ADAPTNRM

Helping Biodiversity Adapt:

Supporting climate adaptation planning using a community-level modelling approach

A GUIDE FOR USE WITH THE DATASETS AND MAPS

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Front Cover Image: Common tree snake (*Dendrelaphis punculatus*), Source: Peter Lowik

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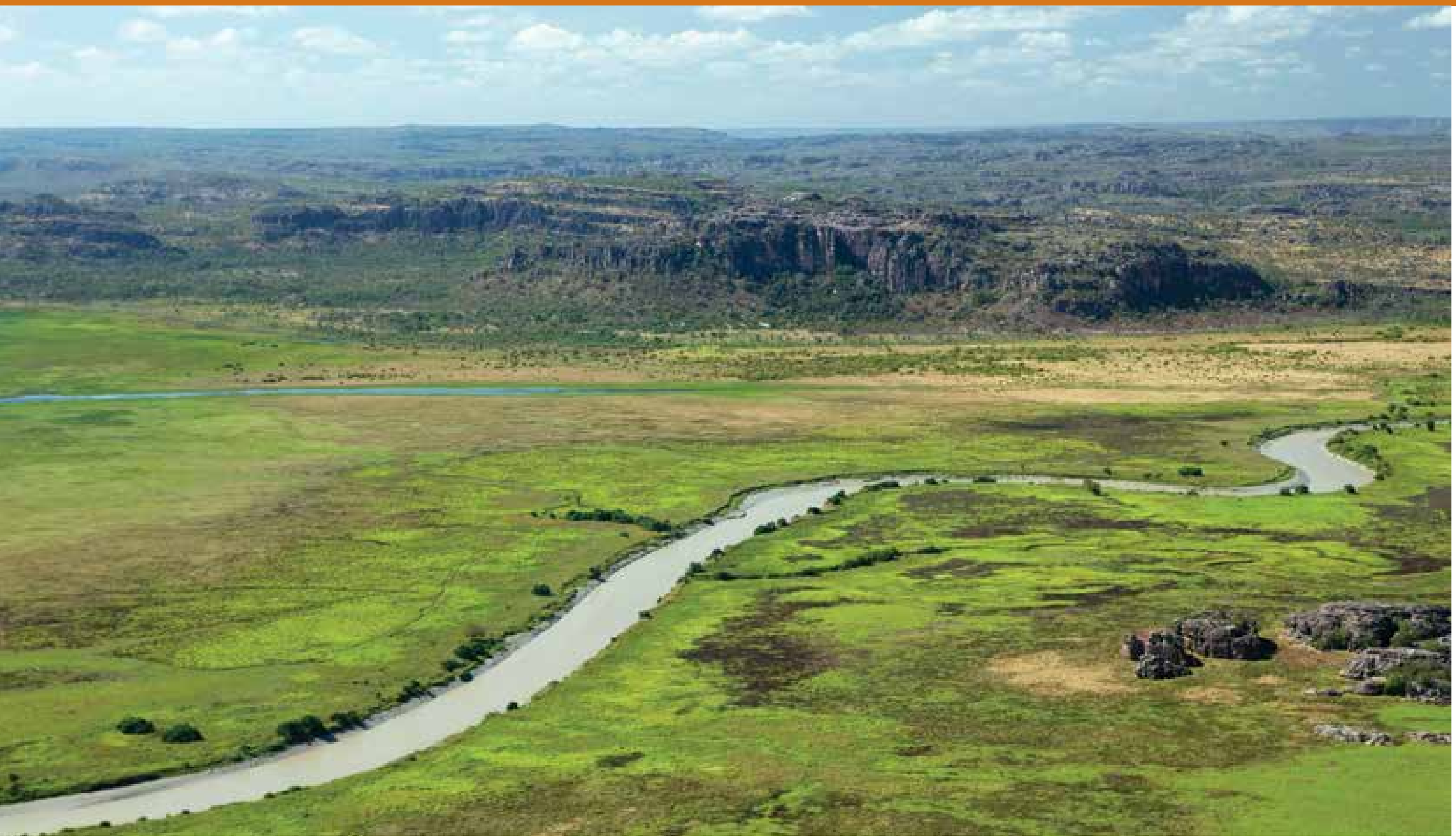
Example Boxes



Summary & Key Messages

Evidence over the last decade has shown that ecological change in response to climate change is likely to be unavoidable, widespread and substantial.

As a result, some of our approaches to biodiversity conservation may need to change – including not just the actions we take now but also the overarching goals of what we aim to achieve.

The scope of the challenge of adapting biodiversity management to account for climate change is shaped by the magnitude and extent of future climate change across Australian landscapes, and by the interactions between climate change and other processes that threaten or support the resilience of biodiversity. Given the likelihood of substantial ecological change, biodiversity managers, and indeed society in general, will want to consider new principles, goals and actions that acknowledge and facilitate change processes. In so doing people will be able to steer change toward more rather than less desirable futures for Australia's biodiversity.

It is in this context that we present the second part of the story bringing biodiversity and climate change into NRM planning. The first part, the AdaptNRM Guide ***Implications of Climate Change for Biodiversity*** and associated datasets and maps, feeds into the assessment phase of adaptation planning. It introduced a new way to view the magnitude, extent and type of changes in biodiversity.

This Guide, ***Helping Biodiversity Adapt***, supports the strategic and implementation phases of planning, including discussion of climate-ready goals for biodiversity conservation and potential options to achieve them.

Biodiversity in an adaptation planning framework

Biodiversity planning viewed through a climate adaptation lens may look quite different when compared with traditional approaches to the protection of assets, managing or eliminating threats, or even managing for the resilience of ecosystems as they appear today. All components of the general planning framework introduced in our first guide, ***The NRM Adaptation Checklist***, may need to be approached differently for biodiversity planning under climate change. Our focus in these Guides is on changes to assessment, strategic planning and implementation planning.

Figure Below.
The five components of planning through an adaptation lens.

Image Previous Page: Aerial shots over Kakadu National Park
Source: Michelle McAulay
Credit: © Department of the Environment

Assessment

will need to incorporate evaluation of potential change in biodiversity and the nature of the changes, including the consequences for community and stakeholder values and aspirations.

Strategic Planning

will need to consider that different types of changes in biodiversity may need different strategic approaches to manage, and that some current values and objectives may be impossible or impractical to maintain.

Implementation Planning

will need to consider a broad range of approaches, including new innovative actions which will need to be matched to the degree and nature of biodiversity change and may need to be adjusted over time.

IMPLICATIONS OF CLIMATE CHANGE FOR BIODIVERSITY (PREVIOUS MODULE) PROVIDES TOOLS TO ASSIST WITH ASSESSMENT AND AN INDICATION THAT DIFFERENT TYPES OF CHANGE MAY NEED DIFFERENT APPROACHES IN STRATEGIC PLANNING

HELPING BIODIVERSITY ADAPT (THIS MODULE) WILL PROVIDE GUIDANCE ON STRATEGIC PLANNING GIVEN THE NATURE OF BIODIVERSITY CHANGE, AND A TOOLKIT FOR CONSIDERING IMPLEMENTATION OPTIONS

From implications to adaptation

Implications of Climate Change for Biodiversity introduced a form of community-level modelling that considers the implications of climate change on all species simultaneously within a single integrated process. From this modelling, four specific measures were developed that each provide a different view of the magnitude and nature of likely change in biodiversity.

This next Guide, *Helping Biodiversity Adapt*, moves beyond the implications of climate change. This Guide introduces the need for new principles to underpin biodiversity conservation decisions in a changing climate, provides an Adaptation Toolbox to link new climate-ready principles with strategic goals and actions, and introduces several new measures for evaluating some of these potential actions to help biodiversity adapt to climate change.

New principles for biodiversity conservation

The biodiversity projections introduced in *Implications of Climate Change for Biodiversity* suggest biodiversity will experience a high pressure to change across Australia. Yet contemporary principles underpinning planning typically focus on preventing change by managing threatening processes or by restoring ecosystems towards a pre-European land use state. Therefore, we are now facing the challenge of transitioning from managing what is known to managing what might be, and new principles that acknowledge change and aim to guide it are required.

The need to establish explicit principles to guide biodiversity conservation in a changing climate is part of a conversation that natural resource managers, policy makers, and the broader Australian public are only just beginning to have. It is too soon to provide an established set of principles. Rather, this Guide aims to help progress this conversation, by offering some ideas to support planning now.

The ideas suggested in this Guide include:

Optimise ecological processes

Encouraging or actively managing things like genetic diversity, landscape connectivity, and hydrological processes to maintain the services we most value and help nature take its course.

Maintain the evolutionary character of the Australian biota

Valuing the uniqueness of Australia's national biological diversity and thus preventing establishment or dominance of non-Australian species; and maintaining evolutionary processes that will keep Australia unique.

Maintain the unique regional character in our biodiversity

Valuing the contribution each region makes to national biological diversity by drawing on regional species pools for conservation management actions and maintaining regionally unique evolutionary environments.

Minimise species loss nationally

Accepting that some species that characterise a region may be lost to that region, this principle promotes their support elsewhere in Australia in the future. It favours management actions that best complement a reserve network targeting a Comprehensive, Adequate and Representative (*CAR*) set of Australian environments, to accommodate the widest possible range of Australian species and ecosystems.

Promote cross-sectoral adaptation planning

Helping to ensure that adaptation in other sectors, like agriculture and urban development, does not inadvertently reduce the ability of biodiversity to adapt and persist.

Building on these new principles, we also suggest new strategic goals and implementation options that could align with them. Collectively, we refer to this set of options – including principles, strategic goals, and management or implementation approaches – as 'The Biodiversity Adaptation Toolbox'. The Toolbox begins to outline some options, and describes how they may be logically connected across levels of planning and action. It also suggests ways in which the measures developed in both *Implications of Climate Change for Biodiversity* and in this Guide can inform the implementation of these options.

Implementing new principles and strategic goals

To connect new principles and goals with actions in NRM, planners and managers may need more information about the nature of change, and guidance on where and when potential actions may be implemented to be most effective over the long term. To contribute to this, four new measures to inform the design and exploration of particular adaptation options are introduced in this Guide. These new measures have been derived from the ecological community-level models and concepts introduced in *Implications of Climate Change for Biodiversity*. This AdaptNRM Module includes this Guide (*Helping Biodiversity Adapt*), and a series of datasets and maps in poster format to support spatial planning. All these resources are downloadable from the *CSIRO Data Access Portal*. The focus of the Guide is to explain how to interpret and use this information. In this Guide, we:

1. Introduce new modelling/mapping for designing and exploring adaptation options for managing biodiversity under climate change developed by CSIRO.
2. Demonstrate the types of data, show how these can be viewed at national, regional and local scales, and explain their interpretation.
3. Provide examples of how this information can be used, with a particular focus on strategic planning and implementation phases in a way that links with climate-ready principles and strategic goals.

To demonstrate the potential for different outcomes for biodiversity, we use two CMIP5 climate models—the Model for Interdisciplinary Research on Climate produced by the Japanese research community (*MIROC5*) and the Canadian Earth System Model (*CanESM2*). For both models, we project ecological change by 2050 under the emissions scenario defined by a Representative Concentration Pathway (*RCP*) of 8.5 at a grid-cell resolution approximating 250m across Australia.

The CSIRO and Bureau of Meteorology *Climate Futures Framework* guided the process of choosing the two climate models. Both of the global climate models selected fall within the spectrum of 'Maximum Consensus' futures for Australia for the high emissions, RCP 8.5 scenario. They represent a relatively mild warming and a hotter climate future, respectively. For simplicity, we call them the high emissions' mild *MIROC5* and hot *CanESM2* climate scenarios.

Where appropriate, the community-level biodiversity models and measures of change consider four separate biological groups – vascular plants, mammals, reptiles and amphibians.

The following outlines some key messages and examples of how the information can be interpreted and used in planning.

Image Left: Bandy-bandy (*Vermicella annulata*)
Source: Peter Lowik

Projected distribution of vegetation types

- Measures of *projected distribution of vegetation types* provide a broad indication of the nature of potential changes in the distribution of Australian plant communities, represented mainly by vegetation structure or dominant species.
- Nationally, under both climate scenarios, vegetation patterns are projected to remain broadly recognizable across the continent in 2050 compared to baseline (1990) patterns. However, notable locational shifts south- or coast-ward are projected.
- At a regional level, substantial redistributions are possible, particularly when exploring specific vegetation types, for example at the boundary of eucalypt versus acacia dominated ecosystems.
- A focus on vegetation types can help support decision-making about which functional types of species to use in ecological restoration plantings, and whether to manage for the persistence of a vegetation type at a location or facilitate its transition to other types.

Revegetation benefit

- *Revegetation benefit* is an indicator of how many more contemporary local species across a landscape are likely to be sustained into the future as a result of revegetating cleared areas, for a given climate scenario.
- Broad spatial patterns of *revegetation benefit* for 2050 are similar across biological groups but the magnitude of the benefit that contemporary revegetation provides into the future tends to be higher for vascular plants.
- Comparing baseline *revegetation benefit* with future *revegetation benefit*, in combination with spatial information on the other benefits desired from restored habitats, can facilitate regional or local-scale prioritisation.

Need for assisted dispersal

- *Need for assisted dispersal* is an estimate of how far an organism might need to move from its current location to find an environment in the future that is ecologically similar to the environment it currently occupies. Greater *need for assisted dispersal* indicates greater potential need to actively move or translocate species.
- *Need for assisted dispersal* differs for the projected climate scenarios. The high emissions' *hot CanESM2* scenario suggests a much greater potential *need for assisted dispersal* across all biological groups than the high emissions' *mild MIROC5* scenario.
- Investigating *need for assisted dispersal* at the regional level helps identify locations requiring close monitoring for population decline and can trigger further investigation into suitable locations for translocation of potentially vulnerable species or ecological communities.

