity problems are complex and multi-dimensional, driven more by overgrazing then over-clearing and interacting with drought phenology, soil degradation and tree-dieback. Of course, saline pans are also a 'natural' feature of the Australian landscape as well as an anthropogenic one. 'Secondary', human-driven surface salinity is, nevertheless, on the increase, and reflects the water regime in a variety of ways. Accordingly we may anticipate associated changes as rainfall regimes change.

As Briggs and Taws (2003) noted some time ago, there are very few well designed and executed studies of the impacts of salinity on terrestrial biodiversity. The information page of the NSW Department of Environment and Heritage, updated in March 2013, notes no more recent studies[5]. There appear to be no studies linking vegetation change to faunal assemblages in Australia.

Techniques for adapting to salinity, especially under changing climate, have received some attention principally in the area of developing salt-tolerant plantings for revegetating salinated areas— although, as Pannell et al. (2004) pointed out, principally these have been for 'cosmetic reasons'. These authors discuss at length the options for preventing surface salination by changing water use practices, strategic plantings to maintain subterranean water tables, and even engineering interventions.

[5] www.environment.nsw.gov.au/projects ImpactsOfSalinityOnBiodiversity.htm

Understanding the severity of likely impacts and opportunities for adaptation requires extensive data on and monitoring of groundwater. Taylor et al. (2013) identify the lack of such observations as a major impediment to understanding the groundwater/climate interface and this remains a significant gap in our knowledge.

In summary, there remain significant knowledge gaps at the interface between groundwater (and salination) and terrestrial biodiversity. These need to be addressed before informed adaptation actions addressing the wider problems of prevention and restoration can be properly developed. Well-designed trials of ecosystem restoration across a range of soil types and conditions will be required. Also useful will be to build soil moisture and salinity explicitly into a new generation of climate models. Finally the lack of effective monitoring of current soil moisture regimes, in a properly stratified and sustained manner, will hinder progress on both understanding and managing the problems associated with the interaction between water availability and terrestrial biodiversity.

Question 3.6: How will climate change interact with emerging diseases and what are the implications for managing ecosystem resilience?

There has been general acceptance and concern that climate change will interact with diseases to become an increasingly problematic environmental stressor in the future (Mills et al. 2010). Impacts related to both changing dynamics of existing diseases and newly invasive/emerging diseases are of great concern (Hoberg & Brooks 2015). Complex interactions between the pathogen, vector-dynamics and host susceptibility are often poorly known and predicting the potential for future changes in diseases as a significant environmental stressor is a high priority.

Changing disease dynamics and transmission under climate change will be influenced by changes in the geographic distributions and population density of both hosts and pathogens and interactions with other anthropogenic disturbances (Mills et al. 2010). Climate change will likely limit the transmission of some pathogens and create opportunities for others. Hoberg and Brooks (2015) suggest that climate change will result in new emerging infectious diseases among species due to 'ecological fitting' – as pathogens rapidly switch hosts under changing conditions. Some studies have suggested that already there has been significant impacts on biodiversity as a result of interactions between a changing climate and disease dynamics - for example the chytrid fungus which affects frogs in Australia and globally (Pounds et al. 2006). Altizer et al. (2013) review the literature and find a number of studies report changes in host-pathogen interactions related to climate change.

In order to improve predictions and design appropriate adaptation responses, we need a multidisciplinary approach to initially identify and prioritise the specific threatening diseases and vulnerable ecosystems/species and then research examining the mechanisms, dynamics and interactions between the ecosystem, climatic changes, and the biology of both hosts and disease.

Question 3.7: How can we assess and quantify the relative impacts and their interactions/synergies of all stressors in a system in order to enable the most effective and balanced adaptation actions?

As discussed in the previous questions within this section, there is a growing concern and body of evidence that it is the interactions between climate change impacts and other environmental stressors that will have the most significant impact on biodiversity and the healthy function of natural ecosystems. Each of the above questions (3.1-3.6) are identified as particularly important stressors, however, in most systems there will be more than one stressor interacting with climatic change and affecting the resilience of biodiversity. This question is to emphasise the importance of developing analytical tools and approaches that integrate multiple stressors and their various interactive effects in a way that can parse out the relative importance of each stressor and their interactions with climate change and each other. Disentangling interacting effects helps to inform better decisions about adaptation actions, with a more integrated cost-benefit evaluation (Question 4.3), that aims to produce the most efficient positive outcomes for biodiversity protection and minimisation of perverse outcomes resulting from an emphasis on a single stressor.

Research theme 4: Managing biodiversity assets

A large proportion of conservation actions are focussed on maintaining a specific biodiversity asset such as a threatened species or habitat. Public support is often more strongly aligned with protecting iconic species or places and, as a result, much conservation effort and adaptation action has been driven by a species focus. There has been considerable debate about the pros and cons of a species-based approach versus a more ecosystem/community focus. Many studies have promoted a more holistic ecosystem approach guided by general conservation principles as discussed in many of the previous sections and questions. However, almost all current ecosystems are at least partially defined by their species composition and the structure of any assemblage will almost certainly change into the future depending on the individual preferences and tolerances and biotic and abiotic interactions that determine the distribution and abundance of each individual species. Species distributions, abundance and interactions will all change in the future and we need to maintain a conservation approach that facilitates unavoidable change and minimises overall loss and degradation of biodiversity and ecosystem function. However, this does not mean that we need to maintain specific groups of species (communities) in their current form and place.

Based on this expected species-specific variation in responses, Boitani et al. (2015) argue that an ecosystem/community approach is conceptually flawed and that it is not a pragmatic approach for spatially-explicit conservation planning into the future. Boitani et al. (2015) also argue that species form tractable units on which to base future biodiversity conservation actions. In contrast, the composition and structure of ecosystems/communities will change, they have vague definitions in space and time and novel assemblages with no current analogue will form as species individually react to a changed climate making robust predictions into the future difficult. On this basis, the authors support a species-based planning approach.

While the previous sections in this NARP have focussed on ecosystem-level principles and design, and supporting policy and law, this section provides the opportunity to focus on research questions aimed at managing specific biodiversity assets, primarily species. This section is divided into three main questions:

1. How do we identify the specific biodiversity assets most deserving of investment for adaptation actions (vulnerability assessment)?
2. How do we adapt current management actions aimed at protecting specific species/habitats/ecosystems or managing problem species?
3. How do we optimise investment to identify actions that provide the best cost-benefit for protecting biodiversity assets?

Question 4.1: How do we identify the specific biodiversity assets most deserving of investment for adaptation actions (vulnerability assessment)?

Efficient prioritisation of investment allocation is crucial to maximise the positive outcomes of any adaptation management action. Resources can be strategically allocated where they will have the most effect on desired outcomes while avoiding waste on assets that have adequate natural resilience. Prioritisation relies on robust and comprehensive assessments of the relative vulnerability of the biodiversity assets being considered (Williams et al. 2008); certain species and suites of species are of higher priority than others, whether threatened, threatening, key to ecological functioning, migratory, or by the provision of important ecosystem services to humans. Understanding how to identify these species and inform management and policy decision is of paramount importance under a changing climate. Efficient prioritisation of the resources for adaptation management requires ongoing long-term environmental monitoring and robust, multi-disciplinary vulnerability assessments that consider bioclimatic distributions, physiology, dispersal, microhabitat bio-energetics, demographic and population viability, disturbance dynamics, biotic interactions, evolutionary potential, ecological plasticity, species resistance and resilience, and potential for successful adaptive management (Williams et al. 2008). Developing general approaches that can be used across suites of species and ecosystems to facilitate sensible and informed decisions will be particularly valuable.

This question has received far more attention than most, with significant advances in research on this topic over the last 10-15 years. Analytical approaches for assessing vulnerability of species and conducting spatially-explicit systematic conservation planning have vastly improved and are more robust (see literature review in Appendix 1 for more details). A number of NCCARF projects have directly addressed this question across a variety of approaches, taxa and scales (e.g. Pacifici et al. 2015; Reside et al. 2013; Doerr et al. 2013; Garnett et al. 2013; Maggini et al. 2013).

However, while large-scale, comparative studies of species vulnerability are now common in conservation science, they seem to have had little influence on conservation practice and uptake into policy (Cardillo & Meijaard 2012). This is largely due to most conservation practice continuing to operate under a reactive paradigm, whereas vulnerability assessment is most useful to a proactive approach.

Future research on prioritisation must build on the advances already achieved in vulnerability assessment and conservation planning. This requires a focus on actions to protect both species and places that will maximise the protection of overall biodiversity and ecosystem function, rather than the preservation of current species assemblages. More research needs to be conducted on how to enhance the uptake of these assessments into a more proactive adaptation approach to conservation management.

Question 4.2: How do we adapt current management actions aimed at protecting specific species/habitats/ecosystems or managing problem species?

Each species will respond differently to the diverse impacts of climate change and natural resource managers face the challenge of predicting multiple species trajectories each with different levels of vulnerability based on their intrinsic resilience, landscape context and changing interactions with both other native species and invasive / problem species (Williams et al. 2008). The previous question (Question 4.1) discusses the identification of priority species, the next logical step is identification of a logical sequence of potential management actions aimed at maintaining or increasing both resistance to change and the resilience to recover from impacts while facilitating responses that enable a transition to new conditions and places and minimising the impacts of invasive problem species. Management decisions are further complicated by the requirement for a dynamic approach (Dunlop et al. 2013) and by scale, with strategies varying depending whether the emphasis is on species-specific actions, site-scale (usually protected area) or regional-scale planning and management.

Shoo et al. (2013) provide a pathway for managers and policy makers to make more proactive decisions, once relative vulnerability has been assessed, by identifying adaptation actions in order from the more feasible through to the more expensive and controversial options including the identification and management of refugia, maintenance / establishment / restoration of habitat connectivity to provide movement pathways, utilisation of existing genetic variation to enhance species resilience, assisted colonisation and ex-situ conservation (Shoo et al. 2013). The utilisation of existing genetic variation based on new genomic and evolutionary approaches was further developed into a decisions framework to guide managers by Hoffmann et al. (2015). However, management and policy decisions are still hampered by insufficient knowledge of species ecology and the consequences of more drastic options such as assisted colonisation (Hancock & Gallagher 2014). There is widespread agreement that although ex-situ strategies need to be considered, protected areas will remain a cornerstone of in-situ species management. Existing protected area networks need to be strategically extended (e.g. Queensland Landscape Resilience Program – Williams & Falconi 2015; Vanderwal et al. 2015) and managed for change, including the changing impacts of invasive species. Responses to changes in CO_2, temperature and rainfall are strongly species and context dependent, such that invasive species will not consistently be favoured (Leishman & Gallagher 2015). However, a reduction in resilience of vegetation assembles due to climatic changes may result in increased colonisation opportunities for invaders.

For some species and communities broad landscape/regional solutions aimed at ecosystem resilience may not be adequate and specific ex-situ actions may be required, and the controversies about assisted colonisation, assisted gene flow and captive breeding show no signs of abatement and require research to resolve these issues. Species-orientated management will also need to take account of the functional importance of species when assessing relative priority for conservation investment, such as how that species contributes to ecosystem function (Lunt et al. 2013; Valiente-Banuet et al. 2015). Despite these uncertainties, progress has been made with a number of frameworks now available for decision-making at the local level. Knowledge gaps appear to be information lacking on species ecology, genetics and biology, which are major impediments to managers utilising assisted colonisation and/or assisted gene flow for the most threatened species (Aitken & Bemmels 2016; Hancock & Gallagher 2014). Monitoring should play an important part in future adaptive management as understanding existing trends and how they might play out in the future relies on sustained monitoring combined with fine-scale modelling (Garnett et al. 2013).

Question 4.3: How do we optimise the investment in adaptation actions aimed at protecting biodiversity assets?

All decisions about investing in any specific adaptation action aimed at a particular biodiversity asset should involve careful consideration of the costs and benefits associated with that investment. We need to integrate knowledge of cost-efficient biodiversity adaptation actions into all existing conservation programs and policies and base decisions on an objective decision framework that guides stakeholders through the important questions to ask and identifies the information required. How effective will the action be? How much will it cost now and what will be the ongoing maintenance costs? What are the opportunity costs of inaction? Are there better, more cost-effective options? Will the actions cause negative impacts for another taxonomic group or in another sector? When will be the most cost efficient timing for the action? These issues become increasingly important, and complex, when we are trying to integrate adaptation in multi-use landscapes and multiple, potentially interacting, adaptation actions and stressors, as outlined in Section 2. This question is aimed at instigating the research necessary for informing these decisions.