Refugial potential

- *Refugial potential* indicates how important a location may be as a habitat for species to retreat to, persist in, and potentially later expand from under climate change.
- At the national scale, areas with high *refugial potential* are more commonly found in areas of high topographic relief.
- Exploring *refugial potential* can help to identify priority areas for conservation efforts.

Mainstreaming biodiversity adaptation planning

Through the two biodiversity Guides and associated maps and datasets, we provide an integrated picture of how biodiversity might respond to climate change, ideas about new principles that we might need to develop in helping biodiversity adapt, and a toolbox of possible ways to maintain Australia's unique biological heritage.

By providing regionally and locally relevant information, as well as suggestions for how these new measures can be integrated with other information in real-world planning, we aim to support the mainstreaming of climate adaptation into biodiversity planning. Through these and previous AdaptNRM Guides, we hope to prompt continued discussion amongst NRM planners, decision-makers, and ultimately society, about the character of our biological heritage that we want to retain into the future. If planning can adapt, then even as species respond and local assemblages reform, we will still live in a world full of the richness and wonder of biodiversity and be sustained by the services it provides.

What to expect in this guide

SECTION 1

This Guide moves beyond the implications of climate change, to introduce new principles for biodiversity conservation and new measures for evaluating potential actions to help biodiversity adapt to climate change.

Image Below: View from Menglers Hill, Source: John Baker, Credit: ©Department of the Environment and John Baker

We build on the earlier ***Implications of Climate Change for Biodiversity***, which introduced the key concepts underpinning a series of new measures for estimating the potential response of biodiversity, as a whole, to climate change. These biodiversity projections and indices were developed using a form of community-level modelling that considers the implications of climate change on all species simultaneously within a single integrated process. This complements individual species models that have been more commonly used in natural resource management (NRM) planning.

In this Guide we introduce the need to adjust our approach to biodiversity conservation to account for a rapidly changing climate. Toward a national conversation, we outline some potential new principles and link them to new or revised strategic goals and potential implementation actions. We then describe a suite of new measures to assist with planning actions, all of which have been derived from the community-level models introduced in ***Implications of Climate Change for Biodiversity***.

This Guide is intended as a reference to explain the interpretation and use of the new measures we introduce. For immediate application, we provide accompanying datasets and maps for each measure that, along with the Guide, collectively constitute this AdaptNRM Module.

1.1 What this guide includes

This Guide, ***Helping Biodiversity Adapt***, comprises seven sections:

Section 2 offers a general discussion of the need for new principles to guide biodiversity conservation in a rapidly changing climate, and associated options for facilitating adaptation of biodiversity to climate change.

Sections 3 to 6 introduce four new measures that aim to inform the design or exploration of particular adaptation options.

- Section 3 describes measures of *projected distribution of vegetation types*. It provides an indication of how present-day vegetation may reorganise spatially with climate change.
- Section 4 outlines a *revegetation benefit* index, to suggest where revegetation actions may support the greatest diversity of species in a changing climate.
- Section 5 introduces an index describing the *need for assisted dispersal*, which estimates how far an organism might need to move, or be moved, to find potentially suitable habitat in the future.
- Section 6 describes a measure of *refugial potential*, to indicate how important a location may be as an ecological refugium through climate change, a place where surrounding species may need to retreat into.

THE FIRST PART OF THIS GUIDE

introduces the need for new principles for biodiversity conservation under climate change.

THIS MODULE

also provides new measures and datasets to help implement new principles and evaluate planning decisions to help biodiversity adapt to climate change.

THIS GUIDE

provides information and guidance for NRM planners wishing to use the datasets and maps of the new measures in their climate adaptation planning.

SIDEBARS

provide key messages from the main text and can be used as a quick reference throughout the Guide.

CASE STUDIES

are provided in Boxes to demonstrate a few ways in which regional groups could or are already considering new biodiversity principles, goals and implementation actions.

TECHNICAL NOTES

provide more detailed explanations and background information on the modelling approach.

Sections 3-6 are structured to provide a brief explanation of each measure and the methods we use to derive them. This is followed by example outputs that present a national overview for context and a regional case study to show in more detail how to interpret the ecological measures for local planning.

Section 7 draws together a summary of the information provided in this Guide and linkages with the earlier *Implications of Climate Change for Biodiversity*.

The emphasis of this Guide is on illustration through examples, to demonstrate how to explore, use and interpret the data in regional planning, and view the data at a range of relevant spatial scales. Suggestions for how the information might be used in planning are provided as case studies in Boxes.

For those interested in learning more about the methods, further explanation and background information is provided in a series of Technical Notes appended with this Guide. Points of referral are given in the main text. Expanded technical details are provided with each dataset series, downloaded from the *CSIRO Data Access Portal*.

BOX 1

Definitions of measures introduced in Implications of Climate Change for Biodiversity and Helping Biodiversity Adapt

For quick reference, definitions for these measures are reproduced below.

Projected ecological similarity:
In the context of climate change, projected ecological similarity measures how similar a single location is over two time periods in its composition. It is calculated between a baseline (e.g., 1990) and future climate scenario (e.g., 2050). Ecological similarity can vary from 0 (no species in common) to 1 (all species the same). This is the basic unit of measurement used for many of the datasets presented in *Implications of Climate Change for Biodiversity* and *Helping Biodiversity Adapt*.

Potential degree of ecological change:
The *potential degree of ecological change* is a direct measure of how much change in composition may occur. It is estimated from the calculation of projected ecological similarity at the same location between different points in time: the lower the similarity between a baseline and a future time, the greater the *potential degree of ecological change*.

Novel ecological environments:
Novel *ecological environments* are places where the future environment that arises is likely to have a species composition that is different from any ecological environment currently known on the continent, in units of projected ecological similarity.

Disappearing ecological environments:
Disappearing ecological environments are places where the species composition in its current form is unlikely to exist anywhere on the continent in the future, also measured in units of projected ecological similarity.

Change in effective area of similar ecological environments:
Change in effective area of similar ecological environments is the proportional extent (within a specified area) to which a particular habitat may have changed in its suitability and therefore reduced or increased capacity to support its original biodiversity. For example, this may occur due to climate change and/or land clearing patterns. If there is a reduction in the effective area of similar ecological environments, we expect a corresponding loss of original biodiversity, and vice versa.

Projected distribution of vegetation types:
Patterns of potential change in the distribution of Australian plant communities, represented mainly by vegetation structure or dominant species, are given as projected probabilities for each vegetation type. As vegetation changes, so do the ecosystems on which populations of plants and animals depend for their existence.

Revegetation benefit:
Revegetation benefit is a relative indicator of how many more contemporary local species are likely to be sustained across a landscape into the future by revegetating cleared areas. It highlights where revegetation using contemporary practice is potentially most beneficial in a changing climate.

Need for assisted dispersal:
The need for assisted dispersal estimates how far an organism might need to move from its current location to find an environment in the future that is ecologically similar to the environment it currently occupies. Greater need for assisted dispersal indicates greater potential need to actively move or translocate species.

Refugial potential:
Refugial potential indicates how important a location may be as a habitat for species to retreat to, persist in, and potentially later expand from under climate change.

1.2
National context, regional focus

CROSS-REGIONAL AND NATIONAL

views illustrate that data can be viewed at a variety of scales to support planning in a range of contexts.

The models underpinning the information presented here were assembled nationally to provide consistent information for cross-boundary planning. Relatively fine-grained source data in the modelling (approximately 250m resolution) captures local, topographic and other influences on biodiversity distribution.

The data and maps can be viewed nationally to provide broad context, or compared across groups of NRM regions to reveal more detail and cross-boundary contexts. Regionally, the data can be used to explore the more local details relevant to individual NRMs.

This Guide provides examples of using views at different scales. Individual regional groups can use the data supplied via the *CSIRO Data Access Portal* to display all the views relevant to their planning.

1.3
Climate projections, datasets and models

TO FACILITATE PLANNING

for multiple futures, we used two contrasting climate scenarios (a *mild MIROC5* and a *hot CanESM2*) to 2050 using the high emissions RCP 8.5 scenario.

To demonstrate the potential for different outcomes for biodiversity, two climate models used in *CMIP5* (the Coupled Model Intercomparison Project) were selected to project ecological change by 2050: the Model for Interdisciplinary Research on Climate produced by the Japanese research community (MIROC5) and the Canadian Earth System Model (CanESM2). These climate scenarios were summarised in a technical note in the AdaptNRM Guide *Implications of Climate Change for Biodiversity*. They represent a relatively mild and a hot climate future, respectively. For simplicity, we call these projections the high emissions *mild MIROC5* and *hot CanESM2* climate scenarios.

Both projections used the high emissions scenario defined by a Representative Concentration Pathway (RCP) of 8.5, which assumes a continuation of recent trends in greenhouse gas emissions. We chose to use the high emissions trajectory to demonstrate the potential outcome for biodiversity by 2050 in the absence of substantial progress in reducing global greenhouse gas emissions.

These are a small subset of the wide range of global climate models, time frames and emission scenarios supporting the Intergovernmental Panel of Climate Change (IPCC) *Fifth Assessment Report*. The CSIRO and Bureau of Meteorology's *Climate Futures Framework* guided the process of choosing the two climate models.

These two were chosen because nationally, they provide contrasting futures and both fall within the spectrum of 'Maximum Consensus' futures for Australia. These climate models are neither the most extreme nor mild for this emission scenario and vary in this respect regionally, across Australia.

Ecological similarity projections for four terrestrial groups of native species were used to demonstrate the key concepts and principles of the community-level modelling applied to climate change. These groups are:

FOUR BIOLOGICAL GROUPS

are modelled to demonstrate the new climate change measures where relevant.

Vascular plants
(ferns, gymnosperms and angiosperms)

Mammals

Reptiles

Amphibians

The biological data we used comprised location records for all relevant species within each biological group, as collated from herbaria and museums and other sources across Australia by the *Atlas of Living Australia*. The community-level modelling used best-available, high resolution, national environmental layers capturing spatial variation in the environment including soils, climate and landform. Details about this method are given in a technical note in the earlier Guide *Implications of Climate Change for Biodiversity*.

THE EARLIER ADAPTNRM GUIDE

Implications of Climate Change for Biodiversity, introduced the community-level modelling approach, the concept of ecological similarity and climate change projections used here.

The earlier Guide on implications for biodiversity also includes an introduction to the concept of projected ecological similarity, which is relevant to this Guide, and describes the four measures:

- *potential degree of ecological change*
- *disappearing ecological environments*
- *novel ecological environments*
- *change in effective area of similar ecological environments*

These concepts underpin some of the calculations used here and so are briefly summarised again in Box 1, along with the measures presented in this Guide.

1.4 Limitations of the modelling

Measures derived from projections of ecological similarity provide one of the few tools available for planners to envisage potential futures for biological communities under climate change. When carefully used in combination with other sources of information, they can help to inform climate adaptation planning.

MEASURES DERIVED

from projections of ecological similarity are tools for envisaging potential futures for biodiversity and, when used with other sources of information, can inform planning.

Nevertheless, models are always subject to limitations. The broad limitations of the data and models provided for use in this module were outlined in *Implications of Climate Change for Biodiversity*. These were:

- Different climate models and emission scenarios will produce different results and there is uncertainty as to which climate future will eventuate. Therefore it is sensible to cater for a range of climate futures.
- Future environments may be outside the range of the data used to fit the biodiversity model. Areas with a high degree of extrapolation into new environments for the two climate scenarios are shown in *Implications of Climate Change for Biodiversity*.
- The environmental coverage of the biological survey data is incomplete, which affects the accuracy of the biodiversity model. Environmental coverage for each biological group is shown in *Implications of Climate Change for Biodiversity*.
- The accuracy of models and projections is limited by the adequacy of environmental variables used to produce the models. As far as possible, the best available sources of spatially explicit environmental data, gridded at approximately 250m resolution, were used at the time the models were developed.
- The models don't account for factors such as time lags, the capacity of organisms to adapt to change, or their functional interactions with other organisms.

LIMITATIONS EXIST

for all types of models. The limitations of these community-level models should be kept in mind to make the best use of the information.

Biodiversity managers will also need to consider the interactions with other processes that threaten the resilience of biodiversity, including how future societies themselves shape the landscape in adapting to climate change. This means that the data provided here are best used in combination with other land use, biodiversity assessment and conservation planning tools and datasets.

More specific limitations of each index are discussed in the relevant sections.

THE MODELS

use fine-grained data (approximately 250m resolution) so they are applicable to local and regional planning

MAPS AND SPATIAL DATASETS

of the measures explained in this Guide can be accessed via the *CSIRO Data Access Portal*.

1.5
Maps and data provided with this AdaptNRM Module

The map series for most measures is provided at the national scale and for eight broad groupings of NRM regions. These maps are offered as a 'quick reference guide' to the extent and nature of projected change in biodiversity.

The nationally-consistent indices for adaptation planning are provided as a grid of raster cells (c.250m x 250m) that can be usefully applied at resolutions approximating a 1:500,000 to 1:1,000,000 topographic map of local to regional relevance.

For planning regions with the capacity to use geographic information systems (GIS), planners or technicians can download the datasets and view their local region, subset the data to match their planning boundaries if so desired, and variously classify, combine and colour the outputs to focus planning attention on potential local areas of interest.

For a list of the maps, datasets and supporting information available on the *CSIRO Data Access Portal*, see Technical Note 1.

1.6
Building knowledge

This Guide also serves as a reference for future applications, as we produce updated maps and datasets with a wider range of alternative climate futures, biological groups, or variants of the indices described here. Additional or revised models and variants of these indices will be made available through the *CSIRO Data Access Portal* as they are developed.