Research and decision-support tools are needed to inform decisions to optimise the investment. Adaptation strategies for biodiversity should consider benefits and risks based on experimental tests (observed natural on-going changes) within an adaptive management cycle as described above. As well as, outline actions to reduce the impacts of climate change and increase the potential for the long-term persistence of species and functional ecosystems. Thus there is a need to develop optimal policy and regulatory framework where there may be a risk in both action, and inaction (Javeline & Shufeldt 2014) and consequences for other biodiversity assets other than the target species or group. For example, Lunt et al. (2013) consider the costs and benefits of assisted migration with the goal of relocating taxa to restore declining ecosystem processes that support biodiversity in recipient sites. A number of other studies have highlighted the fact that we should take a precautionary approach to pre-empt any unintended negative consequences of activities in other sectors that may compromise biodiversity conservation goals (King 2014). For example, the extent of the risks of unintended harmful consequences of assisted migration, such as a successfully relocated species turning invasive and threatening the ecosystem into which it was introduced (Javeline et al. 2015).

Few studies in the past five years have addressed this question. There has been some progress on ideas in the past three years, including the NCCARF project of Lukasiewicz et al. (2013) and also a published framework which allows managers to make decisions on management for climate change adaptation, specifically recognising costs and benefits of different actions (Shoo et al. 2013). However, this priority research question is still lacking sufficient information.

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Appendix 1

National Adaptation Research Plan Terrestrial Biodiversity literature review 2013 -2015

The literature review presented in this document follows the format of the review for the 2013 NARP update by Guitart (2012). The review will be structured in sections based on each sub-theme and its priority research questions. The aim of this literature review is to review the findings and conclusions of the various NCCARF funded projects, with relevance to specific priority research questions, and also to review any other relevant literature published between 2013 and 2015. Research published in late 2012 is also included if it was not found to be included in the previous review of Guitart (2012). A particular focus was made to review research and policy undertaken in Australia, but global studies are also included when considered to have general relevance to a specific priority research question. In total, 156 papers, books, book chapters and reports are included in this review.

Section 5.1 National - continental-scale issues:

Priority research question 5.1.1

How will climate change affect existing conservation goals and how should changed conservation goals be promoted and achieved?

This issue has been examined by Dunlop et al. (2013) as a result of an NCCARF funded study 'Climate-Ready Conservation Objectives: A Scoping Study' (see Table 2). They reviewed 26 strategic conservation documents to assess conservation goals in Australia, and also developed a new way of framing conservation goals – the 'climate-ready' approach (see also section 5.1.2). Dunlop et al. (2013) found little consistency in terms of expressing conservation goals between documents, making it difficult to assess whether plans were climate-ready or not. Despite this, some commonalities were found to give a broad picture of biodiversity objectives in Australia, with key themes including managing threats, building resilience, building connectivity, restoring and protecting species, habitats and ecological processes, and managing at the landscape scale. Protecting threatened and iconic species was found to be a large focus among many documents, with most conservation plans still taking a 'static' approach – trying to maintain biodiversity 'as is', rather than promoting the 'dynamic' approach required to support 'climate-ready' plans (Dunlop et al. 2013). Dunlop et al. (2013) state that while most documents acknowledged the threat of climate change on biodiversity, there was little acknowledgement of the potential for climate change to lead to widespread habitat loss and species extinctions, and climate change threats were not well addressed in management plans. Furthermore, while a few strategic documents recognised some climate-ready concepts (such as uncertainty), they were not widespread and not explicit in stated conservation outcomes (Dunlop et al. 2013).

A number of other researchers have also tackled the issue of how to incorporate climate change into conservation plans. Stein et al. (2013), in agreement with Dunlop et al. (2013) state that adaptation should be viewed as a way of managing change, rather than just focussing on maintaining existing conditions (i.e. taking a dynamic approach and rejecting a static approach) and that we need to not only adjust current management strategies in light of climate change, but also reassess and potentially modify underlying conservation goals. Tingley et al. (2014a) also urge that we must shift our thinking to a new conservation landscape and combine the traditional approaches of fine- and course-scale frameworks in order to accommodate the reality of multiple interacting stressors, and to hedge against uncertainty in both climate impacts and species responses.

Stein et al. (2013) also note that implementation of adaptation plans continues to lag, a sentiment echoed by Wise et al. (2014), who found little evidence of substantial implementation of adaptation actions, despite considerable investments in adaptation science in recent years. They propose a re-conceptualisation of adaptation pathways aims to inform decision makers (Wise et al. 2014). Laves et al. (2014) also state that there is a gap with respect to the provision of information to adequately inform climate change adaptation policy makers and contend that this is in part due to a paucity of research reporting on the effectiveness of implemented adaptation strategies.

However, some researchers disagree that climate change should mean changed conservation and Tingley et al. (2013) argue that changing conservation priorities in light of climate change could be harmful, and suggest considering climate change as one of a 'suite of maladies' that need to be tackled in order to protect biodiversity.

In summary, the in depth analysis provided by Dunlop et al. (2013) and analysis and observations of other researchers demonstrate that while most agree that conservation goals should be revised in light of climate change, currently few strategic documents are sufficiently ‘climate-ready’. The problem of taking a static approach remains - trying to maintain biodiversity ‘as is’ rather than accepting that communities and species will change and shift as the climate changes.

Priority research question 5.1.2

How can the existing Australian legal, policy and institutional architecture for land management and biodiversity conservation respond to changes in conservation goals caused by climate change?

The NCCARF funded project led by Dunlop et al. (2013) also addressed this priority research question, and their findings are discussed below. Climate change impacts and adaptation measures have also been incorporated into a number of conservation plans in the past three years, and these are also reviewed in this section, along with other papers relating to this priority research question.

As discussed in section 5.1.1, Dunlop et al. (2013) advise that conservation plans need to adopt a ‘climate-ready’ approach, and based on an extensive review of the literature developed three ‘adaptation propositions’ that describe key characteristics of conservation strategies and planning processes that might be more effective under significant levels of future climate change.

- Adaptation proposition 1: Conservation strategies accommodate large amounts of ecological change and the likelihood of significant climate change–induced loss in biodiversity.
- Adaptation proposition 2: Strategies remain relevant and feasible under a range of possible future trajectories of ecological change.
- Adaptation proposition 3: Strategies seek to conserve the multiple different dimensions of biodiversity that are experienced and valued by society.

However, through the process of developing the climate-ready adaptation propositions, and undertaking a number of case-studies, Dunlop et al. (2013) acknowledged some substantial barriers that need to be addressed before agencies can fully adopt a climate-ready approach into their conservation plans and strategies, including the need for the following.

- Further development of ecological characterisation of ecosystem health and human activities in landscapes.
- Much better understanding of how society values different aspects of biodiversity, including ecosystems and landscapes.
- Development of policy tools to codify and implement new ecologically robust and socially endorsed objectives.

A number of other authors have also developed frameworks to help land-managers and policy makers incorporate climate change into natural resource management plans, including the NCCARF-funded CATLoG – Climate Adaptation decision support Tool for Local Governments (Trück et al. 2013). Others include the ‘adaptation for conservation targets framework’ (Cross et al. 2012), and the ‘axes of concern’ framework (Gillson et al. 2013). There are now a multitude of frameworks for policy-makers to choose from, and the NCCARF commissioned report by Randall et al. (2012) offers advice for practitioners on choosing a decision-making framework in order to manage uncertainty in climate adaption decision-making. Other researchers state that plans should take an ecosystem-based approach to climate change adaptation (i.e. Munang et al. 2013) and while some authors have questioned the relevance of protected areas in planning for climate change, Thomas and Gillingham (2015) argue that protected areas still have an important part to play in conservation of biodiversity under climate change.

Despite evidence that we need to rethink conservation goals in order to adapt to climate change, Hagerman and Saterfield (2013) note that the majority of adaptation actions continue to follow conventional approaches. They surveyed 160 scientists and practitioners and found that the majority chose conventional conservation actions over less conventional, interventionist actions, despite agreement that there was a need for extensive active management (such as assisted colonisation) and restoration intervention given the threat of climate change. The authors find four key factors that explain the seemingly enduring preference for conventional actions by scientists and policy makers;

- judged most ecologically effective, least risky and best understood
- linked with pro-ecological worldviews, marked by positive affective feelings, and an aversion to the hubris of managing nature
- a function of trust in biodiversity governance
- driven by demographic factors such as gender.

The Fifth Assessment Report of the IPCC (2014) states that, worldwide, adaptation measures are increasing and becoming more integrated within wider policy frameworks. They find that integration, although it remains a challenge, can work to streamline the adaptation planning and decision-making process and embeds climate-sensitive thinking in existing and new institutions and organizations. Indeed, Australia has made some important moves to integrate climate change impacts and adaptation into conservation planning in the past three years. In 2014, the Federal Government announced funding for 53 regional Natural Resource Management (NRM) organisations to update their existing regional plans to incorporate climate change and climate change adaptation approaches. In order to standardise this process, the Department of Environment prepared a document listing principles for NRMs updating their regional plans, which were:

- plans identify priority landscapes for carbon plantings and strategies to build landscape integrity and guide adaptation and mitigation actions to address climate change impacts on natural ecosystems
- planning process is logical, comprehensive, and transparent
- plans use best available information to develop actions and are based on collaboration with government, community and other stakeholders (for more information go to: http://bit.ly/1NWOxuK)

A number of recent conservation plans have also explicitly incorporated climate change impacts and adaptation into their framework. For example, one of the primary aims of The National Wildlife Corridors Plan (Australian Government 2012) is to help strengthen the resilience in our native landscapes against climate change by focussing on improvement of ecosystem resilience and the connectivity of fragmented ecosystems, expanding the National Reserve System and protecting important refugia.

In 2014, the government released the fifth National Report to The Convention on Biological Diversity (Australian Government 2014), which covered the period from January 2009 to December 2013. This report includes a section on climate change as a mounting threat to Australian biodiversity, along with other threats including habitat loss, introduced species, etc. It also mentions a number of initiatives which offer prospects for adaption to climate change; for example through incorporation of different topographies and rainfall gradients in the Victorian Government's programme Delivering Melbourne's Newest Sustainable Communities. It also references NCCARF and the Terrestrial NARP (p.25).

The recently published Threatened Species Strategy (TSS) (Australian Government 2015) acknowledges the threat of climate change (e.g. p.17) and also the work of NCCARF. However, climate change impacts on threatened species are not specifically addressed in any of the key action areas or targets to measure success.

Australia's Biodiversity Conservation Strategy (ABCS) 2010-2030, which was summarised in the updated Terrestrial NARP in 2013 (Kitching et al. 2013) set out its initial targets in terms of achievements by 2015, and Australia is due to review its progress towards ABCS targets and other biodiversity-relevant national targets in 2015-2016.

In summary, while the best way to incorporate climate change adaptation into conservation goals and existing strategic plans is still being debated, research has focussed on both traditional actions, including protected areas, landscape connectivity and corridors and controlling other threats including introduced species, and on less conventional actions including assisted migration and managing for new, novel ecosystems (Hagerman & Satterfield 2013). In the past few years there have been a plethora of frameworks developed in order to help managers and policy-makers in corporate climate change into revised conservation goals. Since 2013 Australia has taken steps to incorporate climate change into both existing and new conservation strategic documents, most notably through the revision of local NRM regional plans, and also in the National Corridors Plan.

Priority research question 5.1.3

What conceptual models and long-term observation systems are needed to support the design, analysis and assessment of active adaptive management and policy experiments at regional and national scales under climate change?

Although there is no specific NCCARF report that has focussed on this priority research question, a number of other NCCARF funded projects address this question indirectly, particularly in terms of the need to understand how landscapes and habitats will be able to support biodiversity in the future. For example, Reside et al. (2013) aimed to identify the spatial location and quality of climate refugia across Australia using a variety of methods; they also state that long-term observations of biodiversity within refugia will be important, as well as understanding the ability of refugia to safeguard long-term population viability and evolutionary processes (Reside et al. 2013). Doerr et al. (2013) similarly aimed to evaluate the capacity of future landscapes to support long-term viable populations of key native species groups, using a metapopulation capacity model.

Species distribution modelling continues to be the primary tool used to predict how species and communities may be impacted by climatic changes, and models are frequently used in planning for active adaptive management (i.e. Shoo et al. 2015). However, models have progressed significantly over the years, and there has been some concern that simply using species bioclimatic envelopes in models does not give a robust prediction of species distributions under future climate change scenarios. For example, VanDerWal et al. (2013) found that if climate change impacts were only measured in terms of poleward species distribution shifts, impacts are underestimated by an average of 26% in temperate regions of the continent and by an average of 95% in tropical regions. In their analysis, Australian bird species were found to shift in multiple directions, not just poleward.

Modelling approaches have thus become more refined and complex and suggested improvements in species distribution models (SDM) have varied from algorithmic development through to more mechanistic modelling approaches (e.g. Howard et al. 2014). Most researchers agree that species-specific biological data is crucial in making models more robust (i.e. Radosavljevic & Anderson 2014), such as abundance data (Howard et al. 2014), information on dispersal (Bateman et al. 2013) and microclimate (Storlie et al. 2013; Kearney et al. 2014).

Pacifici et al. (2015) recently reviewed the performance of the three main modelling approaches to predicting species vulnerability to climate change; correlative, mechanistic and trait-based models. They state that mechanistic models have the greatest power to assess extinction probability under climate change, and also to identify conservation actions and evaluate the potential effectiveness of management interventions. However, due to the need for extensive species specific data on life-history and abundance, mechanistic models can only be applied to a few well-known species. The authors make recommendations as to what model should be used in what situation in order to inform conservation and policy planning.

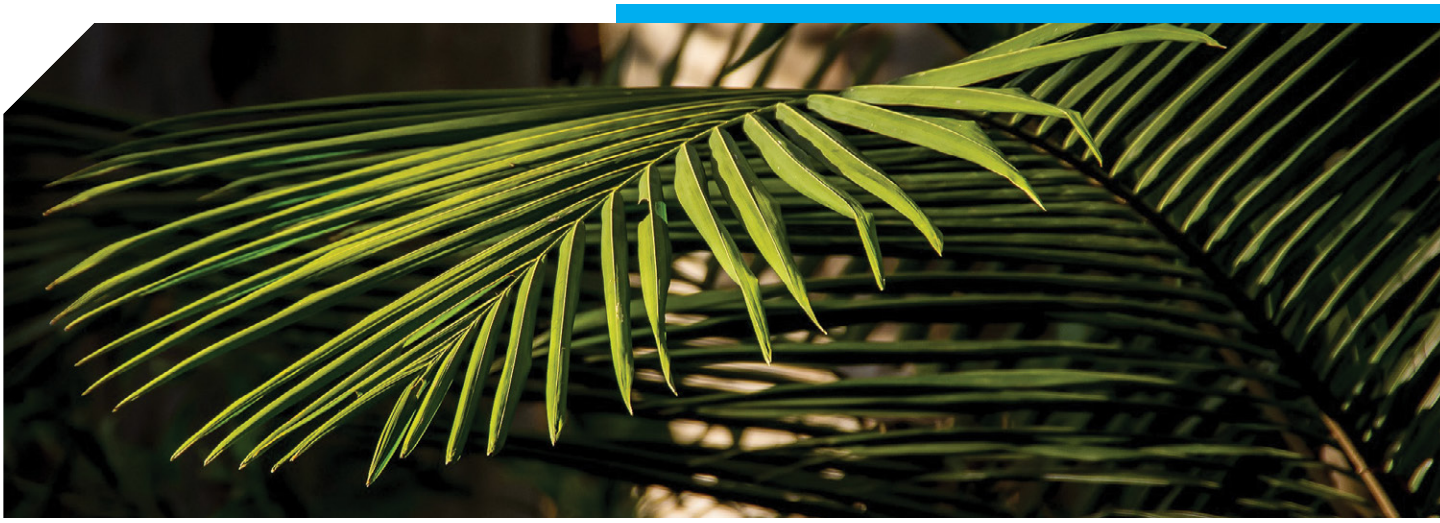
- Site-scale conservation (i.e. in protected areas) – correlative models may be able to identify what species can persist in the area in the future, allowing planning for new species assemblages and conservation actions.
- Regional-scale focus – spatially explicit predictions from correlative and/or mechanistic models could allow predictions of where species could persist in the future.
- Single species focus – trait-based and mechanistic models are required to determine impacts and thus plan for conservation actions and adaption measures to decrease species sensitivity.

The conclusions of Pacifici et al. (2015) highlight the importance of long-term ecological studies of species and ecosystems in providing the data to inform climate change adaptation actions. As well as providing the life-history and population data required to make robust modelling predictions, long-term monitoring may provide key information about how species and ecosystems are responding as climate change progresses. For example, how well climate refugia protect key species during a catastrophic weather event or how fast/well species recover following a weather event. Currently any data of this nature has been collected serendipitously – for example when an extreme weather event effects a species which was already the subject of a long-term study allowing a before-after analysis (Woodward et al. 2015) or by chance observation (e.g. Visoiu & Whinam 2015).

A number of species are now known to be shifting their distributions with climate change (i.e. VanDerWal et al. 2013) and long-term monitoring should provide valuable information on range shifts and allow for conservation planning into the future. However, for some species range shifts are not possible, and there may also be geographical limits on how far species can move (Burrows et al. 2014). Also, there is some evidence that local adaptation and variance in phenotypic plasticity among population of the same species can also influence predicted shifts in range (Valladares et al. 2014). Thus, understanding the capacity of species to adapt to climate changes in-situ will be crucial information for managers and policy-makers.

Phenotypic plasticity and microevolution are the two primary means by which organisms respond adaptively to changes in local climatic conditions (Boutin et al. 2014). Merila and Hendry (2014) review a number of studies which have recorded phenotypic changes in species attributed to climate change and find that evidence for genetic adaptation to climate change has been found, but is relatively scarce. They identify three problems in studies reporting adaptations to climate change; i) the difficulty in distinguishing whether phenotypic changes are genetically based or the result of phenotypic plasticity, ii) assumptions made about whether the shift is adaptive or not, and iii) lack of clarity as to whether the actual driver of change is climate change or another factor. However, despite the problems inherent in understanding adaptation to climate change, further research in this area will be crucial for conservation planning, especially for species with limited ability to shift to new climates. Urban et al. (2014) advocate for more experiments that survey genetic changes through time in response to climate change, while Franks et al. (2014) suggest that future studies with standardised methodologies, and especially those that focus on assessing responses to climate change over time, should facilitate better predictions of the ability for populations to responds to rapid climate change.

Finally, a rapidly increasing area that requires information and long-term observations is that involving the unintended consequences of adaptation actions (also discussed at priority research question 5.3.1 in terms of local land management issues). Choices made in one part of a system may impact other important outcomes, and maladaptation is also possible – whereby adaptation actions not only fail to reduce vulnerability, but actually increase it, and so understanding the potential trade-offs of any adaptation action will be crucial in planning (IPCC 2014; Dilling et al. 2015). Watson (2014) also highlights the fact that how humans adapt to climate change will have repercussions for biodiversity that should be incorporated into conservation planning. He concludes failure to predict likely human adaptations to climate change will result in 'flawed conservation planning, ineffective strategies and potentially avoidable dire consequences for biodiversity'. Further research in this area will rely on the publication of results from adaptation attempts (i.e. Laves et al. 2014).



Section 5.2 Regional issues: Priority research questions

Priority research question 5.2.1

What principles should guide ecosystem-based adaptation in Australia and the design of landscapes to support ecosystem resilience?

This priority research question was rephrased following the Terrestrial NARP review of 2013 (Kitching et al. 2013) in order to more explicitly encompass the broad set of issues associated with ecosystem-based adaptation. Two NCCARF funded projects directly addressed this priority research question (in its original form); Doerr et al. (2013) used modelling scenarios to investigate best design for landscapes in terms of climate change adaptation, while Meyer et al. (2013) worked to develop an online tool and other approaches to help guide principles and decision-making for end-users.

Doerr et al. (2013) modelled the future persistence of four major native groups under three current approaches to landscape design (variations on protecting existing habitat, and revegetation to improve quality, extent and connectivity of landscapes) – native orchids, fauna that specialise on wet forest environments, and two groups of fauna that specialise on grassy woodland and dry forest environments. They also modelled the response of two invasive species –the red fox (*Vulpes vulpes*) and peppercorn tree (*Schinus molle*). Their modelling approach used two case-study landscapes in New South Wales, and they modelled 48 future landscapes for each—future landscapes were constructed from four storylines of land-use change based on different future climates, two global climate models applied with future climates to model future vegetation communities. The goal of this study was to find one or more landscape design principles that improved all future landscapes for native species, allowing planning for the future despite the uncertainties inherent in climate change.

Their results show that all current landscape design approaches failed to fully compensate for losses in population capacity as a result of climate. Doerr et al. (2013) therefore conclude that current approaches to landscape planning may not be sufficient to serve as climate adaptation strategies for biodiversity.

Only one aspirational design—restoring landscapes to approximately 30% native vegetation cover—improved future landscapes relative to current landscapes, and the results demonstrate that the total amount of restoration is more important than detailed spatial configuration, at least at very large landscape scales (Doerr et al. 2013). They further propose that a variety of new approaches need to be explored even if they may be challenging to implement, including the following.

- Greater spatial targeting, with one viable potential metapopulation completely restored before moving on to the next.
- Defining priority areas for spatial targeting based on directions of projected species' distribution shifts rather than based on current landscape fragmentation.
- Designing the location and spatial pattern of productive land uses as well (like woody biofuel plantings or farm forestry projects) to ensure they provide some biodiversity benefits.
- Restoration of native vegetation in much larger units like whole properties (similar to some approaches being used in GondwanaLink).

Until these ideas have been explored in more detail, however Doerr et al. (2013) suggest the following best no-regrets options.

- Aligning local efforts over large scales but empowering local managers to design landscapes based on local knowledge and goals.
- Developing complementary management strategies for a few types of invasive species that are most likely to benefit from restoration at landscape scales.
- Concentrating effort to achieve approximately 30% native vegetation cover over smaller priority areas.

The second NARP to investigate this priority research question was that of Meyer et al. (2013) who worked with the Eyre Peninsula and South Australian Murray-Darling Basin Natural Resource Management (NRM) regions to explore future land use options that could be embedded in NRM Board planning and community engagement. The project also developed the web-based Landscapes Future Analysis Tool (http://www.lfat.org.au/lfat/), which can be used for planning purposes into the future.

Through a series of workshops and collaboration with end-users, this project also developed the application of 'envisioning' and identified a number of core principles relevant to future use of the envisioning process including the following.

- Envisioning operates as a bridge between science and decision making that can integrate more than just 'the science' – it can bring together and integrate the contribution from multiple stakeholders with diverse perspectives.
- One size doesn't fit all – we must be able to adapt the process to local variations in the social, political, agricultural and natural landscape.
- The process must reconnect the notions of planning and implementation. Planning must be seen as part of an integrated process, directed to action on the ground, rather than an end in itself, ticking the regulatory box.
- The role that time plays must be understood and respected. Adaptive work can be uncomfortable and lack of time can be used as a method of avoiding the adaptive work required.

Other NCCARF projects have also indirectly addressed this priority research question; Maggini et al. (2013) examined priorities of protected area and landscape design for threatened species, and their results are discussed in the context of priority research question 5.3.3. Reside et al. (2013) explored the role of refugia in protecting species from climate change; their study suggests that one of the most cost-effective ways to support ecosystem-based adaptation is to identify and protect those places – refugia – in the landscape that will harbour many species from the worst impacts of climate change.

Other research in the area of ecosystem-based adaptation in the past three years has focussed primarily on the resilience approach and resilience thinking, and on the role of ecosystem-based adaptation in multi-use environments (for example, agriculture). For example, a recent paper by Schippers et al. (2015) finds that promoting landscape diversity enhances resilience – they define landscape diversity as a landscape with many small and different ecosystem elements, and suggest that high diversity can contribute to ecosystem stability, because species from a functional group in one ecosystem might temporarily support a functional group in a neighbouring ecosystem.

A key focus of ecosystem-adaptation is to also promote and preserve ecosystem services, such as pollination, and also other services that benefit human well-being and other species. Echoing the proposal of Doerr et al. (2013)— that future directions could focus on defining priority areas for spatial targeting based on projected species distribution shifts— Giannini et al. (2015) use a modelling approach to identify key conservation areas for safeguarding populations of the tropical stingless bee (*Melipona quadrifasciata*), a key pollinator from Brazil. Their analysis identified the most important corridors, which if protected or restored, could facilitate the dispersal and establishment of bees during distribution shifts due to climate change.

The concept of protecting ecosystem services has been extended to the idea of 'climate adaptation services', the capacity of an ecosystem to moderate and adapt to climate change and variability with benefit to human well-being. Lavorel et al. (2015) highlight four general ecological mechanisms that underpin climate adaptation services in Australian landscapes, which are:

- vegetation structural diversity
- the role of keystone species or functional groups
- response diversity and landscape connectivity, which underpin the persistence of function
- the reassembly of ecological communities under severe climate change and variability.

They state that such knowledge should guide ecosystem management towards adaptation planning, in particular focussing on identifying and protecting existing adaptation services, restoring key functional groups to the vegetation matrix, and identification of novel management for emerging adaptation services as climate change progresses (Lavorel et al. 2015).

In summary, narrowing the focus of this priority research question since the review of the Terrestrial NARP in 2013 reveals promising progression in terms of both understanding what principles should guide ecosystem-based adaptation, and tools to guide the design of landscapes at the regional scale to support resilience. The NCCARF reports from both Doerr et al. (2013) and Meyer et al. (2013) have contributed significantly to this growing knowledge base, along with other research in the areas of ecosystem resilience and landscape design. However, as Doerr et al (2013) point out, there are still many knowledge gaps in this area, particularly in terms of developing new landscape management options when traditional designs are seen to be falling short.