We hope that in working through this Guide, individual planners will develop a degree of familiarity with the datasets and the way they can be used to evaluate potential on-ground actions. Planners can then continue to build on the interpretations and uses over time.

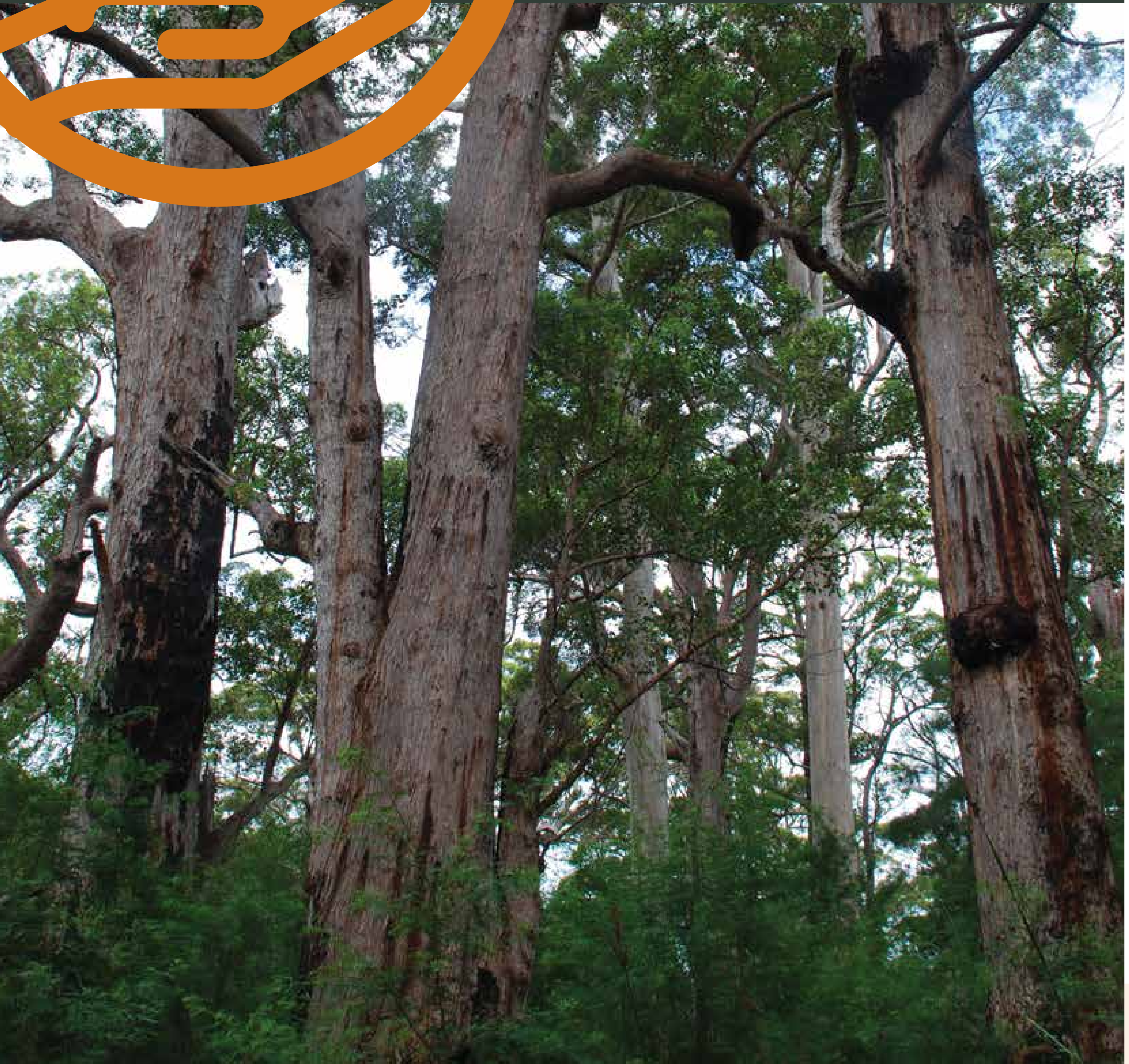
Image Right: Water quality monitoring (Blue Mountains City Council), Source: Greater Sydney Local Land Services, Credit: Esther Beaton.

Principles and approaches for helping biodiversity to adapt

SECTION 2

Given the inevitability of change in Australia's natural ecosystems as the climate continues to change, NRM planners and managers will need to reconsider their strategic goals for biodiversity conservation.

Image Below: Red Tingle (*Eucalyptus jacksonii*), Source: Grant Wardell-Johnson



This will mean applying new, as well as tried and tested, on-ground approaches to achieve these goals.

Establishing biodiversity conservation goals and making planning decisions becomes challenging once the line is crossed from managing what is known, to managing what might be. The AdaptNRM Guide ***The NRM Adaptation Checklist*** introduced four broad, overarching principles for planning that can help ensure management approaches meet the unique challenges of climate adaptation. These include:

- planning for multiple futures
- maintaining flexibility
- preparing for likely future decisions
- strengthening the adaptive capacity of people and organisations.

For biodiversity conservation specifically, contemporary principles underpinning planning typically focus on preventing ecological change by managing threatening processes or by restoring ecosystems towards a pre-European state. Just as new overarching frameworks for climate-ready planning are required, so too are new principles to guide biodiversity conservation. These would need to acknowledge change and provide guidance toward more rather than less desirable futures for Australia's unique species, ecosystems and landscapes.

The need to establish explicit principles to guide biodiversity conservation in a changing climate is part of a conversation that natural resource managers, policy makers, and the broader Australian population are only just beginning. It is therefore too soon to provide an established set of principles. Rather, this section aims to help progress this conversation, by offering some ideas to support planning now.

2.1 What this section covers

We begin by suggesting some new principles that could be adopted to guide biodiversity conservation under climate change. The list of principles that we provide is neither comprehensive nor are the proposed options mutually exclusive. They will need to be added to and refined over time, and combined in different ways. The aim is to stimulate new thinking and provide potential starting points for further discussion.

We then build on these new principles and suggest new strategic goals and implementation options that could align with them. Collectively, we refer to this set of options – including principles, strategic goals, and management or implementation approaches – as '**The Biodiversity Adaptation Toolbox**' (Section 2.3). The Toolbox begins to outline not just some options available, but how they may be logically connected across levels of planning and action; and how the measures developed in ***Implications of Climate Change for Biodiversity*** and later in this Guide can inform their implementation. Again, our intent is that this Toolbox will be improved and added to over time.

WE SUGGEST

several new principles that could underpin biodiversity conservation under climate change as a starting point for discussion.

WE ILLUSTRATE

how new principles could lead to new or revised strategic goals and implementation approaches in 'The Biodiversity Adaptation Toolbox'.

ADOPTION AND IMPLEMENTATION

of new principles will be an ongoing collaborative process. NRM planners could play a lead role.

Finally, we provide a series of diverse planning examples illustrating how the first steps in adopting new principles for biodiversity conservation are commencing across the country.

The challenge of adopting new biodiversity conservation principles should not be underestimated, as it involves many different decision-makers and consideration of the interactions between biodiversity and the social and economic contexts in which it is managed. Natural resource planners and the communities they work with will be in a particularly good position to contribute to this ongoing discussion. They can develop additional new principles to consider, learn from the day to day challenges of implementing new principles, and discover the barriers to implementation that may need to be addressed before effective climate adapted approaches can proceed.

PROJECTIONS SUGGEST

biodiversity will experience high pressure to change.

2.2 Towards new principles underlying biodiversity conservation[1]

THIS MEANS

biodiversity conservation can no longer be wholly centred on preserving or restoring species assemblages as we presently or historically know them.

The biodiversity projections introduced in ***Implications of Climate Change for Biodiversity*** suggest that biodiversity will experience a high pressure to change across many parts of the Australian continent. The high likelihood of change means that biodiversity conservation can no longer be centred wholly on preserving the contemporary assemblages of species at each location or restoring towards the composition of historical assemblages.

Instead, the ideas suggested here move towards a focus on managing processes (including the capacity of species and ecosystems for change), maintaining a unique regional and national character in our biodiversity, and minimising loss of native biodiversity at a national scale regardless of precisely where species may be found in the future. Some of these ideas are already being applied intuitively by natural resource managers (Box 2). They may necessitate planning across boundaries, which the tools and datasets provided in this AdaptNRM Module are designed to facilitate.

[1] Sources and further reading: Dunlop et al. (2012a); Hagerman & Satterfield (2014); Prober & Dunlop (2011); Steffen et al. (2009); Stein et al. (2013)

Optimise ecological processes

The first principle we propose is to be pragmatic: at a minimum, aim to maintain or optimise ecological processes. This is important not only to secure the benefits humans can obtain from the emerging ecosystems, but also to maximise opportunities for other species to survive. It means familiar species may be lost from familiar locations, while unfamiliar species may arrive and, in so doing, promote the maintenance of diverse ecological communities. Maintaining functioning natural ecosystems ensures they can continue to effectively capture and cycle limiting environmental resources (e.g., water and nutrients) and provide benefits to society through ecosystem services, including scenic or wild places for human enjoyment.

THE PRINCIPLE

to maintain ecological processes maximises the survival of species at that location, and provides benefits to society.

The principle of optimising ecological processes could initially favour a low-intervention approach to management: let nature take its course, but ensure conditions are optimal for species to adapt to their changing environments. An important element of this approach is to minimise human-induced ecosystem degradation that reduces natural resilience. This could include ensuring adequate landscape connectivity for species to move through (Box 3), restoring soil condition for optimal water infiltration, and maintaining genetic and trait diversity within species to provide the building blocks for change.

IN THIS APPROACH,

it is important to minimise human-induced degradation that reduces natural resilience.

Another key management action would focus on strategic monitoring to detect change. Where change is expected to be more extreme, this can be done in an adaptation pathways framework, with decision points to trigger more intensive interventions or facilitate ecosystem transitions. Decision points could include loss of a valued ecosystem service such as native trees that also serve as stock shelter (Box 4), or accelerated declines in ecosystem processes, such as soil erosion initiated by loss of ground cover. This concept of 'Adaptation Pathways' is explained in ***The NRM Adaptation Checklist***.

Maintain the evolutionary character of the Australian biota

While a shift towards ecological process-oriented goals is an important element of adapting to change, this principle alone is insufficient to ensure optimal outcomes for Australia's biodiversity. After all, ecological processes could potentially be fulfilled by species from other parts of the world, as indeed is reflected in the legacy of alien, now invasive, grasses such as Coolatai Grass (*Hyparrhenia hirta*) introduced early last century to curb soil erosion. If there is concern for which species constitute an ecological community, additional principles need to be established that target values beyond ecosystem processes.

AUSTRALIA'S UNIQUE

flora and fauna contribute to biological diversity at the global level.

To begin with, many Australians identify with the country's unique flora and fauna, and its uniqueness contributes to biological diversity at the global level. A new principle for biodiversity conservation that captures this value could thus be to *maintain the evolutionary character of the Australian biota.*

A NEW PRINCIPLE

capturing this value could be to maintain the evolutionary character of the Australian biota.

Approaches to management that apply this principle would therefore support an outcome of ecosystems re-assembling from Australian native species rather than species originating from outside Australia. This principle promotes increasing support for alien (i.e., exotic or non-native) species management, where 'alien' in a climate change context is defined as species alien to Australia's evolutionary history rather than alien at a regional or local scale. A framework for implementing this principle would need to consider the potential for Australian native species to become regionally invasive if they are translocated too far beyond their expanding range, as discussed below.

Similarly, towards maintaining the evolutionary character of the Australian biota, processes that have driven the evolution of our distinctive biota need to be recognised and maintained. These include grazing by marsupials rather than hoofed mammals (livestock) in some places, characteristic fire regimes (e.g., Box 5), and the evolutionary influences of low soil nutrient levels. For example, in fragmented agricultural landscapes of southern Australia, remnants that have escaped enrichment in nitrogen and phosphorus are significant both for the flora they conserve now, and for their potential under climate change to promote the assembly of a new, diverse mix of native rather than alien species.

Allowing opportunities for biodiversity to adapt unaided within large, intact natural areas can similarly promote the continued evolution and re-assembly of Australian biota, whilst also maintaining wilderness or related values.

Image Left: Red Tingle (*Eucalyptus jacksonii*) forest occurs in mesic refugia of Australia's south-west, and may not fare well in a drying climate. We need to recognise that some of our valued biota may no longer persist *in situ*, but we need not accept an 'anything goes' approach in their replacement. Source: Grant Wardell-Johnson

Image Above: *Livistona eastonii* (pictured) is a characteristic palm of the Mitchell Plateau in the Kimberley. Other *Livistona* species are restricted to the Arnhem Land (e.g. *Livistona humilis, L. inermis*) and Cape York regions (e.g. *L. concinna, L. muelleri*). The principle 'maintain unique regional character' aims to maintain distinctiveness among regions such as these. Source: Suzanne Prober

Maintain unique regional character

As well as continental endemics, Australia's diverse environments and biogeographic history have resulted in many regional endemics – species that reside in only one part of Australia and nowhere else. Within the broad bounds of maintaining the evolutionary character of the Australian biota, we thus propose a 'proximity principle': to favour community re-assembly by nearby rather than distant Australian species.

This principle aims to help regions with unique biological character remain unique even if the particular species and ecological communities at a location change (e.g. Box 4). It includes acting on the likelihood that a proportion of local species may be able to persist (indicated by the measure *potential degree of ecological change* in ***Implications of Climate Change for Biodiversity***), and that nearby species will better represent regional evolutionary character compared with distant species.

The principle also focuses management attention on maintaining regionally unique evolutionary environments, which may change in climate but are still likely to remain distinctive and hence contribute to diversity at the national level.

Maintaining regional character will be an especially important guide for restoration choices, for example it promotes selecting species for revegetation that will maintain the distinctiveness of the biodiversity hotspot of south-western Australia. Similarly, across Australia's north it would promote management options that help maintain the distinctive character of species and ecosystems among the Cape York, Arnhem Land and Kimberley regions.

MANY SPECIES

in Australia are endemic to specific regions.

THE PRINCIPLE

of maintaining unique regional character favours community re-assembly from species found nearby.

Image Above: Golden-tailed gecko (*Strophurus taenicauda*), Source: Peter Lowik

MINIMISING SPECIES LOSS

nationally will maximise genetic resources for adaptation and reduce the legacy of extinctions.

THIS PRINCIPLE

requires consideration of the full range of Australian ecological environments to accommodate a wide range of species.

Minimise species loss nationally

Another principle might simply be: to minimise the degree of native species loss at the national scale, in order to maximise genetic resources for adaptation and curtail the legacy of extinctions. This is best achieved by managing the full range of Australian ecological environments, including climate refugia, to accommodate the widest possible range of species. This principle provides a parallel to the concept of a Comprehensive, Adequate and Representative (*CAR*) reserve network. It requires the management and conservation of ecological environments through a range of mechanisms, including on- and off-reserve, so as to adequately represent all types of habitats. In this context, natural resource management may have a particular focus on areas that are under-represented by the formal reserve system.

This principle could also be met through assisted movements of species across target regions or across the continent. Such actions would need to be carefully weighed against the proximity principle and potential impacts of native species on ecological communities at recipient locations.

Promote cross-sectoral adaptation planning

In a changing climate, many aspects of a landscape are likely to undergo change, including flora, fauna, land use and human settlements. In these complex situations, it is easy for some actions, even if well-intended, to foreclose other important options or lead towards less desirable or unexpected futures. Such an action is increasingly referred to as a 'maladaptation'; i.e., 'an action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups'[2].

A further principle from a biodiversity conservation perspective would thus be: to promote cross-sectoral adaptation planning in order to minimise maladaptation. This is an overarching principle that involves avoiding undesirable futures by evaluating potential for a proposed action to foreclose future options, or shift impacts of climate change to other species, ecosystems, sectors or communities. It aims to ensure biodiversity is considered in decisions made in other sectors.

The latter is likely to include favouring land uses that promote positive rather than negative biodiversity outcomes, especially where production trade-offs are small. For example a shift from dryland cropping to low-input native pastures is likely to support more native biodiversity than a shift to high-input irrigated cropping or alien grass/legume-based pasture systems.

ACTIONS TAKEN

to respond to climate change that result in adverse impacts to other systems or sectors are referred to maladaptation.

THE PRINCIPLES

of promoting cross-sectoral adaptation planning aims to ensure biodiversity is considered in the decisions for other sectors.

2.3 The Biodiversity Adaptation Toolbox – options for putting new principles into practice

As new principles for managing biodiversity under climate change are developed, we envisage this will lead natural resource managers to develop a range of additional or revised strategic goals for biodiversity conservation, and associated new and creative ideas for on-ground implementation.

To help align new principles with new strategic goals and implementation options, we present **The Biodiversity Adaptation Toolbox** (Figure 1). We first suggest a suite of potential strategic goals that could be established to support the new principles discussed above, and support these with a suite of implementation options to achieve these goals.

Again, these options are intended to stimulate new thinking and provide starting points that could be used in planning now, illustrating how new principles can lead to the adoption of new or revised goals and approaches. We hope that NRM planners can draw on, add to or adjust this Toolbox according to their own goals, thus contributing to the ongoing discussion of how best to conserve and manage biodiversity into the future.

[2] Barnett. & O'Neill. (2013)

Image Below: Coastcare on Northern Beaches, Sydney
Source: Greater Sydney Local Land Services
Credit: Esther Beaton

Figure 1.
The Biodiversity Adaptation Toolbox, linking possible new principles underlying biodiversity conservation for a dynamic future with associated strategic goals and options for action. See main text and Table 1 for more details.

From new principles to strategic goals

Drawing from the previous discussion, the potential new or revised strategic goals described below address the new principles from a diversity of angles. Each goal can also simultaneously address more than one of the new principles, for example, 'Help nature take its course' simultaneously helps to 'Optimise ecological processes', 'Minimise species loss nationally', and 'Maintain regional and national evolutionary character'.

Help nature take its course

Target actions to increase natural resilience and adaptability; i.e., ensure that species and ecosystems can rely on their inbuilt strategies to respond to environmental change. This is particularly relevant to restoration to enhance resilience in highly fragmented and degraded landscapes.

Manage change in key ecosystem services

While allowing climate-driven ecological change to happen, ensure that key processes and functions are monitored and decision points are identified. This allows active choices to more intensively manage ecosystem services in order to maintain them, or to manage transitions in community reliance on these services.

Manage for diversity and monitor what works

Maintain or provide high diversity of habitats, microenvironments, species, and genes to increase the probability that some species will persist and continue to evolve and adapt to environmental change.

Promote re-assembly with native species

Ensure that if local native species disappear and are replaced, the new ecological community is still dominated by native species, with native defined broadly (i.e., native to Australia, not just by locality) or more narrowly (i.e., native to the broad region, again, not just by locality) depending on the underlying context.

Identify, manage, and protect refugia

Include priorities to manage areas where species are most likely to persist or retreat to in the landscape.

Use CAR principles to conserve environment types

Employ analyses based on Comprehensive, Adequate and Representative (CAR) principles to protect and manage the greatest range of Australian environments, to have the greatest chance of capturing the diversity of the biota into the future. The CAR principle, if well implemented, is recognised to be a robust strategy under climate change, meaning that it will continue to achieve its goals into the future, irrespective of change in the specific plants and animals that it supports. This goal includes a focus on managing areas that best complement gaps in the National Reserve System using CAR criteria.

Actively manage ecological processes

Manage specific processes to achieve desired outcomes as efficiently as possible. This can include managing natural ecological processes such as fire or dispersal, enhancing connectivity, or more interventionist approaches such as engineering water flows, or establishing or maintaining species that provide supporting habitat for a wide range of other species over time.

Intensively manage 'museums'

Where species or communities are so highly valued that change or loss is too much to accept, use intensive management to maintain them somewhere, even if in a very artificial state (e.g., captive populations, intensively managed reserves, wild zoos).

Encourage positive land use changes for biodiversity

Where land use transitions are necessary, favour those that have positive or neutral consequences for biodiversity, even if the land use is still predominantly focused on human needs. Aim for actions with multiple benefits.

Image Previous Page: Rangers, Land Managers and Traditional Owners meet at Moreton Telegraph Station on the Wenlock River in 2013 to discuss strategies for the Wenlock Catchment Management Group
Source: Lyndal Scobell
Credit: Cape York NRM

Image Right: Micro bat
Source: Peter Lowik

Practical implementation

A wide range of implementation options are potentially available to help achieve these strategic goals. Some of them are already commonplace in NRM planning and management, while others are unusual, creative or potentially confronting when first introduced (Table 1).

It is important that all ideas be considered and carefully weighed using a range of practical and ethical considerations, including potential multiple benefits. Developing adaptation pathways that map out potential decision points, actions and outcomes can provide a useful framework in which to consider alternative options, screen for potential maladaptations and establish decision points (e.g., Box 4). Viable actions can then be undertaken using an adaptive learning approach, by applying a number of different options and comparing the outcomes.

To make practical choices about which management options to employ now and which to consider for the future, it is helpful to consider the relative risk of each and the type of biodiversity responses they are most applicable to.

Here we have collated an 'options toolbox', elements of which can be selected for incorporation into overarching climate adaptation plans. Options are arranged in two tables broadly reflecting a gradient from low risk or preventative approaches, to options involving more risk and investment:

- **Table 1a:** 'No regrets' approaches, particularly restoring resilience or reducing non-climatic stressors. These form a baseline approach that is suitable now or for lesser degrees of change, but not necessarily adequate for high degrees of change;
- **Table 1b:** Higher risk or expensive options (with greater potential to be maladaptive). These might be reserved for high value targets as the pressure to change increases and decision points are reached.

Many of these options will need to be underpinned by an appropriate monitoring strategy for detecting change in valued ecosystem services and biodiversity. Further, the options toolbox is not intended to be comprehensive, rather it offers a potential starting point to which NRM planners and managers can add new ideas.

To conclude, managing biodiversity under climate change will largely be about facilitating nature's response. Change is inevitable, but it is possible to influence trajectories of change through strategic planning informed by new principles that recognise the inherent dynamism of our natural systems under climate change. Achieving the most desirable outcomes depends on identifying principles and goals that target the essence of what Australians value in their native biodiversity, and shaping implementation actions to address these. The case studies in this section (Boxes 2-5) highlight some of the ways in which this process is already beginning.

Image Left: Fire management at Girralang, facilitated by the Orange Local Aboriginal Land Council, NSW Central Tablelands Local Land Services, NSW Rural Fire Service, and Victor Steffensen, Source: Suzanne Prober

TABLE 1a

'No Regrets'

OPTIONS CAPITALIZING ON NATURAL RESILIENCE AND ADAPTABILITY

A toolbox of implementation options to achieve new or revised strategic goals: 'No-regrets' options capitalizing on natural resilience and adaptability. These options are likely to benefit biodiversity regardless of the degree of climate change, but may not go far enough under substantial change. Use *potential degree of ecological change* and/or *composite ecological change*[1] to identify areas with substantial change that may need additional approaches (Table 1b).

Help nature take its course *(Facilitate resilience and adaptability)*

ACTIONS	RESOURCES
MAINTAIN LARGE POPULATIONS Maintain or restore large population sizes, because larger populations generally have more capacity (genetic and otherwise) to respond to environmental change. Population sizes could be increased by allowing regeneration around small remnants, or increasing connectivity so multiple sub-populations function collectively like one larger population.	• Use *revegetation benefit* (Section 4) to also target areas that will minimise species loss nationally • Use fine-scale connectivity and/or metapopulation capacity models[2].
PROMOTE SPECIES-LEVEL GENETIC DIVERSITY IN PLANTINGS For revegetation, promote adaptive diversity by using seed sourced more widely across the species' climatic range, with emphasis in the direction of projected climates ('climate-adjusted provenancing'[3]). This option needs to be weighed against the usually small risk of outbreeding depression, and disruption of local adaptation to non-climatic factors.	• Use *projected distribution of vegetation types* (Section 3) to identify the ecological direction driven by projected climates. • Simulate trajectories of provenance shifts to inform climate ready restoration practice.
MANAGE AND RESTORE CONNECTIVITY TO SUPPORT MIGRATION AND RANGE SHIFTS In addition to maintaining large populations, connectivity will need to be increased or maintained to promote other movement-based ecological processes like migration and range shifts. This may involve using established approaches (e.g. restoring woody connectivity) or more novel options (e.g. enhancing connectivity of water sources or grassland environments).	• Use models of connectivity between similar ecological environments over time to support range shifts.
MINIMISE HUMAN-INDUCED NON-CLIMATIC STRESSORS Optimise ecosystem and landscape functioning in relation to interactions with human-induced (non-climatic) pressures, to maximise persistence of local or regional biodiversity. Options include restoring compromised soil-water relations, reducing ongoing pressure from livestock or feral grazing, managing alien diseases, plants and animals, reversing effects of fragmentation habitat loss through revegetation, and managing soil nutrient levels.	• Use *change in area of similar ecological environments*[1] with clearing to prioritise areas with high interaction between climate and non-climate stressors.
MONITOR AND ACCEPT CHANGE If natural ecosystems are adapting adequately to maintain ecosystem processes and diverse native communities, intervention may not be desirable. A key action could involve building capacity among stakeholders and the broader community for understanding and accepting some degree of change in biodiversity.	• Use *disappearing and novel ecological environments*[1] and *projected distribution of vegetation types* (Section 3) to engage with stakeholders about the need to expect change.

Manage change in key ecosystem services

ACTIONS	RESOURCES
IDENTIFY AND MANAGE ECOSYSTEM SERVICES This could be done within an adaptation pathways framework, incorporating decision points, such as loss of key ecosystem services, to trigger management responses (Box 4). Management responses could include replacing the service using alternative species, managing intensively for a key process (see Table 1b), or managing transitions towards lower reliance on these services.	• Use *projected distribution of vegetation types* (Section 3) to identify areas vegetation types may change. • Use *potential degree of ecological change*[1] and *disappearing and novel ecological environments* to identify areas with high pressure to change.

Promote re-assembly with native species

ACTIONS	RESOURCES
MANAGE NATIONALLY ALIEN SPECIES Prioritise managing potential transformer or displacer aliens suited to projected future climates, and manage at site to regional scales, to allow native species and associated processes to dominate in the assembly of new ecological communities.	• Use *projected distribution of vegetation types* (Section 3); and *novel ecological environments*[1] to identify places where new communities are particularly likely to assemble. • Use *Weeds and Climate Change* to guide managing transformer species.
CONTINUE TO INCLUDE 'LOCAL SPECIES' IN PLANTINGS, AS SOME MIGHT SURVIVE At ecological similarities of >0, some species are projected to persist. Others will have wider tolerances than indicated by the current environments they live in. Don't give up on local or regional native species prematurely.	• Use *potential degree of ecological change*[1] and *projected distribution of vegetation types* (Section 3) to identify areas with lower levels of change where local species may persist.
INTRODUCE NON-LOCAL NATIVE SPECIES USING THE PROXIMITY PRINCIPLE Introducing non-local species risks displacing local species, but may be needed to maintain valued ecosystem services (e.g. Box 4), or ensure plantings are viable. Sourcing species from as close by as feasible within expected climatic limitations will help maintain regional character. This is similar to assisted dispersal (see Table1b) but focuses on conserving processes instead of species. We include this option in both Table 1a and 1b because it may be lower or greater risk depending on context.	• Use *potential degree of ecological change*[1] and *projected distribution of vegetation types* (Section 3) to identify areas with high projected change where non-local species are more likely to be needed.