Priority research question 5.2.2

How will climate change interact with other key stressors such as fire, invasive species, salinity, disease, changes to water availability, grazing and clearing, and what are the integrated implications for ecosystem structure and functioning?

Following protocol from Guitart (2012), this section is structured by dealing with the major stressors separately. NCCARF funded reports that addressed specific topics will be referred to within the appropriate section.

Fire

This section will review new literature that considers how climate change will interact with fire at the regional scale – fire and fire management at the local scale will be addressed at priority research question 5.3.2.

A review of the literature from 2013 highlights that there are increasing numbers of papers reporting observed effects of climate change and fire, although predictive studies still remain important. A large body of research, reviewed in Guitart 2012, and referenced in Kitching et al. (2013) already highlights the predicted complex nature of the interaction of fire and climate change at the regional scale; hotter, more widespread fires are predicted in many regions, but interactions with fuel load, uncertain precipitation patterns and other factors make general predictions difficult at best (i.e. Williams et al. 2009).

Recent observations back up these earlier predictions; a large-scale analysis by Bradstock et al. (2014) across south-eastern Australia investigated changes in area burnt from 1975–2009 in relation to changes temperature and precipitation during the same time period. They found that significant warming and drying occurred during study period in most of the 32 bioregions examined. There was also an increase in area burned in the majority of forest bioregions, whereas area burned declined or did not change in drier woodland bioregions. They suggest this divergence may be due to differences in the dominant fuel type (woody litter versus herbaceous fuels).

Enright et al. (2014) used experimental fires to investigate density of shrubs before and after fire in 33 shrubland sites, covering four post-fire rainfall years and fire intervals from 3–24 years. They find that species solely dependent on seedling recruitment for persistence were most vulnerable to local extinction; however seedling recruitment was also essential for population maintenance of resprouting species. They also found that, critically, a 20% reduction in post-fire winter rainfall, essential for seedling recruitment, was predicted to increase the minimum inter-fire interval required for self-replacement by 50% which would leave many species vulnerable.

More frequent and intense fires may also have implications for biodiversity at the landscape scale; Bowman et al. (2014) investigated the impact of two intense fires in the Australian Alps on the survival of the obligate seeding forest tree, alpine ash (*Eucalyptus delegatensis*). Following one high-severity fire, there was high adult mortality, but mass regeneration was also triggered. However, a second fire in quick succession killed 97% of regenerating trees. The authors indicate that the first fire removed above ground tree biomass, resulting in a switch from low loads of herbaceous and litter fuel to high loads of flammable shrubs and juvenile trees.

Coming to similar conclusions to those of Bowman et al. (2014), Enright et al. (2015) propose that three interacting processes will combine to increase threat in vulnerable woody plant species beyond that currently proposed based on climate envelope or fire-regime change alone. They call these combined effects ‘interval squeeze’ and develop a conceptual model in order to predict the outcome. The three processes are:

- demographic shift – altered rates of plant growth, reproduction, and survival in response to changed growing conditions
- post-fire recruitment shift – altered levels of plant recruitment in the first year after fire, associated with increased frequency of years unfavourable for seedling establishment and survival
- fire-interval shift – altered mean time between successive fires due to changes in the drivers of ignition and fire spread.

Predicted increases in fire intensity will also impact vertebrates—for example Penman et al. (2015) modelled the abundance of a fire-responsive amphibian—the giant burrowing frog (*Heleioporous australiacus*) under different climate change and fire scenarios. They found that increased frequency of low-intensity fires reduced abundance by less than 5%, while increased frequency of high-intensity fires reduced predicted abundance by up to 40%.

Gibson et al. (2014) contend that climate change could result in a change in the ratios of woody to herbaceous fuel types in some regions due to related changes in rainfall and soil type – thus altering the nature of fuel, flammability and fire regimes in general. There is also increasing recognition that fire and climate change may interact to cause biome-switching - irreversible climate and fire-driven conversion of high biomass forests to low-biomass, non-forest states. For instance, some fire-suppressed forests of the western United States are vulnerable to conversion to non-forest states because of increasingly severe fire weather and prolonged drying (Bowman et al. 2013).

In summary, the literature concerning the impact of climate change on fire and fire regimes has begun to move from projections only to observations in the field as the impacts of climate change on fire behaviour become apparent. Earlier predictions highlighting the complex nature of this interaction, particularly in terms of temperatures, precipitation and variation in fuel loads, are supported by empirical data. Adaptation management options suggested include heightened wildfire suppression and interventions to reduce fire severity (Enright et al. 2014) and new approaches to fire management that will maximise the in situ adaptive capacity of species to respond to climate change and fire regime change (Enright et al. 2015). Some researchers are moving away from the conventional wisdom that more managed burns could mitigate wildfire risk, with Enright et al. (2014) advocating for lengthened intervals for prescribed fire to best support the in situ persistence of plant species and of plant biodiversity, and Enright and Fontaine (2014) finding little evidence that fuel reduction burning produces benefits for wildfire control.

Invasive species

Many species will shift their current range and distribution with climate change, and this is true for invasive species as well as natives. Since 2013, there have been a number of new studies on the impacts of climate change on invasive plants, and also an extensive assessment of the potential risk of naturalised, but not yet invasive, plants in the NCCARF report by Hughes et al. (2013). There has also been some, although rather less, research on climate change and invasive fauna. This section is concerned with the general impacts of climate change on invasive species; management of specific problem species at the local level will be considered at priority research question 5.4.3.

In their book chapter, Webber et al. (2014) highlight that climate change will impact on plant invasions directly through factors including changed temperature and rainfall, and increasing CO_2. Indirect effects might include changes in human behaviour (changed land-use and/or introduction pathways), disturbance and altered biotic interactions. In a review of the literature, they find 153 studies that have examined the potential future distribution of invasive, non-native or weedy species using a variety of distribution modelling techniques. They highlight a number of knowledge gaps that need to be addressed, including:

- geographic bias – invasives in the north and west of Australia are understudied
- getting the measure of climate change impact – a better understanding of, and ability to quantify, all measures of impact is required
- improving confidence and certainty in the face of uncertainty – identifying the impacts of climate change over and above other drivers, such as habitat modification
- advancing concepts and value systems – understanding people's perceptions of invasive species
- revising management needs – understanding interactions between traditional management, such as herbicides, with climate change to inform management into the future.

Climatic niche modelling continues to be the primary tool used to assess the invasive potential of weeds under climate change. However, a number of limitations of this approach have been identified; for example Beaumont et al. (2014) modelled the climatic niche of the invasive weed *Chrysanthemoides monilifera* in both its native South Africa, and where it is invasive in Australia. They show that the native climatic niche differs to that found in Australia, and modelling with MaxEnt failed to classify one-third of Australian populations as inhabiting suitable climatic niche space. In one of the few recent studies on vertebrate invasive species, Tingley et al. (2014b) use a sophisticated model that combined a physiologically mechanistic model of the fundamental niche of cane toads with correlative models based on the realised niche. They found that the success of the cane toad in Australia also reflects shift in the species realised niche, rather than shifts in evolutionary traits. In its native South America, the toad is not able to fill its fundamental niche due to the presence of a closely related species with which it hybridises. However, with this species absent in Australia, the cane toad is largely able to fill its fundamental niche, contributing to its spread.

The data to make sufficiently robust models are also lacking for many species, and Martin et al. (2015) demonstrate the utility of Bayesian Networks for projecting distributions of invasive species when data are lacking, using the introduced pasture species, buffel grass (*Cenchrus ciliaris*) in Australia. They employ a framework where expert knowledge and available empirical data are used to build a Bayesian Network, and find that while conditions in the north may become less suitable for this species under climate change, buffel grass management may become more important in the southern part of the continent in the future. Another strategy to improve model predictions where data is lacking is to use data from well-established 'avatar' invaders (i.e. Larson et al. 2014).

However, despite limitations associated with climatic niche modelling, one of few studies to compare the performance of models with field data finds generally high correlations between field observations of newly naturalised plants and predictions based on species distribution models (Sheppard et al. 2014).

The NCCARF report from Hughes et al. (2013) considered the emerging problem of naturalised, but not yet invasive plant species – so called 'sleeper weeds'. They used distribution models to assess the threat of 292 naturalised plants. They also identified 'hotspots' across the continent where invasions may be more common – the southern coast and Tasmania were identified as high risk. The species which were most likely to become invasive varied across the continent, and one of the key outputs of the project was the development of a web-based tool to determine actions by decision makers (http://weedfutures.net/).

In summary, Webber et al. (2014) stress that climate change is important enough to be considered an essential component of invasive species research in Australia, otherwise generalised adaptation responses, such as corridors, maybe inadvertently exacerbate threats. With the probability that climate change will interact with traditional forms of management such as herbicides, new forms of invasive plant management— underpinned by revised conceptual and policy frameworks— may be required, especially for emerging novel plant communities (Webber et al. 2014).

Salinity and water availability

Climate change will impact water availability through a combination of shifts in temperature, precipitation and evaporation, and also indirectly through increases in atmospheric CO_2 and associated shifts in vegetation water use (Cheng et al. 2014). Observations of climate indicate that Australia is indeed becoming hotter and drier—2013 was the hottest, driest summer on record—explained as a result of anthropogenic warming and extreme drought (King 2014). The IPCC (2014) identify water constraints in southern Australia as a key risk, driven by rising temperatures and reduced cool-season rainfall. They suggested implementing integrated responses encompassing management of supply, recycling, water conservation, and increased efficiency across all sectors.

Recent models essentially confirm previous predictions, for example while Kumar et al. (2014) show that wet regions will get wetter, their study also suggests greater dryness during dry seasons even in regions where the mean climate becomes wetter.

In a recent study among four catchments in Australia, Cheng et al. (2014) find that rising atmospheric CO_2 has a large effect on water availability, in terms of runoff, in most catchment areas. They state that failure to account for direct atmospheric CO_2 effects, or its interactive effects, could lead to bias in predictions of future water budgets, especially for the water-limited catchments of Australia.

The area of south-western Western Australia has been highlighted as particularly vulnerable to the impacts of climate change on water availability; for example rainfall has reduced by 2.3% compared to the recent past, resulting in a corresponding 14% reduction in runoff (Islam et al. 2014). A recent modelling analysis in the Murray–Hotham catchment suggests that these impacts will continue and intensify into the future (Islam et al. 2014). Jeppesen et al. (2015) also highlight the combined effects of a decline in rainfall and increases in temperature on salinity and water levels in lakes in areas with a Mediterranean climate. Decline in runoff and ground water may also have a negative impact on soil moisture which is crucial in regulating vegetation productivity and controlling terrestrial carbon uptake (Chen et al. 2014).

Since 2012, a number of studies have predicted the effects of climate change on water availability and biodiversity in wetland regions, including the Lake Eyre Basin (Pisanu et al. 2015), the Macquarie marshes (Fu et al. 2015) with varying results.

Human actions, such as increasing water consumption and damming of rivers is also predicted to interact with climate change to exacerbate water shortage (Haddeland et al. 2014). In the wetlands of the wet-dry tropics, for example, models show that changes in rainfall under a wetter and drier future climate could have large impacts on area, duration and frequency of inundation and connectivity of floodplains and wetlands. Combining the construction of a dam with the impacts of climate change decreased average duration of connectivity by a further 1-2% (Haddeland et al. 2014).

Taylor et al. (2013) reviewed the literature available on climate change impacts on ground water, and examined possible opportunities and challenges of using and sustaining groundwater resources in climate adaptation strategies. Their review highlights a lack of groundwater observations, which currently limits our understanding of the dynamic relationship between ground water and climate.

In summary, recent research supports previous forecasts; climate is already resulting in hotter, drier conditions in much of Australia with resulting negative impacts on water resources, including the drying of ephemeral ponds, increasing salinity, and knock-on effects for vegetation and wildlife (e.g. Greenberg et al. 2015).

Other stressors

Other stressors to biodiversity which may interact with climate change include disease, and also grazing and habitat clearance. However, there is currently much less recent literature on these aspects.

Past studies have suggested that climate change could interact with pathogens to increase mortality in some species – for example the chytrid fungus which affects frogs in Australia (i.e. Pounds et al. 2006). A recent study on chytrid fungus found that short-term changes in minimum water temperature do have an impact on levels of infection (Fernández-Beaskoetxea et al. 2015).

Hoberg and Brooks (2015) suggest that climate change will result in new emerging infectious diseases among species due to ‘ecological fitting’, as pathogens are able to rapidly switch host under changing conditions. Similarly, Altizer et al. (2013) review the literature and find a number of studies report changes in host-pathogen interactions related to climate change. They conclude that climate change will continue to limit the transmission of some pathogens and create opportunities for others and that in order to improve predictions and responses we need to deepen our understanding of mechanistic factors.

A further stressor that will interact with climate change is grazing; climate change is expected to have an adverse impact on grazing industries, such as beef (Whish et al. 2014), with declines in carrying capacity expected that may result in changes in land use of graziers including expansion of grazed areas, higher water use for stock, and addition of different forage plants (see also Bastin et al. 2014).