TABLE 1a (CONTINUED)

Identify, manage, and protect refugia

ACTIONS	RESOURCES
IDENTIFY, MANAGE AND PROTECT REFUGIA Prioritise biodiversity conservation and management in places where existing native species are most likely to persist and/or retreat to under future climates. These could be identified nationally and regionally.	• Use *refugial potential* (Section 6) to identify regional refugia. • Use *projected distribution of vegetation types* (Section 3) or *potential degree of ecological change*[1] to identify where little change is expected.

Manage for diversity and monitor what works

ACTIONS	RESOURCES
PROMOTE RESILIENCE THROUGH DIVERSITY Manage for diversity in natural ecosystems (e.g., by maintaining appropriate disturbance regimes) and incorporate a high diversity of locally or regionally native species into revegetation. This will increase the probability that enough species will persist to maintain ecosystem functions.	• Use *potential degree of ecological change*[1] to identify areas with greater projected change.

Use 'CAR' principles to conserve environment types

ACTIONS	RESOURCES
USE COMPREHENSIVE, ADEQUATE AND REPRESENTATIVE (*CAR*) PRINCIPLES TO PROTECT THE FULL RANGE OF CHARACTERISTIC AUSTRALIAN ENVIRONMENTS Identify areas that represent critical gaps in the National Reserve System as potential priorities for management and/or revegetation. This will help ensure the maximum diversity and optimal extents of environments are available in the future to accommodate today's biota.	• Use analyses of biodiversity representativeness over time. • Use *revegetation benefit* (Section 4) to target areas that will minimise species loss nationally based on trying to maintain the full range of current environments as much as possible.

Encourage positive land use changes for biodiversity

ACTIONS	RESOURCES
FAVOUR LAND USE CHANGES WITH POSITIVE RATHER THAN NEGATIVE BIODIVERSITY OUTCOMES This is likely to favour low-input agricultural systems (e.g., carbon plantings, native pastures or sandalwood plantations) rather than intensive agriculture, to maintain options for native biota and associated ecosystem services.	• Use *change in area of similar ecological environments with clearing* to identify areas where land use change may make the most difference for biodiversity.

TABLE 1b

'Intensive Options'

RELEVANT TO MORE EXTREME CHANGE

A toolbox of implementation options to achieve new or revised strategic goals: 'Intensive options' relevant to more substantial change. These may be expensive and/or higher risk, but may be desirable to meet specified goals.

Actively manage ecological processes

ACTIONS	RESOURCES
ASSISTED DISPERSAL Actively facilitate movement of species to projected suitable habitat. Risks to local species and processes in the recipient environment need to be assessed	• Use *need for assisted dispersal* (Section 5) to identify where assisted dispersal may be needed to reach suitable habitat.
MORE INTENSIVELY MANAGE FIRE REGIMES AT SITE AND LANDSCAPE SCALES TO FAVOUR DESIRED TRAJECTORIES Fire management can sometimes be used as a tool to maintain elements of present-day communities. This includes application of fire to promote grassy rather than shrubby understoreys in eucalypt woodlands (see Section 3.3), or control of fire to limit loss of fire-sensitive ecosystems. Decision points might include the manageability of wildfire and concerns around loss of ecosystem functions or declining taxa.	• Use *potential degree of ecological change*[1] and/or *Projected distribution of vegetation types* (Section 3) to identify areas where change is substantial enough that fire regimes may be quite different than at present.
CONSIDER LANDSCAPE ENGINEERING SOLUTIONS Solutions that involve engineering of coastlines or topography to influence water incursions or flows are likely to be expensive and controversial. Nevertheless there may be instances where they are cheaper to implement (e.g., in association with mining restoration). For example, hydrological engineering to create run-on zones might be used to protect a highly-valued species or community from drought or maintain patches of vegetation in aridifying landscapes.	• Use *potential degree of ecological change*[1] and/or *projected distribution of vegetation types* (Section 3) or *refugial potential* (Section 6) to identify areas where such intensive solutions may be required.
INTENSIVELY MANAGE NATURAL PRESSURES TO HELP CONSERVE HIGHLY VALUED SPECIES OR ECOLOGICAL COMMUNITIES Managing natural pressures, such as natural diseases or competitors, could help target species or communities survive climate stress. For example, reducing natural parasite infestations in chicks of a rare Tasmanian albatross is compensating for reductions in breeding success due to the warming climate[6].	• Use *potential degree of ecological change*[1] to identify areas where such intensive solutions may be required.

Promote re-assembly with native species

ACTIONS	RESOURCES
INTRODUCE NON-LOCAL NATIVE SPECIES USING THE PROXIMITY PRINCIPLE Introducing non-local species risks displacing local species that may otherwise persist, but may be needed to maintain valued ecosystem services (e.g. Box 4), or ensure plantings are viable. Sourcing species from as close by as feasible within expected climatic limitations will help maintain regional character. This is similar to assisted dispersal but focuses on conserving processes instead of species. We include this option in both Table 1a and 1b because it may be lower or greater risk depending on context.	• Use *potential degree of ecological change*[1] and *projected distribution of vegetation types* (Section 3) to identify areas where non-local species are more likely to be needed.

Intensively manage 'museums'

ACTIONS	RESOURCES
MAINTAIN EX SITU POPULATIONS AND BREEDING PROGRAMS FOR ICONIC SPECIES Species that may have no or very little suitable habitat left in the future may need to be maintained as purely captive populations if their continued existence is deemed important enough.	• Use *disappearing ecological environments*[1] to identify areas where iconic species are at risk of being lost *in situ*.
CREATE RESERVES WITH HARD BOUNDARIES AND INTENSIVELY MANAGE WITHIN THEM Ecological environments likely to disappear could potentially be maintained as 'living museums' or 'wild zoos', though methods to do so may not be readily available. An example could be preserving alpine grasslands using fire or slashing to control invading trees.	• Use *disappearing ecological environments*[1] to identify areas where iconic species are at risk of being lost *in situ*.

[1] AdaptNRM Module *Implications of Climate Change for Biodiversity*
[2] Drielsma & Ferrier (2009)
[3] Prober et al. (2015)
[4] Drielsma et al. (2014) *Biodiversity Management under Future Climate Change*
[5] Ferrier et al. (2012b)
[6] Alderman & Hobday (in review)

Image Below: Mary River turtle (*Elusor macrurus*), Source: © Stewart Macdonald / Ug Media

BOX 2

Integrating new principles into resilience planning in the Goulburn Broken

The Goulburn Broken Catchment Management Authority (GBCMA) in Victoria is commencing an update of its Biodiversity Strategy, so this is an ideal time to consider how the CMA might begin incorporating new principles for biodiversity conservation under climate change. The precise way they do this will depend on diverse input, stakeholder engagement, and resources available, but initial conversations with Kate Brunt and Carla Miles of GBCMA suggest the following possibility:

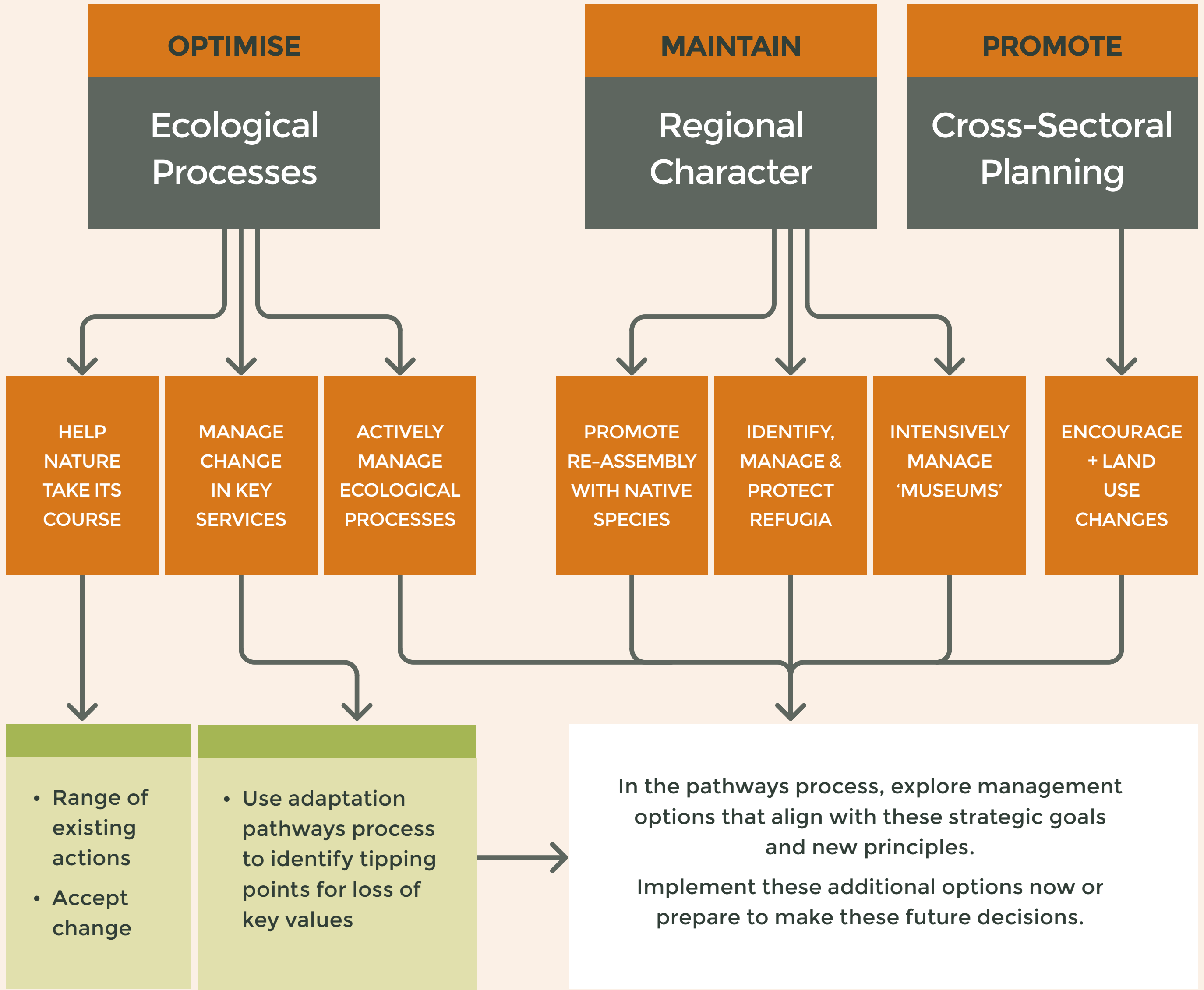
As the GBCMA has a Regional Catchment Strategy (RCS) currently in place until 2019, it makes sense to consider which of the potential new principles are most reflected already in the language and approaches used in the RCS and the existing Biodiversity Strategy. The RCS was developed using a resilience planning approach with a focus on system dynamics and tipping points. There is an emphasis on ecological processes in both documents, suggesting that the CMA have in essence already adopted the principle 'Optimise ecological processes' – particularly the strategic goal of 'Help nature take its course' through strategic initiatives and actions like biolinks (connectivity) projects and supporting local/ landscape-scale implementation plans.

The CMA also divided their catchment into social-ecological systems (SES) where different land uses, ecosystems, and histories of human engagement mean that different assets are valued. This suggests that regional character (even sub-regional character) is valued, and thus the principle of 'Maintain regional character' already has a foundation in the Goulburn Broken. Finally, both the RCS and the existing Biodiversity Strategy focus on capturing opportunities for biodiversity associated with land use change for other reasons, revealing that the building blocks to adopt the principle 'Promote cross-sectoral adaptation planning' are already in place.

These three new principles ('Optimise ecological processes', 'Maintain regional character', and 'Promote cross-sectoral adaptation planning') could then be incorporated into a revised vision statement for the GBCMA's Biodiversity Strategy. The current vision focuses on healthy ecosystems and viable populations. But one that acknowledges the pressure to change under climate change and embraces new principles could read something like this: 'Ecosystems and landscapes that may change over time but where key processes, services and values are maintained. Also, our region and its sub-catchments maintain a unique sense of identity, and land uses change to adapt to global pressures without harming the capacity of biodiversity to similarly adapt and change.'

Some existing strategic goals in the GBCMA's Biodiversity Strategy ('outcomes') and implementation approaches ('strategic initiatives')

Image Below: A meeting of community and industry representatives discussing the climate change vulnerability assessment and adaptation prioritisation process GBCMA undertook as a part of the Regional NRM Planning for Climate Change project, Source: Melanie Haddow, Credit: GBCMA



align with this vision and could continue under a more climate-adapted strategy. But one key goal to consider explicitly introducing may be 'Maintain key services'. Aligned with a systems planning approach with a focus on tipping points, the GBCMA could identify the services or values most important in the catchment and then undertake an adaptation pathways planning process to identify tipping points beyond which those values or services would be lost (see *The NRM Adaptation Checklist* for more on adaptation pathways).

The GBCMA is in fact currently implementing an Adaptation Pathways planning process in one SES. The Biodiversity Strategy update could apply learnings from this process to explore alternative strategic goals and implementation options beyond those tipping points across the whole region. The possibilities to consider would be drawn from the set of goals and implementation options that are aligned with the new principles they choose to adopt. Focusing on the vision and new principles thus helps to readily identify a suite of options to consider and can ensure consistency across all the different services/values, thus further minimising the risk of mal-adaptation. The figure above thus illustrates what the set of new principles and potential strategic goals might look like for GBCMA. It is a subset of Figure 1 in the main text, showing how new principles, goals and actions could be tailored to each region's preferred approach. For GBCMA, it shows the new principles highlighted above, along with the implementation approaches that would be used now, with others planned for the future through the pathways process.

BOX 3

Managing and restoring connectivity to optimise multiple processes

Managing and restoring ecological connectivity is possibly the most frequently adopted approach for biodiversity adaptation under climate change to date. However, confusion can arise because there are often many different analyses and recommendations. Recognising the way these are aligned to different strategic goals and ultimately the new principles for biodiversity can help reduce the confusion and make the most of connectivity initiatives. For example, Jason MacKenzie from the ACT Environment and Planning Directorate (ACT EPD) has three different connectivity analyses to draw on for the region. But each of them addresses a different ecological process that depends on landscape connectivity and could help nature respond naturally to climate-driven environmental change. All three could be used in concert to achieve the goal of 'Help nature take its course' under the principle of 'Optimise ecological processes'.

1. Connectivity to support adaptive processes of large populations:
Traditionally, fine-scale connectivity has been restored to facilitate dispersal in fragmented landscapes and allow multiple smaller populations to function as one larger population (a meta-population). Larger populations have greater genetic, phenotypic, and behavioural diversity, suggesting larger populations also have greater capacity to respond and adapt to climate change. Thus, fine-scale, local connectivity can also be used to foster the natural adaptive capacity of species through creating larger functional populations. ACT EPD has a fine-scale model[1] showing where connectivity is likely to exist (and thus require protection) and not exist (and thus require replanting) based on a synthesis of empirical research on connectivity for woodland and forest birds and mammals[2].

2. Connectivity to support migration processes:
Multiple migratory birds often share the same migratory pathways. Thus, even though the actual species migrating may change over time under climate change, management to support general migratory pathways can help ensure the key process of migration continues. An analysis by Birds Australia suggests that the ACT is part of a key flyway for migratory woodland and forest birds in southeast Australia so maintaining stop-over habitat in the ACT could contribute to migratory connectivity, even under climate change.

3. Connectivity to support range shifts:
Connectivity for climate change is often only considered in the context of supporting dispersal movements that will allow species to shift their ranges to new areas of suitable habitat. An analysis of potential paths connecting similar ecological environments between current and future time periods[3] shows that the southern part of the ACT will serve a critical role in providing this type of climate change corridor. It also shows that links eastward through the north of the ACT and then northward into NSW may serve as pathways for potential range shifts.

Putting them together in one 'connectivity strategy':
ACT EPD can use connectivity management and restoration as a way to support all of these processes at once, often in the same places. By building fine-scale connectivity to connect woodland and forest remnants, but doing so particularly east-west across the north of the ACT and extending northward into the 'Greater Goorooyarroo' area in NSW, larger populations and range shifts are likely to be supported. Ensuring that some larger habitat areas are part of these 'corridors' also provides for migration stop-over points for woodland birds.

[1] Barnett. & Love (2012), [2] Doerr et al. (2010), [3] Drielsma et al. (2014)

Image Below: Molonglo River corridor – restoration to widen the corridor is a centrepiece of the ACT Government's connectivity initiative, Source: ACT Government, Credit: Brett Howland

BOX 4

A decision point triggers actions to maintain key services on the Monaro Tablelands[1]

In areas where effects of climate change are expected to be pronounced, decision points can be established to guide when adaptation interventions need to be considered. Principles for biodiversity conservation under climate change can then be used to guide which (or whether) actions will be taken.

The Monaro region on the NSW Southern Tablelands supports extensive areas of grassland interspersed with mosaics of mature *Eucalyptus viminalis* trees. These trees are important to graziers for stock shelter and shape the distinctive scenery of the region – key services that are valued by residents of the Monaro.

In recent years many of the mature trees have begun to die. The deaths have been linked to an outbreak of the eucalyptus weevil (*Gonipterus sp.*), but the ultimate cause of the weevil outbreaks and hence the dieback is not known. The region's climate has undergone warming and drying over several decades and *Eucalyptus viminalis* is also at the fringe of its range in the harsh Monaro climate. It is thought that recent changes in climate are pushing the species beyond a critical threshold.

The widespread deaths of *Eucalyptus viminalis* provide evidence that key services are being lost, triggering a decision point for local Landcare groups to explore whether and how more intensive management should occur.

A range of potential futures need to be considered and decisions made regarding on-ground actions. Decisions can be guided by the new principles suggested in this section, as illustrated in the following steps already being considered by local communities:

1. 'Optimise ecological processes':
Rather than accepting a transition to grassland, with consequent loss of fauna habitat, stock shelter and scenic values, dieback areas could be replanted with other species that are likely to provide similar services. Dead trees are best retained as interim habitat, and planting a diversity of species will optimise likelihood of success in an uncertain future.

2. 'Maintain the evolutionary character of the Australian biota':
Under this principle, replanting would avoid the alien tree *Pinus radiata*, which is widely used as a wind shelter on the Monaro already, in favour of other species of Australian *Eucalyptus*.

3. 'Maintain unique regional character':
Under this principle, replanting would focus on eucalypts from as close by as possible, including variants of *E. viminalis* that are estimated to have the potential to persist in current and projected future climates.

Reflecting on the principles underlying the replanting options can provide greater clarity about the choices and help to ensure consistency with other adaptation actions in the region. A clear monitoring approach is also needed for adaptive learning over time.

[1] Drawn from Ross (2013)

Image Below: A typical vista of dead trees in the Monaro, Source: Tim the Yowie Man

BOX 5

Managing characteristic processes to maintain evolutionary character

As the species composition of plant communities changes with the climate, it will be possible to influence trajectories of change towards maintaining important values such as the distinctive evolutionary character of the Australian biota. One way to facilitate this is to help maintain the drivers of this evolutionary character, such as aspects of fire regime.

Australia is a fire-prone continent and its flora has adapted to this in different ways. One of the most familiar responses of Australian vegetation to fire is that of 'fire-resilient' communities such as most eucalypt forests and native grasslands – these have the ability to bounce back quickly after fire by re-sprouting.

A less-well known but surprisingly common alternative strategy is that of 'fire-resistance' – avoiding fire by developing characteristics that make the vegetation difficult to burn. These characteristics can include low flammability leaves and bark (e.g. succulent saltbushes), and sparse or discontinuous distribution of flammable fuels[1].

This strategy is characteristic of iconic Australian communities such as the Mulga (*Acacia aneura sens. lat.*) woodlands across inland Australia, fire sensitive eucalypt woodlands of the south-west, chenopod shrublands prominent on the Nullarbor, and native pine (*Callitris spp.*) communities in northern and southern Australia, and creates diversity in fire-prone landscapes. The dominants of these communities are easily killed by fire and typically regenerate slowly from seed. If the fire frequency is too high, these communities transform to fire-resilient communities such as grasslands.

Many of these fire-resistant communities are currently or potentially threatened with invasion by highly flammable alien grasses such as Buffel grass (*Cenchrus ciliaris*; see **Weeds and Climate Change**). With increasing summer rain and increasing temperatures in the south especially, such species have the potential to spread widely through characteristically fire-resistant communities, potentially transforming them to highly flammable, fire-resilient grasslands.

Intensive monitoring and management to prevent incursion or spread of Buffel grass from areas where it is not yet present or common, or intensive management to exclude it from valued places, is an option to help maintain the evolutionary character of Australia's fire-resistant communities, even if the particular species constituting those communities changes with the climate.

[1] e.g. Prober et al. (2012c)

Image Below: An example of potential transformation of a fire-resistant (Mulga) woodland to a grassland resulting from Buffel grass invasion. Buffel grass is expected to increase its south- and coast-ward range under climate change. Preventing expansion into new areas could help maintain the diversity of fire responses in the Australian vegetation. Dotted lines indicate transitions that are difficult to reverse. Source: (left to right): Suzanne Prober; Invasive weeds, Colin G. Wilson © Colin G. Wilson and the Department of the Environment; Christine Schlesinger.

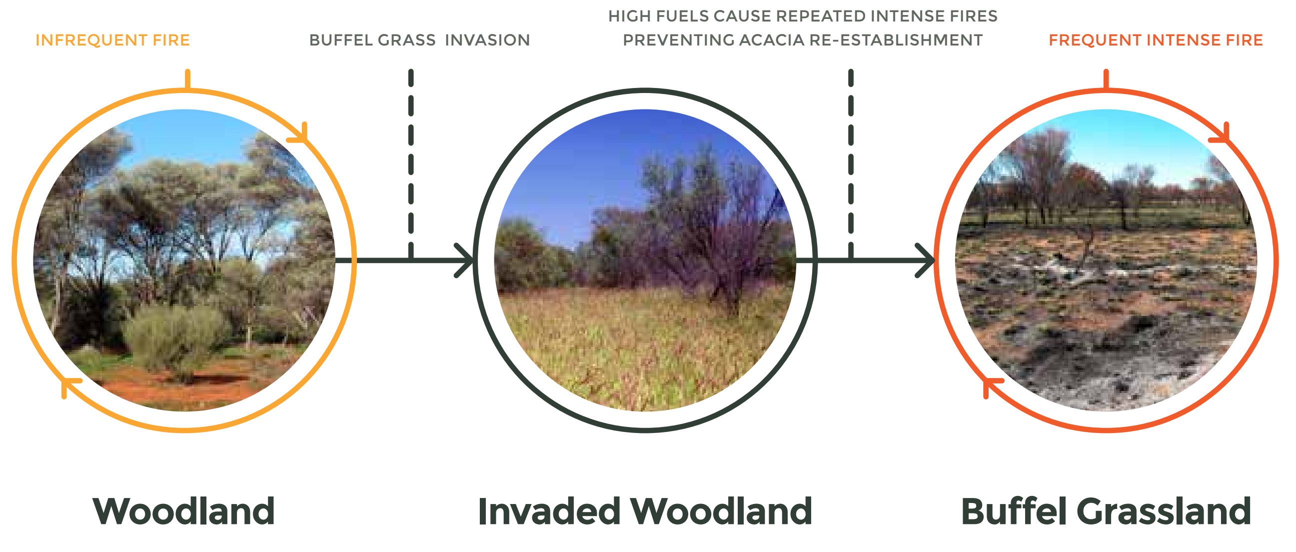
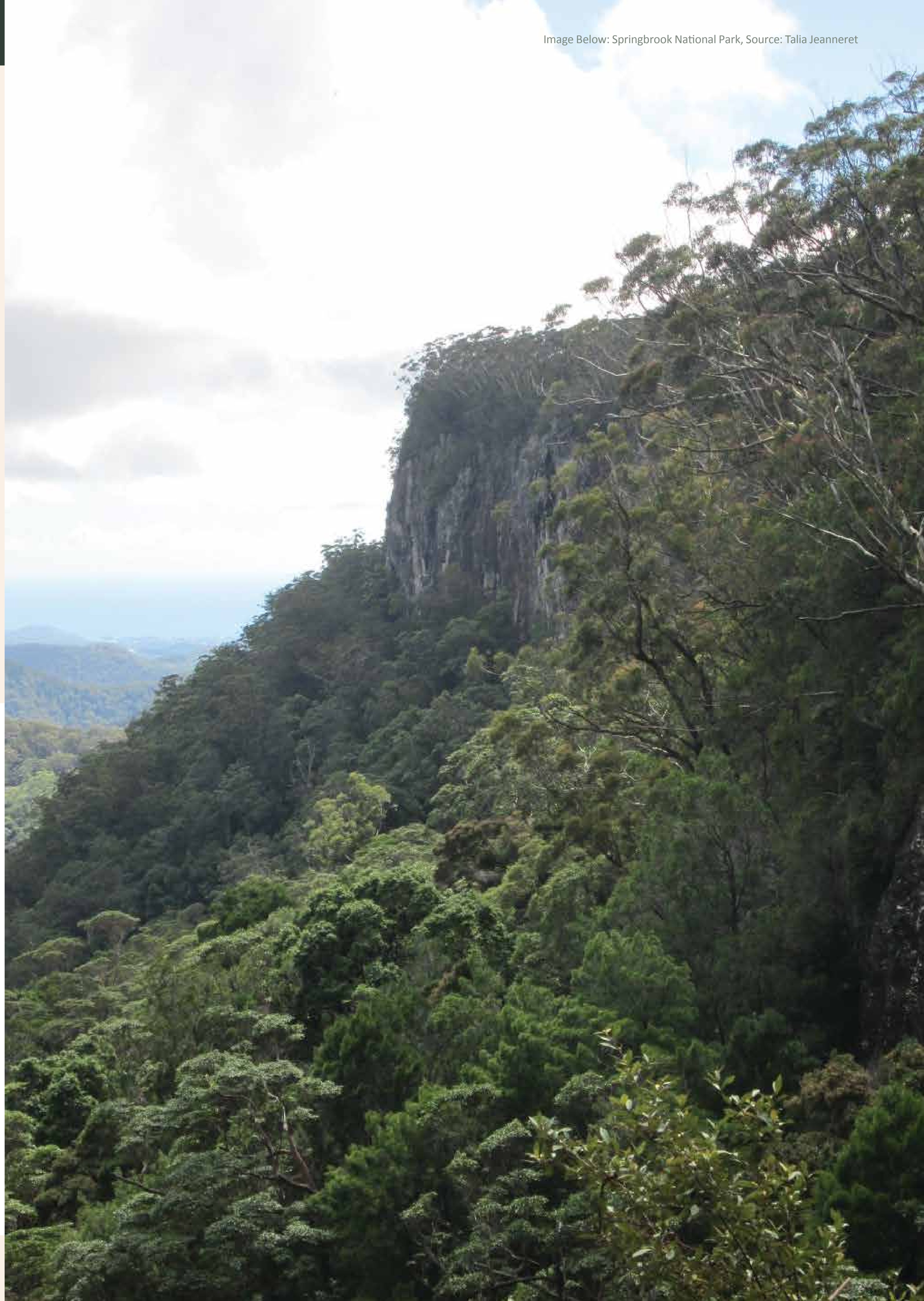


Image Below: Springbrook National Park, Source: Talia Jeanneret



Projected distribution of vegetation types

SECTION 3

In this section we view the potential outcomes of climate change through the projected distribution of native vegetation types across Australia.