Land-use change and habitat loss are still currently thought to be the primary drivers of biodiversity loss, though it is widely acknowledged that climate change will exacerbate the loss of certain types of habitat. For example climate change is expected to result in the contraction and loss of alpine grasses and other plant species in Australia (Parida et al. 2015). Large-scale intense fires could also cause significant habitat loss in fire-prone forests (Swab et al. 2012) and possibly biome-switching (Bowman et al. 2014). The combined impacts of human land-use change and climate change have not been modelled extensively; however a recent study in California suggests that anthropogenic land use can drive greater relative habitat losses compared to projected climate change for many species (Riordan & Rundel 2014).

Climate change mitigation strategies may also compound habitat loss and extinctions; Jantz et al. (2015) modelled the potential impact of climate change mitigation strategies on further habitat loss in biodiversity hotspots due to associated land use changes; they find land-use changes are projected to reduce natural vegetative cover by 26-58%.

While the capacity of climate change to interact with other key stressors including disease, grazing and land-use change and loss of habitat, the nature of these interactions and the implications for biodiversity, are still uncertain for the most part.

Priority research question 5.2.3

How can Australia's land-based carbon mitigation initiatives be designed to enhance ecosystem services, ensure appropriate ecological connectivity, deliver biodiversity conservation benefits and avoid adverse impacts on biodiversity?

This priority research question was re-worded in the 2013 revision to reflect government initiatives at the time, including the Clean Energy Fund, currently managed by the Clean Energy Finance Corporation. However, since 2013 there have been no recent funding rounds of some initiatives, including the Biodiversity Fund. The future of the Clean Energy Finance Corporation under the current government is uncertain.

Major global drivers of land-based carbon mitigation with co-benefits for biodiversity are the REDD schemes, which were summarised in Guitart (2012) and are also highly relevant to this review— whereby carbon credits are provided to avoid deforestation— and for increasing carbon storage in the form of reforestation, afforestation and restoration measures.

Using conservation planning analyses, Thomas et al. (2013) show that a combined carbon-biodiversity approach could simultaneously protect 90% of carbon stocks and >90% of biodiversity. These results are more successful than either a carbon-only approach or a biodiversity-only approach. Their combined approach uses the principle of complementarity – locations that contain different sets of species are a priority, and thus safeguard localised species that would not be protected by a carbon only strategy. They conclude that efficient compromises can only be achieved when biodiversity and carbon are incorporated together in a spatial planning process. Budiharta et al. (2014) also examined the cost-benefits of restoring forests for carbon and biodiversity benefits. They find that when the objective is to solely enhance carbon stocks, restoration of highly degraded lowland forest is the most cost-effective activity. However, if the objective is to improve the habitat of threatened species, multiple forest types should be restored but this reduces the accumulated carbon by up to 24%.

The role of the agriculture section to contribute to carbon sequestration with co-benefits for biodiversity was examined by Bryan et al. (2014) who found that a carbon market could motivate supply of substantial carbon, but would result in only modest amounts of biodiversity services from agricultural land. They suggest a complementary biodiversity payment could synergistically increase the supply of biodiversity services but would not provide much additional carbon sequestration. Their results were also highly sensitive to changes in carbon price.

Evans et al. (2015) explore the role and economics of carbon farming to offset carbon emissions with benefits to biodiversity in Queensland. They compared the potential benefits of both environmental plantings (replanting) and assisted natural regeneration and find that the average carbon price required to make assisted natural regeneration viable was 60% lower than what was required to make environmental plantings viable. They also demonstrate that assisted natural regeneration could sequester 1.6 to 2.2 times the amount of carbon compared to environmental plantings alone over a range of hypothetical carbon prices.

Canadell and Schultze (2014) examine the capacity of different biospheric solutions, such as bioenergy and reforestation, to mitigate climate change globally and provide co-benefits to biodiversity. They find that if executed accordingly, through avoided emissions and carbon sequestration, biological carbon and bioenergy mitigation could save up to 38 billion tonnes of carbon and 3–8% of estimated energy consumption, respectively, by 2050. Their research highlights three major components of future research and development that could potentially increase the current contribution of biologically based mitigation in significant ways:

- sustainable intensification of land
- algae-based biofuels
- bio-inspired catalytic systems.

Other authors have suggested that planning focussing on spatially explicit wildlife corridors and/or habitat refugia could provide a win-win situation for carbon mitigation and biodiversity outcomes. In their 2013 NCCARF report, for example, Reside et al. highlight the potential for refugia to act as both a haven to biodiversity and a carbon trap, although specific analyses on the carbon storage of identified refugia has not been undertaken at this point. Jantz et al. (2015) investigate the role of carbon stock corridors for carbon storage and biodiversity outcomes in the tropics. They assert that preserving carbon stored in vegetation between protected areas provides an opportunity to mitigate the effects of land use and climate change on biodiversity by maintaining habitat connectivity across landscapes.

They show that a large number of corridors had carbon densities that approach or exceed those of the protected areas they connect, suggesting these are suitable areas for achieving both habitat connectivity and climate change mitigation benefits; corridors contained 15% of the total unprotected aboveground carbon.

Renwick et al. (2014) also demonstrate that there could be significant potential for Indigenous communities to achieve carbon sequestration and biodiversity goals through planting native vegetation on Indigenous Land, particularly in southern and eastern Australia. However the economic feasibility of this idea is dependent on carbon market assumptions.

In summary, the area of land-based carbon mitigation with biodiversity co-benefits is an active area of research. Knowledge gaps on new technologies have been highlighted and these technologies may play a larger role in the future (i.e. Canadell & Schultze 2014). There is also a need to characterise and quantify the carbon storage potential of newer adaptation efforts for biodiversity, including protection and restoration of climate refugia, and to better understand the costs and benefits of replanting for different outcomes. A number of authors highlight the potential to tailor the spatial arrangement of climate mitigation activities to coincide with biodiversity priorities including maintaining connectivity and providing habitat refugia.

Priority research question 5.2.4

How can the major socio-economic trends occurring in many regions of Australia contribute to effective climate change biodiversity adaptation responses?

The effectiveness of climate change responses will be influenced by the adaptive capacity of communities within regions over time and space (Roiko et al. 2012). Despite the importance of understanding how socio-economic trends could contribute to compliment biodiversity adaptation actions, much of the literature continues to focus on major socio-economic trends (such as increasing populations, aging populations, increased water demands, etc.) as a barrier to adaptation (i.e. Roiko et al. 2012; Keys et al. 2014). However, a number of researchers have identified the need to incorporate different socioeconomic pathways into climate change adaptation planning (i.e. O'Neill et al. 2014; Kriegler et al. 2012).

The carbon credits scheme, already discussed in priority research question 5.2.3, is one trend that is already having a positive impact on climate change adaptation management and mitigation in terms of supporting private land holders to undertake adaptation measures on their land. The role of private land in climate change adaptation initiatives at the local level is discussed further in priority research question 5.3.4. Boulter (2012) states that society, both on a national and international level, is re-evaluating the value it places on ecosystem services (i.e. carbon, water, biodiversity) and finds that this is being reflected in practice, policy and legislation. On public land, for instance, this has seen the rise of national parks and the evolution of a policy and legal framework to accommodate it, while some private landholders are paid habitat managers.

In urban areas there has been a surge of interest in community gardens, including in schools and other privately owned areas. If managed and planted with appropriate practices (i.e. planting native species, permaculture) a network of community gardens could provide refuge and habitat for native wildlife, offer other ecosystem services, and offset disadvantages of industrial agricultural practices, by decreasing food miles, improving food security, reducing environmental costs and promoting agro-biodiversity (i.e. Guitart 2011). There are also education benefits to community gardens, particularly in schools, where there is a lack of environmental knowledge especially of climate change impacts and adaptation (i.e. Boon et al. 2014). The IPCC (2014) also note that other solutions for reducing energy and water consumption in urban areas can have co-benefits for biodiversity and climate change adaptation, such as greening cities/roofs and recycling water.

There has also been increased uptake of more sustainable agricultural systems in recent years, and there is potential for agroforesty and conservation agriculture to contribute to adaptation and mitigation measures, with co-benefits to biodiversity (Mbow et al. 2014; Harvey et al. 2014).

As mentioned in priority research question 5.2.3, there is also the potential for Indigenous communities to contribute to adaptation initiatives on their land (i.e. Renwick et al.) and others have explored how Indigenous and local knowledge could contribute to management of biodiversity under climate change (i.e. Tengo et al. 2014). The West Arnham Land Fire Abatement (WALFA) project has already demonstrated how Indigenous local fire knowledge has benefited fire management under climate change in tropical savannas (Fitzsimmons et al. 2012).

In summary, very few publications were found that directly addressed this priority research question, making it a priority for future focus. A number of publications were found which examined socioeconomic trends as a barrier to adaptation actions, but this priority research question requires a reframing of the questions asked in those papers. As stated in the updated Terrestrial NARP (Kitching et al. 2013), opportunities arising from socio-economic trends are likely to be locally specific (for example, the WALFA project) and managers should be focussed on identifying potential opportunities in their region.

Section 5.3 Local land management issues: Priority research questions

Priority research question 5.3.1

What are the costs and benefits of different climate change adaptation measures in vulnerable ecological communities and ecosystems?

In the last Terrestrial NARP review (Guitart 2012; Kitching et al. 2013) few papers were found that addressed this priority research question. The IPCC (2014) also identified that the literature on the costs and benefits of adaptation options is quite limited and fragmented. However, the NCCARF Synthesis and Integrative Research project of Lukasiewicz et al. (2013) examined in detail the costs and benefits of different adaption measures on catchments in the Murray-Darling basin. Their project involved an extensive literature review and consultation with stakeholders and end-users through workshops. They summarised that the best low cost, high benefit action for the catchments was to take an ecosystem-based approach to adaption measures. Their study highlights key lessons for adaptation under four themes:

- implementation of the ecosystem-based approach at the catchment level
- the need for a suite of complementary measures
- addressing institutional complexity
- consideration of the triple-bottom line and the implementation of adaptive management.

A number of other studies have highlighted the fact that we should take a precautionary approach to pre-empt any unintended negative consequences of activities in other sectors that may compromise biodiversity conservation goals (King 2014).

For example, understanding the scale of the risks of unintended harmful consequences of assisted migration, such as a successfully relocated species turning invasive and threatening the ecosystem into which it was introduced (Javeline et al. 2015). Similar concerns surround the costs and benefits of another common regional adaptation strategy—increasing habitat corridors—including the potential of corridors to exacerbate the threat of introduced species. Recent studies indicate this is a real risk and show that corridors can increase invasion by exotic species and decrease diversity of native species (i.e. Haddad et al. 2014; Resasco et al. 2014). In models of wet tropical species, Doerr et al. (2013) found that and the invasive peppercorn tree increased with landscape improvements for native species in a project funded by NCCARF.

Thus there is a need to develop optimal policy and regulatory framework for actions like assisted migration where there may be a risk in both action, and inaction (Javeline et al. 2015). Assisted migration/colonisation has most often been considered as a tool to relocate a threatened species of interest to an area with a more conducive climate, and as such will be further discussed in Section 5.4.2. However, Lunt et al. (2013) consider the costs and benefits of this strategy with the goal of relocating taxa to restore declining ecosystem processes that support biodiversity in recipient sites. They conclude that since maintenance of ecosystem processes is a key component of climate change adaptation strategies, assisted colonisations that maintain ecosystem function may be prioritised above those that simply conserve threatened species, if relocation costs are similar, benefits are greater and risks deemed acceptable.

This priority research question is still lacking sufficient information, although there has been some progression on ideas in the past three years, including the NCCARF project of Lukasiewicz et al. (2013) and also a published framework which allows managers to make decisions on management for climate change adaptation, specifically recognising costs and benefits of different actions (Shoo et al. 2013).

Priority research question 5.3.2

How should fire management adapt to climate change?

The interaction of fire and climate change at the landscape level was addressed at priority research question 5.2.2, and this section will deal with fire management at the local level. While there was no NCCARF project that addressed this priority research question, there has been considerable new research in this area, both in Australia and more broadly.

Bowman et al. (2013) state that fire management approaches are undergoing a rapid change in thought, as there is widespread recognition that fire suppression at large scales is not sustainable either financially and ecologically. The utility of prescribed burning to reduce fire severity appears to differ among ecosystems, and is currently controversial as in some regions emissions from prescribed burning will exceed the emissions avoided by reducing wildfire extent and intensity (Bowman et al. 2013). Bowman et al. (2013) indicate that the best fire management strategy for a local region should be assessed on a case by case basis; in some regions prescribed burning may remain the best option, while in other cases fire suppression or mechanical thinning could be better options.