Image Below: Rainforest trees
Source: © Stewart Macdonald / Ug Media

This view, which we call *projected distribution of vegetation types*, provides an indication of the nature of potential changes in plant communities, including vegetation structure (e.g., grassland vs woodland) or dominant species (e.g., acacia vs eucalypt woodlands or chenopod shrubland vs grassland).

A focus on vegetation type can provide insights for informing adaptation responses. For example, management of vegetation structure can be tailored to favour birds or mammals that depend on structural elements such as trees or shrubs. It can also inform the broad functional types of species (e.g., rainforest vs sclerophyllous) to use in ecological restoration plantings where historically-occurring species appear unlikely to persist in the long term (i.e., low projected *ecological similarity*). Such actions would be guided by principles such as 'Maintain the evolutionary character of the Australian biota' at regional and national scales

THE MEASURE

of *projected distribution of vegetation types* provides an indication of future locations of plant communities.

THIS MEASURE

can inform adaptation decisions about the management of vegetation structure, and species used in ecological restoration.

3.1 Estimating projected distribution of vegetation types

Our approach to estimating *projected distribution of vegetation types* uses the *ecological similarity* model developed for vascular plants (see *Implications of Climate Change for Biodiversity*). An existing vegetation map is linked to the baseline ecological environments derived from this model to predict the distribution of each vegetation type (Technical Note 2). Distributions are then projected using climate scenarios.

The established vegetation classification used for our analysis is the Major Vegetation Sub-group level of Australia's National Vegetation Information System (NVIS) database, managed by the Australian Department of the Environment in partnership with State agencies. This classification delineates 77 vegetation types based on major structural and floristic characteristics as extant prior to European settlement (see legend in Figure 2).

TO ESTIMATE

projected distribution of vegetation types we use the ecological similarity model developed for vascular plants.

BY LINKING

established vegetation classes to this model, we project which vegetation classes are likely to be favoured in a given location under future climate scenarios.

PROJECTED DISTRIBUTION OF VEGETATION TYPES

can be viewed in two main ways:

- **Probability maps:** show probability of individual vegetation classes occurring
- **Generalised maps:** show only the vegetation class with the highest probability of occurring at each location

IT IS IMPORTANT

to view the 'generalised' maps in combination with the underlying probabilities.

Projected distribution of vegetation types can be viewed in two main ways:

- 'probability' surfaces showing the projected occurrence (scaled between 0 and 1) of each individual vegetation class in each location (see greyscale maps in Figure 3c, d and Boxes 6, 7). These datasets are available for each of the 77 Major Vegetation Sub-groups via the *CSIRO Data Access Portal.*
- 'generalised' maps showing the vegetation class having the highest probability of all classes potentially occurring at each location (Figure 2b,c; Figure 3a, b, Box 6).

Both of these views support local interpretation of change processes. The probability maps highlight the potential futures for particular vegetation types and provide a clear indication of projected suitability in each location (e.g., see Box 6 for *Banksia woodland* and Box 7 for *Cool temperate rainforest* in the Corangamite CMA).

The generalised maps are valuable as a regional overview to suggest which vegetation types to investigate using the individual probability maps. They also indicate which of present-day vegetation classes is projected to be more probable than any other for any particular location, accepting that this probability may still be low (e.g. see Box 6).

These two map types need to be interpreted with a clear understanding of their limitations. These include the general limitations of the biodiversity modelling as described in Section 1.4, as well as the following specific limitations:

- The accuracy of projections is limited by the quality of the baseline vegetation mapping and the ecological consistency of the classification used to train the models.
- Projections of vegetation type are constrained by the set defined in the baseline classification. For example, historical classifications do not cater for the potential assembly of new combinations of species; i.e., new vegetation types emerging in places where *novel ecological environments* are projected to develop.
- The class with the maximum probability selected to represent the vegetation type on the generalised map will often be biased towards a surrounding common type, as seen in the comparison between the NVIS and 1990 predicted vegetation maps below (Figure 2a & b). Fine-grained patterning of locally rarer types is less well-resolved by the methodology, and this needs to be considered in interpretation.
- An inherent feature of the method is that all class probabilities in a grid cell add to one. As a result, the maximum grid cell probabilities will be relatively low if a large number of vegetation types are predicted to potentially occur there (for details see Technical Note 2).
- The use of the maximum grid cell probability to decide which vegetation class to show on the generalised map is relatively arbitrary, because many interacting ecological processes determine persistence. More sophisticated decision rules could be developed, using local ecosystem knowledge.

To avoid misinterpretation of generalised maps it is therefore important to view them in combination with information about the underlying probabilities for all vegetation types potentially occurring there. Insights can be obtained from:

- probability maps showing the probability of occurrence of each relevant vegetation type (e.g., as shown in Figure 3c, d; Boxes 6,7), or
- maps showing the maximum probability score for the vegetation class shown on the generalised map (shown in Technical Note 2), or
- maps showing the number of vegetation classes that had a probability >0 of occurring in each location (shown in Technical Note 2).

3.2 Projected distribution of vegetation types – the national context

Figure 2a shows the pre-clearing map of Major Vegetation Sub-groups (generalised to approximately 250m grid resolution), and Figure 2b shows how the model predicts their distributions for the baseline period (1990). Viewed continentally, the match is exceptional. The local details are less well replicated by the mapped predictions, but some of this detail can be revealed by examining the predicted probabilities for each vegetation class.

Figure 2c shows which of Australia's Major Vegetation Sub-groups are projected with the highest probability for each grid cell by 2050 under the high emissions' *mild MIROC5* climate scenario, and Figure 2d shows projections for the high emissions' *hot CanESM2* climate scenario.

In the broadest sense, many of the 77 Major Vegetation Sub-groups are projected to remain in a somewhat familiar pattern across Australia, but with potential for south or coast-ward re-assembly.

Image Left: Tree ferns, Source: Talia Jeanneret

Image Right: Gluepot Reserve, Source: © Stewart Macdonald / Ug Media

WE USE THE TERM

'projected' for maps and datasets showing projections under a future climate scenario.

WE USE THE TERM

'predicted' for maps and datasets showing modelled current vegetation types that can be validated from observed vegetation.

AT THE NATIONAL SCALE,

under even the high emissions' *hot CanESM2* climate scenario, vegetation patterns are projected to remain broadly similar by 2050. However they are likely to shift in location, primarily towards the south or coast.

While the projected vegetation patterns of 2050 are broadly comparable with baseline patterns (1990), the vegetation at any particular location is often expected to alter in character, and in many locations becomes more uncertain than baseline predictions. (depicted in Figure 2 of Technical Note 2).

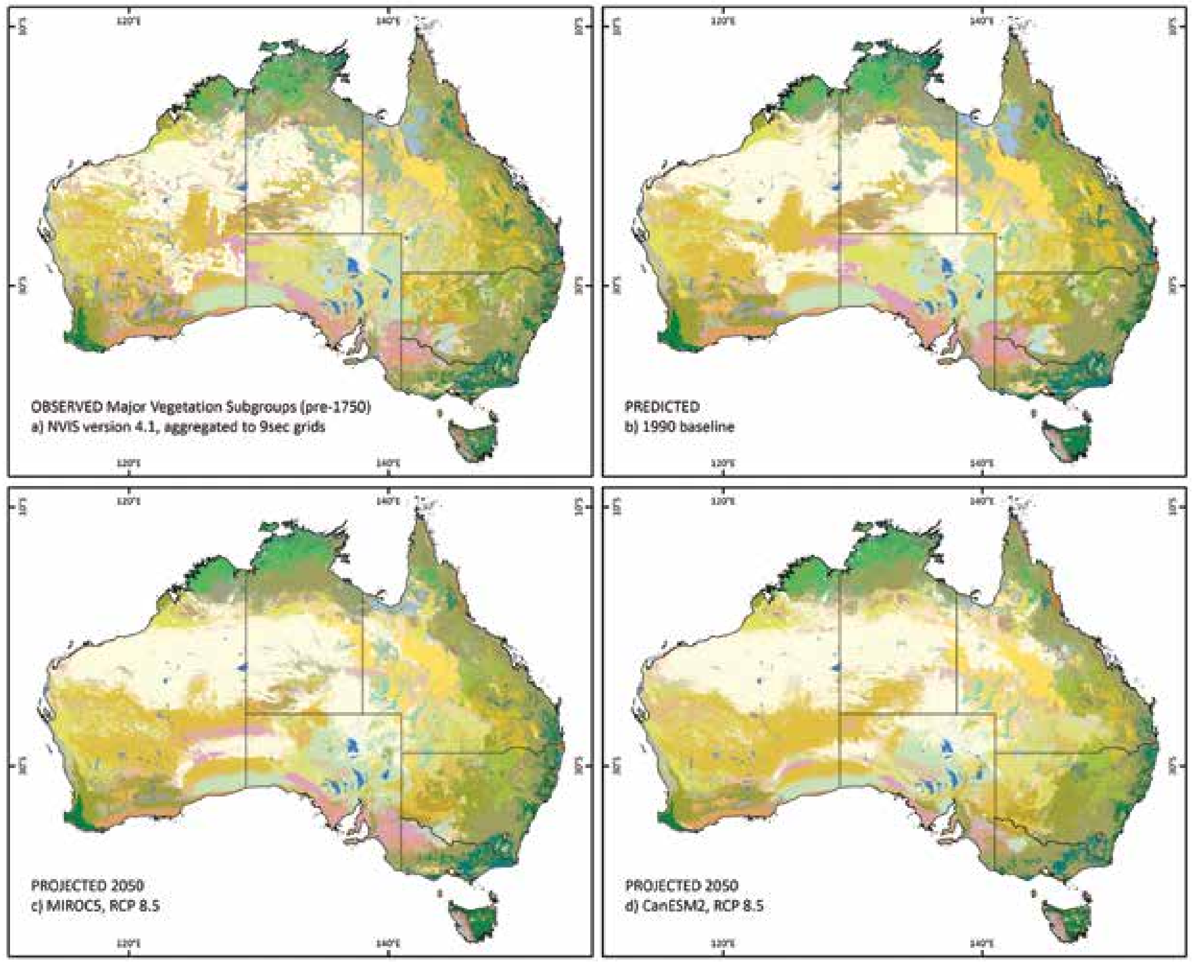
Some of the more striking trends at the broad scale (under both scenarios) include an apparent simplification of vegetation patterns in the Northern Territory and far west Queensland, including potential loss of various types of wooded hummock grasslands and *Mitchell grassland.* Likely replacements are projected to be more similar to treeless *Hummock grassland*, and under the high emissions' *hot CanESM2* climate scenario, *Mulga woodlands with tussock grass*.

In south-western Australia, there is a clear suggestion that the Mulga line (the boundary between *Eucalyptus* and *Acacia* dominated vegetation) will protract southwards under the hotter scenario, leaving significantly less area suitable for *Eucalyptus* forests and woodlands. Similarly in south-eastern Australia, re-assembly among structural vegetation classes from forest to grassy woodland to shrub woodland are projected (see Figure 3).

Not all vegetation classes are expected to be disadvantaged. Some, such as *Tropical Eucalyptus forest and woodland with a tall annual grassy understorey, Hummock grasslands* and *Mu lga woodlands with tussock grass,* are projected to expand.

FIGURE 2

(a) Observed Major Vegetation Sub-groups for Australia, (b) model predictions of Major Vegetation Sub-groups for Australia in the baseline period (1990) indicating effectiveness of the modelling; and generalised maps of the *projected distribution of vegetation types* by 2050 for the high emissions' (c) *mild MIROC5*, and (d) *hot CanESM2* climate scenarios. Maximum probabilities underlying the generalised vegetation types and their associated number of vegetation types are shown in Technical Note 2.