Other studies highlight how different ecosystems will respond to both climate change and fire, and potential management actions. For example, Penman et al. (2013) modelled factors related to ignition in the Sydney Basin area, and found that all types of ignition (arson and natural) are predicted to increase with severe fire weather expected with climate change. For this densely populated region, they urge urban planning and management to minimise the exposure of new housing developments to flammable bushland high-risk fire zones, and provide measures that reduce potential for ignitions in fire-prone areas.

Results from the West Arnhem Land Fire Abatement (WALFA) project demonstrate how utilising Indigenous local knowledge of fire can improve fire management in the tropical northern savannas (Fitzsimmons et al. 2012). Indigenous fire management regimes have been re-established, particularly to increase the extent of early season burning using strategically prescribed fires, with benefits to both biodiversity and greenhouse gas reduction (Fitzsimmons et al. 2012).

King et al. (2013) modelled the behaviour of fire to climate and management strategies under future climate scenarios in two contrasting landscapes; the mesic forests of Tasmania, and an arid landscape in central Australia. They found under future warmer, drier climates, prescribed burning had the potential to partially diminish increases in unplanned fire activity in mesic ecosystems, but may reinforce a decline in unplanned fire activity in arid ecosystems. However, their models also demonstrated that, in the mesic ecosystem, prescribed burning may need to increase by approximately an order of magnitude by 2070 in order to maintain unplanned fire activity at contemporary levels. Such a massive increase in prescribed burning is unsustainable both due to limited resources and a predicted reduction in the number of days suitable for burning; thus for forests and scrublands of southern Australia at least, prescribed burning may be unable to counteract the effects of climate change on fire risk (King et al. 2013).

Fire management for climate change adaptation at the local scale is currently an active area of research and it is increasingly recognised that prescribed burning will not be a sufficient management option for many ecosystems. King et al. (2013) suggest that land management agencies may need to strategically target burning around key habitats and populations in some systems, in order to reducing the overall levels of treatment required to maintain contemporary levels of protection to biodiversity assets. Bowman et al. (2013) state that crucial steps in better understanding the relative risks of both orthodox and unconventional fire management interventions are required, and an evidence-based understanding of the inherent trade-offs between different fire management regimes is imperative. They also conclude that no single objective should define fire management. There is also increasing awareness that different fire management options could either increase or decrease the risk of biome-switching in forests (as discussed in priority research question 5.2.2).

Priority research question 5.3.3

How can management of local protected areas incorporate and adapt to climate change?

In the review of Guitart (2012), and also in the updated Terrestrial NARP (Kitching et al. 2013), this section was structured around three main questions as stated in Ervin (2011); to maintain consistency this review will also use these subheadings, which are; (a) where should new protected areas be located in order to maximise climate change adaptation, (b) how should they be managed, and (c) what are the necessary factors and policies to enable protected areas to maximise climate change resilience and adaptation.

a. Where should new protected areas be located in order to maximise climate change adaptation?

A number of NCCARF projects addressed various aspects of this question, in particular Maggini et al. (2013) and Reside et al. (2013) modelled the exact specific locations that new protected areas (including refugia) might be located in order to maximise resilience to climate change impacts.

Maggini et al. (2013) extensively examined and modelled how additional protected areas could best protect 504 threatened species under future climatic changes. Their results demonstrate that the southern and eastern parts of the continent contain refugia that many species could retreat to over the next 75 years; important areas were identified in the Great Dividing Range, the MacDonnell Ranges, and in the south of the continent (Tasmania) and some other high elevation regions. However, they also found that the current reserve system and protected areas are not sufficient to allow species to move into identified refugia areas, and also for many vertebrate species there appear to be no natural refugial areas for them to relocate.

Reside et al. (2013) state that the most cost-effective solution for biodiversity conservation under climate change is to identify and protect those places in the landscape that will harbour many species from the worst impacts of climate change. They modelled the location of these climate change refugia across the Australian continent, with a view to their future protection. They identified refugial areas as those that are predicted to experience the least climatic change into the future, particularly in terms of temperature and rainfall, and also regions that are predicted to retain most of their biodiversity and provide opportunities for additional species to relocate to into the future. Their results identify potential refugia in upland areas along the east coast, and a smaller area in South Australia. They note that challenges still remain, specifically with respect to assessing the quality of refugia at the level of both species and whole assemblages.

Lucasiewicz et al. (2013) in their NCCARF project state that a major problem with the current fragmentation of protected areas in Australia is that it poses a problem for migration, especially for those species with poor mobility or those who face human-made barriers and that. They suggest that habitat connectivity will be a necessary component of providing climate refugia if species change their migration patterns due to climatic changes. Doerr et al. (2014), however, suggests that perhaps the ‘how’ of future landscape designs is more important than the ‘where’; in their models they found that total amount of restoration was more important than detailed spatial configuration to counteract declines in biodiversity from climate-related changes, at least at very large landscape scales. This differed amongst species assemblages.

In addition to the research undertaken in NCCARF projects, there have been several other studies that have examined where protected areas should be located in order to maximise adaptation to climate change. For example, Brodie et al. (2012) state that synergisms between climate change and land use in tropical regions require a renewed focus on ecological connectivity with an emphasis on protecting latitudinal and elevational gradients. They argue that that there should be an expansion of protected areas along key ecological gradients in tropical regions. Gillson et al. (2013) similarly suggest that we need to include the widest possible altitudinal range within protected areas to preserve a greater variety of microclimates. Protecting areas of the greatest abiotic diversity in terms of geology, soils, topography, and hydrology should further enhance habitat diversity (Gillson et al. 2013). They also contend that, in terms of configuration, single large reserves are not necessarily the best option in a changing climate, for three reasons:

- for the same habitat area, a biologically connected network of habitat patches covers a larger space, thereby extending the potential climate space
- a string of reserves arranged linearly over a climate gradient might preserve more future climate space

- multiple reserves spread extinction risk across populations and are more resistant to threats, such as pathogens and invasive species.

Mokany et al. (2013) modelled the outcome under climate change for plant biodiversity in Tasmania using four contrasting reserve designs and found that adherence to a single habitat configuration strategy, such as connectivity, was unlikely to result in the best outcomes for biodiversity under climate change. Their results indicate that the best reserve design strategy under climate change is likely to vary between regions due to unique combinations of attributes and between taxa due to contrasting dispersal abilities.

Finally, some researchers have also developed tools to allow managers to determine potential spatial configuration of future protected areas. Keppel et al. (2012) present an evaluation of methods to identify climate change refugia in the landscape, and similarly Schut et al. (2014) provide a framework to rapidly identify climate change refugia using granite outcrops in Southwest Australian Floristic Region as a case study. Shoo et al. (2013) demonstrate that by coupling spatial information on biological assets (i.e. ecosystems and species) with future climate scenarios and process models to anticipate movement of critical habitats, they could specify priority actions for climate change adaptation in Queensland, including situation of new protected areas.

b. How should new protected areas be managed to maximise climate change adaptation?

A number of authors have indicated that the fragmented nature of the current protected areas system is problematic in terms of management for climate change impacts. Thus, many researchers stress that connectivity should be a key focus of management; Moritz and Agudo (2013), for example, conclude that managing and restoring eco-evolutionary dynamics across large ecologically heterogeneous landscapes, including long-term climatic refugia, and enabling habitat connections to these refugia should be management priorities. Reside et al. (2013) note that the majority of their identified areas of climate change refugia occur in areas which are also heavily modified by human activities, and recommend management actions to facilitate species movement and persistence in these areas. Similarly, Brodie et al. (2012) maintain that, to enhance the resilience of protected areas, governments and conservation organisations need to protect or restore viable habitat linkages among existing protected areas, and fund and manage protected areas and habitat corridors for biodiversity conservation adequately. They suggest that enhancing connectivity could be achieved via a combination of mechanisms, including national parks established by central governments, community-managed forests, international trans-boundary areas and carbon-financing projects.

In a recent study in the Australian Capital Territory, Doerr et al. (2014) tested the CSIRO model, or 'The 100m/1.1km/10ha Rule', that suggests connections between patches of native vegetation will generally support most species' movements if the connection does not have any gaps in it >100m, if the inter-patch distance (the distance between patches being connected) is no longer than 1.1km, and if the patches at either end are at least 10ha in size. Their results indicate that this rule should be slightly adapted to become 'The 150m/1.0 to 1.3km/10ha Rule'. Lechner et al. (2015) also recently published a flexible, scenario-based approach for modelling fine-scaled connectivity, using the Hunter Valley as a case study.

Sgro et al. (2012) also note that ecological processes must be conserved on biologically relevant scales which often do not fit within the fixed boundaries of protected areas which, as they currently stand, are poorly situated to accommodate in situ evolution in response to climatic changes. They state that with new genomic tools, and enhanced understanding of adaptive responses to climate change, we are now in a unique position to consider evolutionary processes in conservation planning and management of protected areas.

Other studies stress that due to the uncertain nature of climate change and climate change impacts, and the cost-benefit nature inherent in adaptation strategies, management may need to 'hedge its bets' in terms of the best approach. The research of Lukasiewicz et al. (2013) demonstrates the need to look at a suite of complementary actions that spread risk, rather than investing in one or two perceived best actions. Similarly, Gillson et al (2013) state that hedging management strategies is particularly appropriate when expected changes are foreseeable, but uncontrollable, in order to spread or accommodate risk.

c. What are the necessary factors and policies to enable protected areas to maximise climate change resilience and adaptation?

A number of studies stress that a coordinated approach is required to maximise the climate change resilience and adaptation capacity of protected areas. The NCCARF-funded project by Boulter (2012) notes that while climate change impacts will differ across regions, adaptation responses will cross regional and state borders in Australia. The development of corridors, for example, will require national coordination to ensure correct spatial locations. Boulter (2012) suggests that potential policy instruments at the regional level, such as the Regional Forest Agreement, already exist and could be adapted to meet this need. Brodie et al. (2012) also argue that a coordinated approach at both regional and international levels is explicitly required to increase resilience of forests and forest-dependent taxa to climate change. There have recently been some encouraging moves to integrate conservation plans across state borders, such as 'The Border Ranges Rainforest Biodiversity Management Plan—NSW & Queensland', which was conceived to reduce organisational-related impediments to biodiversity planning (DECCW 2010) through such actions as supporting coordinated cross-tenure management and planning controls and establishing compatible mapping systems and data management systems (Shoo et al. 2013).

A number of authors have highlighted the need for governments and industry bodies to work together to agree on how adaptation management actions should be prioritised. Boulter (2012) observes that because some of the socio-economic impacts of climate change are diffuse and indirect, and some are intangible, governments and industry will find it difficult to decide on priority areas, and so agreement on indicators of change would be helpful. Lucasiewicz et al. (2013) agree; they note that the adoption of a system-wide approach is constrained through institutional complexity and geographical, temporal and organisational boundaries, and the limitations of the existing legal frameworks. Shoo et al. (2013) also observe that socioeconomic-environmental planning and investment is likely to be required to overcome human barriers to forest recovery in Queensland, and a major obstacles include conflict between urbanisation and priorities for habitat conservation.

Ervin (2013) states that we need to repurpose protected areas in order to attain not only ecological, but also sustainable, development goals. She urges that we must reposition protected areas within a specific policy context in order to ensure policy relevance, including within the development of national sustainable development goals and national biodiversity plans.

Finally, Boulter (2012) suggests we should consider the introduction of more novel or innovative governance structures that might incorporate a principle of climate change adaptation, and consider new categories of land use such as carbon conservation areas or climate change adaptation areas.

Priority research question 5.3.4

How can we better integrate conservation plans and actions across landscapes, incorporating protected area management, off-reserve conservation measures and other land uses, in order to maximise biodiversity conservation benefits / outcomes under a changing climate?

A number of aspects of relating to this priority research question have already been discussed in depth – for example the importance of habitat connectivity and a focus on connecting existing and new protected areas with corridors has been covered as part of priority research question 5.3.3 (b). Similarly, the need for collaboration between regional and state governments in order to integrate conservation plans and actions across landscapes was addressed in priority research question 5.3.3 (c). Land-based carbon initiatives, which may be developed to provide a win-win situation for carbon mitigation and biodiversity, including carbon stock corridors, may be another way to integrate different land uses in at the local level to maximise benefits in a changing climate, and these were discussed in priority research question 5.2.3.

As addressed in priority research question 5.2.1, an ecosystem-based approach has been identified as the best approach for ecosystem resilience to climate change. However, implementing any spatially-explicit landscape plan requires cooperation from and coordination among private land holders, often in very specific local areas (Whitten et al. 2013) and thus conservation actions on private land and off-reserve are another important way in which conservation plans need to be integrated local landscapes.

Boulter (2012) notes that there are a number of government funded programs for extension of the reserve system, protection of wildlife habitat on private land and planting for ecosystem services such as shade or shelter, and that there is considerable scope to expand and coordinate such programs for multiple benefits under climate change. For example, an agency managing a conservation stewardship program could undertake to additionally negotiate and validate carbon sequestration outcomes, allowing the agency to bundle sequestration parcels and conservation lands and so reduce transaction costs.

However, government and regional bodies have limited ability to act on private land, so the full benefits of an ecosystem-based approach may not be realised due to the reluctance of landowners to participate. Lukasiewicz et al. (2013), though dialogue with private landowners, find that obstacles to incorporating private land into conservation initiatives are driven by funding, peer pressure and economic circumstances of private landholders. They found that private landholders were often unwilling to undertake actions such as restoration if the financial costs of undertaking the action, and maintenance, were judged to outweigh the financial benefits. Landholders perceived costs to be government intervention and interference, and increased fire and weed risk (Lukasiewicz et al. 2013). A number of studies have highlighted the need to establish a particular policy process or institutional structure for the purpose of improving biodiversity conservation outcomes, for example, the development of market-based instruments to create incentives for biodiversity conservation on private land (i.e. Dunlop et al. 2013).

The results from the NCCARF report of Reside et al. (2013)—modelling the spatial distribution of climate change refugia areas — have recently been taken up by the Queensland Government in The Nature Refuges Program, part of their commitment to ‘Investing in our Environment for the Future’. Under the program land owners can partner with the government to protect key refugia areas identified in modelling outputs. This relatively new initiative is an excellent example of research rapidly informing policy and management to produce positive outcomes in on-the-ground environmental management (VanDerWal et al. 2015).

In addition to the research undertaken in NCCARF-funded projects, other studies have highlighted the need for the cooperation of private land holders to achieve integration of climate change conservation actions across landscapes. Gollan et al. (2014) identified the location of two types of refugia (ephemeral and stable refugia) in New South Wales. They found that many stable refugia were small and located on private land and highlight the need for off-reserve conservation measures. They suggest that currently unprotected stable refugia could be added to existing protected area systems or targeted for conservation as part of incentive schemes on private land - such as biodiversity or mitigation banking. They add that when considering cool environments on private land for adaptation strategies, conservation planners may only need to consider the small pockets of stable refugia (Gollan et al. 2014). Shoo et al. (2013) note that conservation covenants such as State Nature Refuge agreements, local higher voluntary conservation agreements and/or Land for Wildlife Schemes are providing low-cost options to increase protection and management of private land for conservation.

In a recent study, Raymond et al. (2015) develop a method to integrate social data on land manager adaptive capacity and factors associated with participation, along with biophysical data on the current and projected-future distribution of climate suitable for vegetation communities; they use habitat in Tasmania as a case study. They assert that their results could be utilised to help design community engagement programs, and to tailor messages to land managers with different capacity types and information behaviours.

The IPCC report (2014) finds that in terms of successful adaptation planning, two roles will be critical to progress; those associated with local government and those within the private sector. This review essentially concurs, with research indicating that better integration of conservation plans and actions across landscapes will require a coordinated approach across local councils and state and federal governments, particularly to manage existing and new protected areas and to effectively place new habitat corridors and locate other restoration efforts in order to increase habitat connectivity. Models of the spatial location of climate change refugia in the landscape have increasingly highlighted the importance of private land, and thus effective policy and incentives to encourage land owners to participate in restoration and other conservation actions on their land need to be developed.

Section 5.4 Managing key species and communities

Priority research question 5.4.1

How can investment in climate change adaptation measures to conserve species and communities be prioritised?

In the review of the updated Terrestrial NARP (Kitching et al. 2013) this priority research question was reworded in order to reflect a change of focus. The original priority research question was 'Which species should be the focus of investment in climate change adaptation?' However, while there has already been a great deal of research focussing on identifying the most at risk and vulnerable species, it was considered that there had been little effort on understanding how best to prioritising investment in species or communities at risk.

First, the identification of the most vulnerable species and communities remains an important step in prioritising adaptation actions. Shoo et al. (2013) examine decisions to conserve species under climate change and note that the first step should be to ensure that vulnerable species are identified as candidates for management intervention. Species distribution models continue to be a useful tool in assessing which species and communities may lose habitat to climate change in the future (see also priority research question 5.1.3). However, models can have their shortcomings; for example Small-Lorenz et al. (2013) note that species distribution models fall short and may even be misleading in predicting the vulnerability of migratory species to climate change. Biological trait based assessments, which can include life history traits, and consideration of other sensitivities and adaptive capacity, are also becoming increasingly common (i.e. Reece & Noss 2014; Pearson et al. 2014), but can sometimes provide conflicting vulnerability assessments to distribution models (Willis et al. 2015). Some researchers have also utilised criteria from the IUCN Red List and other lists that, while useful, can also have limitations (Keith et al. 2014).

Cardillo and Meijaard (2012) contend that while large-scale, comparative studies of species extinction risk are now common in conservation science, they seem to have little influence on conservation practice and uptake into policy. They suggest that this may be because comparative studies are often ambiguous, inconsistent and difficult to translate into policy, and also because current conservation priorities emphasise the rescue and protection of currently threatened biodiversity, whereas comparative studies are often better suited to a proactive approach that anticipates and prevents future species declines.

Willis et al. (2015) recently developed a methodological framework for assessing climate change impacts on species that uses both traditional species distribution modelling approaches and biological trait-based assessments, and contend that these models can be used conceptually as inputs to guide priorities in conservation monitoring and planning. Similarly, Fordham et al. (2012) suggest that models that couple habitat suitability with demographic processes offer an improved approach for estimating spatial distributional shifts and extinction risk under climate change, and apply this approach to five species of Australian plant with contrasting demographic traits.

Increasingly though, analyses demonstrate that the most cost effective management decisions for climate change adaptation will be based at the ecosystem level. For example, Shoo et al. (2013) state that actions concerned with species' spatial adjustments (identified through species distribution models) should begin with assessments of potential refugia.

A number of NCCARF projects that have addressed this priority research question concluded that we should be prioritising ecosystem-based adaptation options that benefit a suite of species and communities. For example, Doerr et al. (2013) urge that we need to identify regional priority areas and then revegetate or manage for natural regeneration anywhere within those regional priority areas, with local actions to match local goals. In their continent-wide analysis of the impact of climate change on Australian birds, Garnett et al. (2013) state that a key priority is fine scale modelling of regions identified as having numerous highly exposed bird taxa in order to identify climatic refugia within the landscape. They conclude that modelling of refugia and a continuation of species management are the principal actions recommended for immediate implementation. In the future, however, the management of refugia and captive breeding for the most threatened species may become priorities (Garnett et al. 2013).

Pickering and Venn (2013) used a functional traits approach to assess the threat of climate change on Australian alpine flora. Based on results from the composition and trait analyses, they make recommendations regarding prioritising resilience adaptations strategies, which include enhancing resilience by minimising existing threats, particularly those from fire, weeds and hard-hooved grazing animals which will be exacerbate by climate change.

In their analysis of low-risk management options, Lukasiewicz et al. (2013) note that state governments often prioritise resilient, rather than degraded, habitats. However, their definition of resilient habitats still rests on an assessment of present conditions, rather than on considerations of where optimal habitat may be located in the future under climate change, and effectively, those ecological communities that are already fragmented and degraded are further marginalised because investment is concentrated in more intact, more currently valuable habitats.

Conservation decision making tools, such as the software package 'Zonation' (Moilanen et al. 2005) which is freely available (http://conservationcorridor.org/corridor-toolbox/programs-and-tools/zonation/), will play an increasingly important role in prioritising actions under climate change. Reside et al. (2013) used landscape software Zonation in Australia's Wet Tropics and found that the tool identified all known refugia and could ensure that the areas of highest priority incorporate complementarity across both species and sites. They state that application of this kind of analysis at the regional level will be the obvious way forward in clarifying the location and quality of climate change refugia in a way that can also incorporate socio-economic objectives. Similarly, Maggini et al. (2013) used Zonation to prioritise habitat for 504 threatened Australian species; the scale of the prioritisation analysis implemented in their report was unprecedented in the conservation literature, and revealed that for an available budget of $3 billion, protecting an additional 877,415 km^2 of intact habitat, and restoring 1,190 km^2 of degraded habitat immediately was identified by our analysis as the optimal set of actions to help the 504 threatened species adapt to climate change assuming early mitigation. Under a more pessimistic business-as-usual climate change scenario, 837,914 km^2 of protection is required, along with 77 km^2 of restoration. In all cases, appropriate threat management within protected areas was also required. Meyer et al. (2013) also utilised Zonation to identify priority areas for reducing species vulnerability under the three climate change scenarios in South Australia, and assessed the levels of species representation in these priority areas.

Boulter (2012), in the NCCARF project assessing the vulnerability of forests to climate change, notes that to prioritise responses to climate change impacts, land managers and policy makers will need to assess the costs and benefits of adaptation actions. The Systems Thinking Tools for Climate Change Adaptation (Maani 2013) incorporates cost-benefit analysis of any trade-offs within a risk assessment framework and can help decision makers to prioritise alternative actions. Similarly, in their NCCARF report, Trück et al. (2013) develop CATLoG ('Climate Adaptation Decision Support Tool for Local Governments') to assist decision makers in comparing and prioritising climate change adaptation investments with particular reference to extreme events. Cost-benefit analysis that calculates the costs and benefits of a number of alternative adaptation options is used to prioritise the adaptation options.

Additional to the research undertaken through NCCARF, other research has also focussed on methods to prioritise species and landscapes under climate change. Gillson et al. (2013) prioritised landscapes based on two 'axes of concern', which were: i) landscape conservation capacity attributes (percentage of protected area, connectivity, and condition of the matrix); and ii) vulnerability to climate change (climate change velocity and topographic variation). Harris et al. (2015) used endangered lowland grassland communities in Tasmania as a case study to identify management options where e future climatic conditions become unsuitable for the current threatened community. They conclude that priorities will need to focus on maintaining diversity, structure and function, rather than attempting to preserve current species composition. Options for achieving this include managing related grassland types to maintain grassland species at the landscape-scale, and maximising the resilience of grasslands by reducing further fragmentation, weed invasion and stress from other land uses, while accepting that change is inevitable.

The various NCCARF-funded projects have contributed significantly to a new understanding of both the best ways to prioritise actions for species and communities, the tools and frameworks available for priority analysis, and also highlight the current priorities for a number of communities and species. Recent studies highlight the need to incorporate multiple strategies in order to inform conservation decisions and prioritise actions. For example, Tingley et al. (2014a) state that we need to combine coarseand fine-scale approaches; fine-filter strategies to assess species vulnerability and prioritise the most vulnerable species for conservation actions, and coarse-filter strategies to conserve key sites. In this way, they contend, conservationists can hedge against the uncertainty inherent in climate change.

Priority research question 5.4.2

How will climate change affect current management actions for protecting priority species and communities, and what management changes will be required?

This priority research question was reworded to add 'communities' in the updated Terrestrial NARP (Kitching et al. 2013).

Since the last review (Kitching et al. 2013) little research was located that focussed specifically on this priority research question, although a number of NCCARF studies and other research address it indirectly.

As covered in priority research question 5.1.1, it is necessary that conservation goals, at all scales, should take a more dynamic rather than static approach, and managers need to understand that is not valid under climate change to aim to keep the same suite of species in communities and ecosystems (i.e. Dunlop et al. 2013; Harris et al. 2015).

Adaptive management can take both active and passive forms in both a general context and in terms of climate change management actions; active adaptive management is where options are viewed as hypotheses to be tested and considers that experimentation is key and both formalised learning and management are objectives. Passive adaptive management, on the other hand, implements a single preferred course of action based on the best available modelling and planning, which is then modified as experience grows (Rist et al. 2013).

In their NARP, Garnett et al. (2013) list the most common goals in current adaptation strategies for biodiversity:

- Resistance to climate change – such as active management to maintain conditions 'as is', and forestall impact of climate change. Examples include revegetation, control of invasive species.
- Resilience to climate change - improve the capacity of populations to recover from disturbance, such as ensuring viable population size and habitat connectivity through corridors, etc.
- Facilitate response – enable transition to new conditions through habitat connectivity, and/or through assisted migration or assisted gene flow.

The most common practical management actions proposed for vulnerable species and communities include:

- in-situ management – most commonly focussing on protecting and restoring habitat and corridors.
- assisted colonisation and assisted gene flow – active and intensive species level management aimed at moving endangered species and/or improving genetics to aid resilience.
- ex-situ management – often considered 'last resort' options, including captive breeding and storing germplasm.
- monitoring and research – long term monitoring over periods of climate change and extreme events will provide answers for the management of species and communities into the future (Garnett et al. 2013).

For some critically endangered species, all of these management options may be necessary and complementary.

As mentioned in priority research question 5.4.1, response to climate change may more often require an emphasis on ecosystem processes and function rather than a single species (Garnett et al. 2013), and habitat manipulation is rarely undertaken with the interests of just a single species in mind. However, as Garnett et al. (2013) note, habitat issues remain at the core of both biodiversity and species management, and some key species may require a more active and intensive approach.

Many of the in-situ actions at improving ecosystem resilience and resistance to climate change are tried and trusted conservation measures that are unlikely fundamentally change in adaptation measures for climate change. However, as detailed in other sections, habitat protection and restoration efforts need to be more spatially specific in order to protect the greatest number of species and ecosystems (such as identifying and protecting refugia, connecting disparate protected areas, etc.).

However, it is the more contentious intensive and active species management options, such as assisted colonisation (AC) and captive breeding, which still polarises researchers. The pros and cons of AC have been discussed widely, and were covered in detail in the review of Guitart (2012) and in the Terrestrial NARP review (Kitching et al. 2013). However, the topic continues to be debated widely in the literature; Hancock and Gallagher (2014) surveyed more than 150 participants who were involved in flora translocation and/or conservation in Australia, and find that while most acknowledge the potential benefits of such action, impediments to AC included prohibitive costs, lack of knowledge of species ecology and biology, and risk of disease spread. Most respondents preferred actions that mitigated proximal threats (such as improving habitat) over ones that move species beyond their current range.

Another form of AC is assisted gene flow (AGF) – the enhancement of genetic adaptedness of a population by translocation into it of individuals from another population or even subspecies within the current range (i.e. Garnett et al. 2013; Aitken & Bemmels 2015). Kelly and Phillips (2015) further contend that AGF could be used for other, more wide-ranging conservation benefits, from the management of invasive species and their impacts to controlling the impact and virulence of pathogens. Hoffman et al. (2015) explore how new genomic knowledge might be combined with evolutionary thinking, and develop a decision framework aimed at reducing the long-term impacts of climate change on biodiversity and ecosystem services.

In their analysis of adaptation strategies for Australian birds, Garnett et al. (2013) specifically consider the cost and feasibility of AC for the most threatened birds. They find that some species are already being translocated (e.g. Eastern bristlebird, *Dasyornis brachypterus*) and for these species there is an opportunity to consider immediate adaptation of the assisted colonisation process to also incorporate climate change predictions. However, for most taxa, AC and AGF were considered to be distant events and the only action postulated was research on their feasibility in the future.

Captive breeding and reintroduction to the wild are expensive options which target only a single species, and are thus often considered a 'last resort'. However, this is a strategy already used for some endangered species (i.e. Helmeted honeyeater *Lichenostomus melanops cassidix*), and Pritchard et al. (2012) argue that increasing extinction rates, exacerbated by climate change, challenge the wisdom of dependence on in-situ strategies, and necessitate the development of ex-situ approaches. They contend that the tradition divide between in-situ and ex-situ approaches may diminish as approaches are combined for the most vulnerable species.

Finally, active species specific management options at the local level could include activities which are based on traditional conservation measures, but which may need to be adapted in order to remain useful under a changing climate. For example, the provision of nest boxes has been a species specific conservation strategy for a suite of arboreal birds and mammals for many years. Nest boxes, and other artificial refuges, may be used as a potential adaptation management measure for some species, but in light of rising temperatures and more extreme weather events, the location of such refuges, and the materials from which they are made, will need to be taken into account if they are to be useful, thermally buffered, microhabitats (i.e. Goldingay 2015).

A number of papers now provide a framework for decision making, including at the level of species and communities. For example, Shoo et al. (2013) develop a decision framework which incorporates the full complement of actions aimed at conserving species under climate change, from ongoing in-situ conservation in existing refugia, through various forms of mobility enhancement to ex-situ actions. Their framework also explicitly recognises that allocation of conservation resources will be governed by factors such as the likelihood of success, cost and likely co-benefits to non-target species, in addition to perceived vulnerability of individual species. Rout et al. (2013) and Gallagher et al. (2015) both provide frameworks to inform AC; deciding whether or not a particular introduction should go ahead, which species to prioritise for introduction, and where and how to introduce them (Rout et al. 2013), and identification of a series of scenarios that may predispose terrestrial species to the need for AC (Gallagher et al. 2015).

As the very least, species-orientated investment will need to take account of the functional importance of species when assessing relative priority for conservation investment, such as how that species contributes to ecosystem function and ecological interactions within a community (Valiente-Banuet et al. 2015). However, for some species and communities, specific actions will be required, and the controversies about AC, AGF and captive breeding show no signs of abatement. Despite this, progress has been made with a number of frameworks now available for decision-making at the local level. Knowledge gaps appear to be information lacking on species ecology, genetics and biology, which are major impediments to managers utilising AC and AGF for the most threatened species (Aitken & Whitlock 2013; Hancock & Gallagher 2014). Monitoring should play an important part in future adaptive management as understanding existing trends and how they might play out in the future relies on sustained monitoring combined with fine-scale modelling (Garnett et al. 2013).

Priority research question 5.4.3

How will climate change affect current or potential problem species and what management responses will be required?

Many of the potential impacts of invasive and problem species at the local level are also relevant at the regional level, as addressed at priority research question 5.2.2. It is well established that climate change will result in shifting distributions of invasive flora and fauna— some species may decrease their range, while others will expand their range— and species distribution modelling remains the most common tool to predict range expansions of invasive or problem species at the local level (i.e. Vicente et al. 2013). However, Bellard et al. (2013) also urge that while we also need to increase the power for predicting the potential impacts of invasives under climate change, it is also crucial to move beyond predictions. In particular, to strengthen risk assessment, protocols of screening and of early detection, vector control and integrated management in area and/or of invasive species that will become at higher risk following climate change (Bellard et al. 2013). Vicente et al. (2013) encourage the coupling species decision models and connectivity analysis to support resource prioritisation for monitoring invasive impacts under limited resources.

In general, alien plant management typically focuses on either controlling selected alien species (‘species-led’), or on minimising invasions within selected biodiversity or cultural assets, such as protected areas (‘asset-led’). Gosper et al. (2015) recently compared and combined species- and asset-led approaches to prioritise alien plant management activities in the world’s largest Mediterranean-climate woodland, in south-west Western Australia (Gosper et al. 2015). They find that addressing the highest management priorities of each approach is a complementary way forward for alien management for biodiversity conservation.

Leishman and Gallagher (2015) reviewed the main drivers of vegetation change under climate change to assess whether these are likely to favour invaders over other species. They find that responses to changes in CO_2, temperature and rainfall are strongly species and context dependent, such that invasive species will not consistently be favoured. However, a reduction in resilience of vegetation assembles due to climatic changes may result in increased colonisation opportunities that invaders could exploit. They suggest that management should focus on actions that increase native resilience as well as monitoring and early eradication efforts. Similarly, Firn et al. (2015) contend that there has been no assessment of the extent of ecosystem intactness that may be lost without effective invasive plant species management strategies. In their study on the Eyre Basin, they conclude that, given that there are insufficient resources to manage all invasive plant species everywhere, this information could have the potential to improve current investment decisions (Firn et al. 2015).

A further concern is that climate change could interact with other drivers to increase interactions between native and non-native species through invasive hybridisation, potentially threatening endangered species (i.e. Muhlfeld et al. 2014). Muhlfeld et al. (2014) warn that conservationists will be faced with a stark choice: protect the genetic integrity of native species via isolation management (at the risk of losing genetic and life-history diversity), or allow hybridisation to proceed, causing extinction of native genomes.

Over the past three years, a number of studies have developed frameworks in order to identify priority threat management of invasive and/or pest species at the local scale. For example, as discussed previously, some invasive species are known to tolerate, or even thrive, under conditions found beyond their current distributions, which alters their future potential risk and the usefulness of alternative management strategies (see priority research question 5.2.2). Sax et al. (2013) propose a conceptual framework within which empirical data can be used to generate hypotheses regarding the realised, fundamental and 'tolerance' niche of invasive species.

As also discussed in priority research question 5.2.2, the NCCARF funded project by Hughes et al. (2013) developed a framework to allow managers to prioritise control of 'sleeper weeds' at the local level. Hughes et al. (2013) conclude that they envisage that their prioritisation approach for determining weed management priorities for naturalised plants, will be the basis for a tool for allocating economic and human resources for on-the-ground actions now and in the future in light of climate change.

Finally, Mainali et al. (2015) recently compared the performance of different modelling techniques on projected distribution changes in the weed *Parthenium hysterophorus* in Australia and other regions where it is invasive. They found model accuracy was much improved by using a global dataset for model training, rather than restricting data input to the species' native range. Interestingly, however, although large tracts of Queensland were shown to be highly climatically suitable, no infestation records were found for those areas. The authors suggest that this discrepancy between projected habitat suitability and actual occurrence in this invasive weed is due to Queensland already having effective management interventions in place, including eradication, strict quarantine measures, biological control and grazing management strategies that reduce parthenium in the region. Their results are encouraging as they suggest, in some cases at least, combined current management strategies for invasive species could also remain valid as climate change adaptation measures.

In summary, the impacts of climate change on the distribution of invasive and/or pest species will vary, and models demonstrate that different species and areas will be impacted in different ways. In the past three years progress has been made both in terms of combining different approaches in order to predict impacts, and also in terms of the development of tools which allow local end-users to predict how certain species may be impacted by climate change, and thus to make informed management choices on the ground.

Overall conclusions

Since the last update of the Terrestrial NARP in 2013, there has been considerable research effort focussed on most of the priority research questions. The various NCCARF funded projects in particular have contributed to new knowledge in a wide range of areas; from policy, to landscape design, identification of refugia and protected areas management, to invasive species and species-specific conservation strategies. Importantly, a number of NCCARF projects have also provided end-users with frameworks and tools with which to identify the potential impacts of climate change, and make informed adaptive management decisions in their regional or local area.

In contrast to the review of Guitart (2012), this review found a much greater research focus on identifying the costs and benefits of different adaptation measures, and this is a promising trend. Similarly, there was a great deal of new research found on how Australia's land-based carbon mitigation initiatives could be designed with biodiversity co-benefits.

One area that was found to be lacking in new information was that of how the major socio-economic trends occurring in many regions of Australia could contribute to effective climate change biodiversity adaptation responses: this priority research question still remains deficient in appropriately focussed research.

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Appendix 2

Cross-matching current and previous priority research questions

Current Priority Research Question	Previous PRQs 2013[1]
1. Developing general conservations goals, policy and implementation strategies aimed at maximizing the long-term resilience of biodiversity in a changing climate	5.1.1
1.1 What are the general principles that should guide conservation goals and decisions?	5.1.1
1.2 What are the necessary factors and policies to enable the implementation of these modified principles and goals?	5.1.1; 5.3.3
1.3 What are the social and institutional barriers to the implementation of adaptation change and how do we overcome them?	New
1.4 How should the existing Australian legal, policy and institutional architecture for land management and biodiversity conservation respond to changes in conservation goals and principles?	5.1.2
1.5 How can major socio-economic trends occurring in Australia contribute to effective adaptation responses?	5.2.4
2. Integrating conservation management and adaptation actions across diverse, multi-use, multi-scale landscapes to support ecosystem resilience and maximise positive biodiversity outcomes in a changing climate	5.3.4
2.1 What principles should guide ecosystem-based adaptation and the design of landscapes?	5.2.1
2.2 How should new protected areas be selected?	New
2.3 How can management of protected and non-protected areas incorporate and adapt to climate change?	5.3.3
2.4 How can Australia's land-based climate change mitigation initiatives be designed so they also enhance ecosystem services and resilience and deliver biodiversity conservation benefits?	5.2.3
2.5 What conceptual models and long-term observation systems are needed to support the design, analysis and assessment of active adaptive management and policy experiments?	5.1.3
3. Managing threats and stressors to maximise ecosystem resilience in a changing climate	
3.1 Which extreme events and aspects of their regime (frequency, magnitude, duration and the return period) are associated with the vulnerability of biodiversity and how can we adapt to minimise their impacts on natural ecosystems?	New
3.2 How will climate change interact with habitat change (loss, fragmentation & degradation) and what are the implications for managing ecosystem resilience?	5.2.2 New
3.3 How will climate change interact with fire and what are the implications for managing ecosystem resilience?	5.2.2; 5.3.2
3.4 How will climate change interact with invasive species and what are the implications for managing ecosystem resilience?	5.4.3
3.5 How will climate change interact with salinity and water availability and what are the implications for managing ecosystem resilience?	5 .2.2 New
3.6 How will climate change interact with emerging disease and what are the implications for managing ecosystem resilience?	5.2.2 New
3.7 How can we assess and quantify the relative impacts and their interactions/synergies of all stressors in a system in order to enable the most effective and balanced adaptation actions?	New
4. Managing biodiversity assets	
4.1 How do we identify species/communities that should be the focus of investment in climate change adaptation?	5.4.1
4.2 How will climate change affect current management actions for protecting priority species / communities and managing problem species, and what management changes will be required?	5.4.2; 5.3.3
4.3 How do we optimise the investment in adaptation actions aimed at protecting biodiversity assets?	5.3.1

[1] See table 2 with description of previous PRQs Terrestrial NARP (Kitching, et al., 2013).

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