Legend

- Cool temperate rainforest
- Tropical or sub-tropical rainforest
- Eucalyptus (+/- tall) open forest with a dense broad-leaved and/or tree-fern understorey (wet sclerophyll)
- Eucalyptus open forests with a shrubby understorey
- Eucalyptus open forests with a grassy understorey
- Warm temperate rainforest
- Tropical Eucalyptus forest and woodlands with a tall annual grassy understorey
- Eucalyptus woodlands with a shrubby understorey
- Eucalyptus woodlands with a tussock grass understorey
- Eucalyptus woodlands with a hummock grass understorey
- Tropical mixed spp forests and woodlands
- Callitris forests and woodlands
- Brigalow (Acacia harpophylla) forests and woodlands
- Other Acacia forests and woodlands
- Melaleuca open forests and woodlands
- Other forests and woodlands
- Boulders/rock wtih algae, lichen or scattered plants, or alpine fjaeldmarks
- Eucalyptus low open woodlands with hummock grass
- Eucalyptus low open woodlands with tussock grass
- Mulga (Acacia aneura) woodlands +/- tussock grass +/- forbs
- Other Acacia tall open shrublands and [tall] shrublands
- Acacia (+/- low) open woodlands and shrublands with chenopods
- Acacia (+/- low) open woodlands and shrublands with hummock grass
- Acacia (+/- low) open woodlands and shrublands +/- tussock grass
- Acacia (+/- low) open woodlands and sparse shrublands with a shrubby understorey
- Casuarina and Allocasuarina forests and woodlands
- Mallee with hummock grass
- Low closed forest or tall closed shrublands (including Acacia, Melaleuca and Banksia)
- Mallee with a dense shrubby understorey
- Heath
- Saltbush and Bluebush shrublands
- Other shrublands
- Hummock grasslands
- Mitchell grass (Astrebla) tussock grasslands
- Blue grass (Dicanthium) and tall bunch grass (Vitiveria syn: Chrysopogon) tussock grasslands
- Temperate tussock grasslands
- Other tussock grasslands
- Wet tussock grassland with herbs, sedges or rushes, herblands or ferns
- Mixed chenopod, samphire +/- forbs
- Mangroves
- Saline or brackish sedgelands or grasslands
- Naturally bare, sand, rock, claypan, mudflat
- Salt lakes and lagoons
- Freshwater, dams, lakes, lagoons or aquatic plants
- Mulga (Acacia aneura) open woodlands and sparse shrublands +/- tussock grass
- Sea, estuaries (includes seagrass)
- Eucalyptus open woodlands with shrubby understorey
- Eucalyptus open woodlands with a grassy understorey
- Melaleuca shrublands and open shrublands
- Banksia woodlands
- Mulga (Acacia aneura) woodlands and shrublands with hummock grass
- Mulga (Acacia aneura) open woodlands and sparse shrublands with hummock grass
- Eucalyptus low open woodlands with a shrubby understorey
- Eucalyptus tall open forest with a fine-leaved shrubby understorey
- Mallee with an open shrubby understorey
- Eucalyptus (+/- low) open woodlands with a chenopod or samphire understorey
- Lignum shrublands and wetlands
- Leptospermum forests
- Eucalyptus woodlands with ferns, herbs, sedges, rushes or wet tussock grassland
- Eucalyptus tall open forests and open forests with ferns, herbs, sedges, rushes or wet tussock grasses
- Mallee with a tussock grass understorey
- Dry rainforest or vine thickets
- Sedgelands, rushs or reeds
- Other grasslands
- Eucalyptus woodlands with chenopod or samphire understorey
- Open mallee woodlands and sparse mallee shrublands with an open hummock grass understorey
- Open mallee woodlands and sparse mallee shrublands with an open tussock grass understorey
- Open mallee woodlands and sparse mallee shrublands with an open open shrubby understorey
- Open mallee woodlands and sparse mallee shrublands with an open dense shrubby understorey
- Callitris open woodlands
- Casuarina and Allocasuarina open woodlands with a tussock grass understorey
- Casuarina and Allocasuarina open woodlands with a hammock grass understorey
- Casuarina and Allocasuarina open woodlands with a chenopod shrub understorey
- Casuarina and Allocasuarina open woodlands with a shrubby understorey
- Melaleuca open woodlands
- Other open woodlands
- Other sparse shrublands and sparse heathlands

VEGETATION TYPES

at any particular location are often expected to change.

UNDERSTANDING THIS

change can help when prioritising management actions.

3.3 Projected distribution of vegetation types – a regional focus

Understanding the potential for redistribution of vegetation types helps us to better envisage the outcomes of climate change, and focus on a range of priority management actions. For example, knowing where to expect different habitat structures to emerge can prompt decisions about whether that change maintains environmental values, and if not, whether intervention is justified to manipulate the outcome in particular locations.

In the wheat-sheep belt of New South Wales for example, remnant grassy woodlands support a suite of iconic wildflowers in the grassy ground-layer and provide important habitat for woodland birds. The *projected generalised distribution of vegetation types* map for the high emissions' *hot CanESM2* climate scenario (Figure 3) suggests environments most suited to grassy woodland will be replaced by environments more suited to shrubby woodland across extensive areas, from Griffith to Trangie.

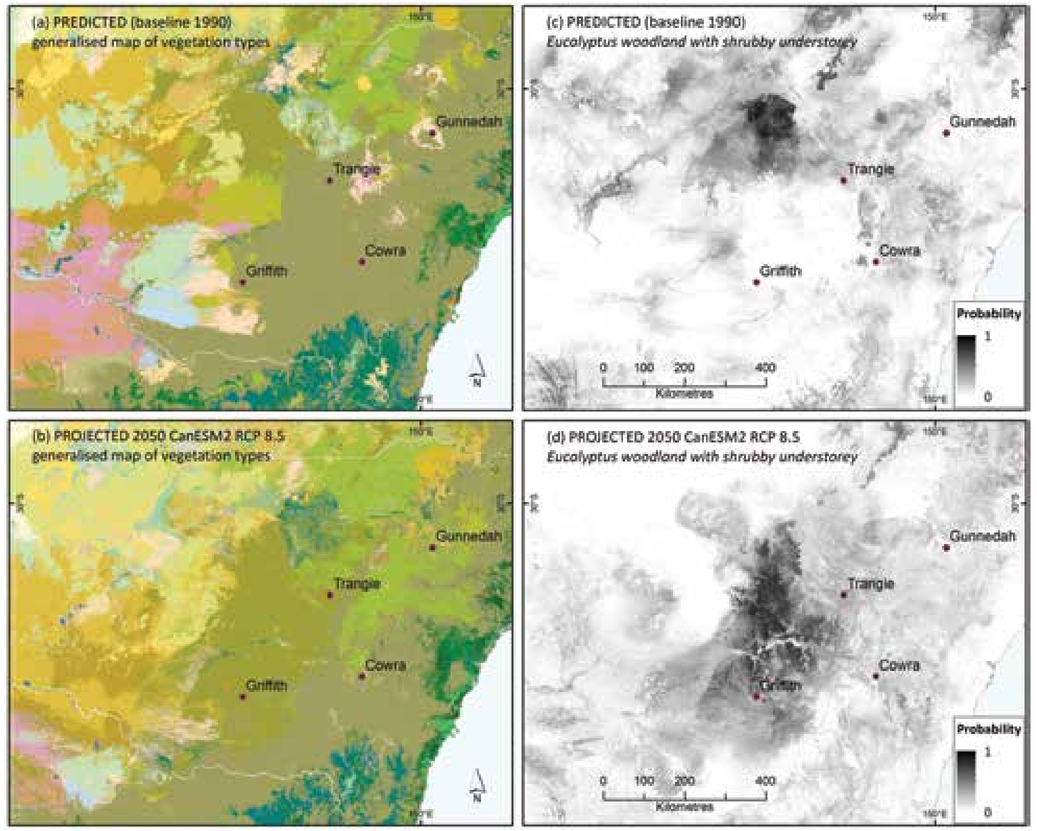
This indication of potential structural change suggests that some woodland species, including birds that favour a dense shrub layer (such as many fairy-wren and thornbill species), may benefit from climate change. On the other hand, ground-layer wildflowers, and birds favoured by grassy understorey, would be disadvantaged. Species that have already declined substantially due to widespread clearing and modification of grassy ground-layers, such as the Fringe Lily (*Thysanotus tuberosus*), the Yam Daisy (*Microseris lanceolata*), the Diamond Firetail (*Stagonopleura guttata*) and Grey-crowned Babbler (*Pomatostomus temporalis*), are thus in danger of becoming even more threatened.

It is well-known that the grass-shrub balance in woodlands can be manipulated using disturbance regimes. Prolonged livestock grazing reduces grasses and limits ground fires, promoting shrub understoreys in semi-arid environments. By contrast, fire can be used to promote grassy ecosystems. Given the threatened status of many grassy woodland species, planners might decide to use light grazing regimes and fire management to maintain open grassy ecosystems in selected areas.

Image Right: Ground-layer plants such as these yellow Buttercups (*Ranunculus lappaceus*) would be disadvantaged with a structural change from grassy to shrubby woodland. Source: Suzanne Prober.

FIGURE 3

The colour maps show baseline (1990) observed (a) and 2050 projected (b) vegetation classes for central NSW, showing potential replacement of *Eucalyptus woodland with grassy understorey* (grey-green) with *Eucalyptus woodland with shrubby understorey* (olive green) under the *hot CanESM2* climate scenario (full legend is shown in Figure 2). The grey scale maps show the 1990 baseline predicted (c) and 2050 projected (d) probabilities for *Eucalyptus woodland with shrubby understorey*, highlighting the potential southward spread. The probability maps also indicate uncertainties, such as low probabilities for shrub woodland around Trangie despite its projection as the most probable vegetation class on the generalised map (See Technical Note 2 for details).



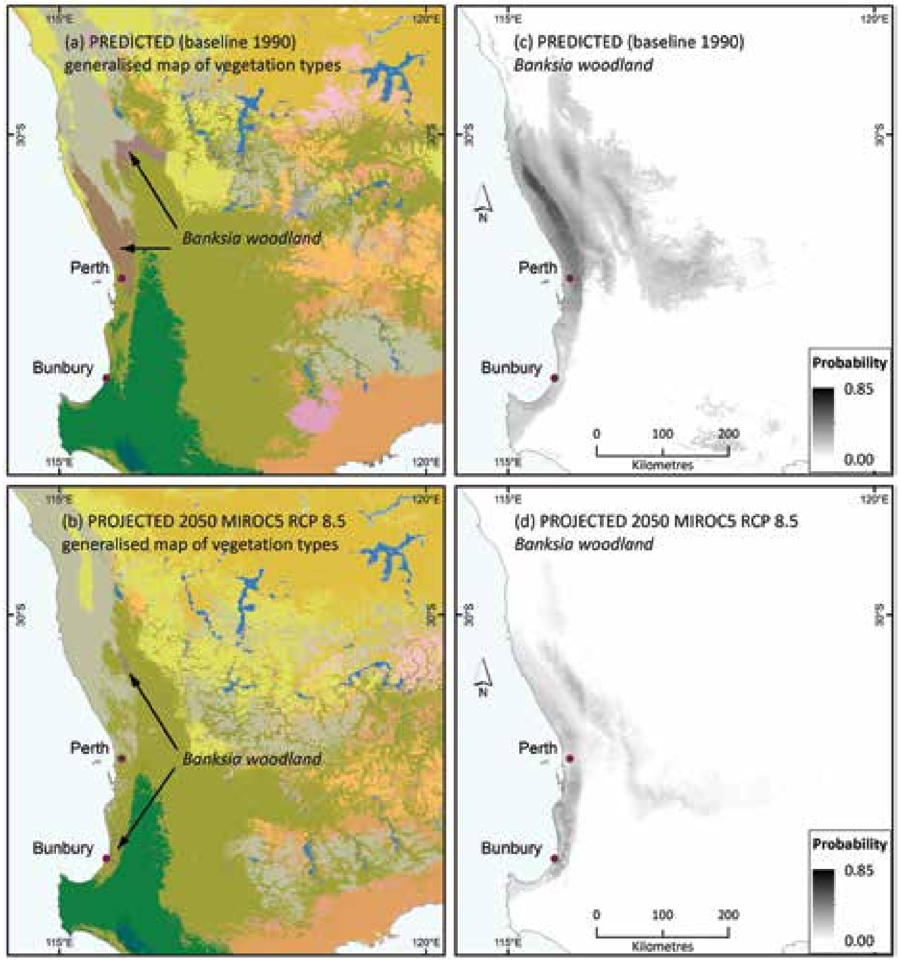
BOX 6

Using generalised versus probability projections for vegetation classes

The different ways of presenting *projected distribution of vegetation types* can provide different types of information to inform planning for vegetation and habitat management.

Generalised (colour) maps show broadly which vegetation class has the highest modelled probability, at baseline or under a specified climate scenario. For *Banksia woodlands*, comparing the generalised maps (panel (a) and panel (b) in the figure below) tells us that environments throughout much of its current distribution will favour shrubland under the high emissions' *mild MIROC5* climate scenario. We also see that there are only scattered locations between Bunbury and Perth where *Banksia woodlands* have higher modelled probability than other vegetation types by 2050.

Probability (greyscale) maps of individual vegetation classes on the other hand, do not show which vegetation classes have highest probabilities. Rather, they provide a clearer view of potential pressures and opportunities for each vegetation class to persist. Importantly, while few areas of high suitability (dark grey to black) are projected for *Banksia woodlands* in 2050, areas of potential moderate suitability do remain throughout the current distribution and elsewhere (panels (c) and (d) in the figure below). Not considering probability maps could risk giving up too soon on existing *Banksia woodlands* where generalised maps project alternative vegetation classes.



Colour maps show generalised mapping of predicted major vegetation subgroups for baseline climates in south-western Australia (a), and projected under the 2050 *mild MIROC5* climate scenario (b). See Figure 2 for legend to vegetation classes; *Banksia woodlands* are pinkish-brown. Grey scale maps show the predicted probability of *Banksia* woodland occurrence for baseline (1990) climates (c), and projected under the 2050 *mild MIROC5* climate scenario (d).

Taking this information together, planners and managers can weigh up options between supporting persistence of *Banksia woodlands* species *in situ*, or facilitating their transition to locations likely to have more suitable environments in the near future.

First, using the probability projection, planners might seek the areas with highest probability for conserving the community *in situ*, regardless of whether other vegetation classes might be more suitable.

Second, using the generalised map, planners could infer that a projected change from *Banksia woodlands* to shrubland environments suggests the overstorey *Banksias* may not persist. *Banksia woodlands* support a high diversity of plant species in the shrub layer so a diverse shrub layer might still be retained *in situ*.

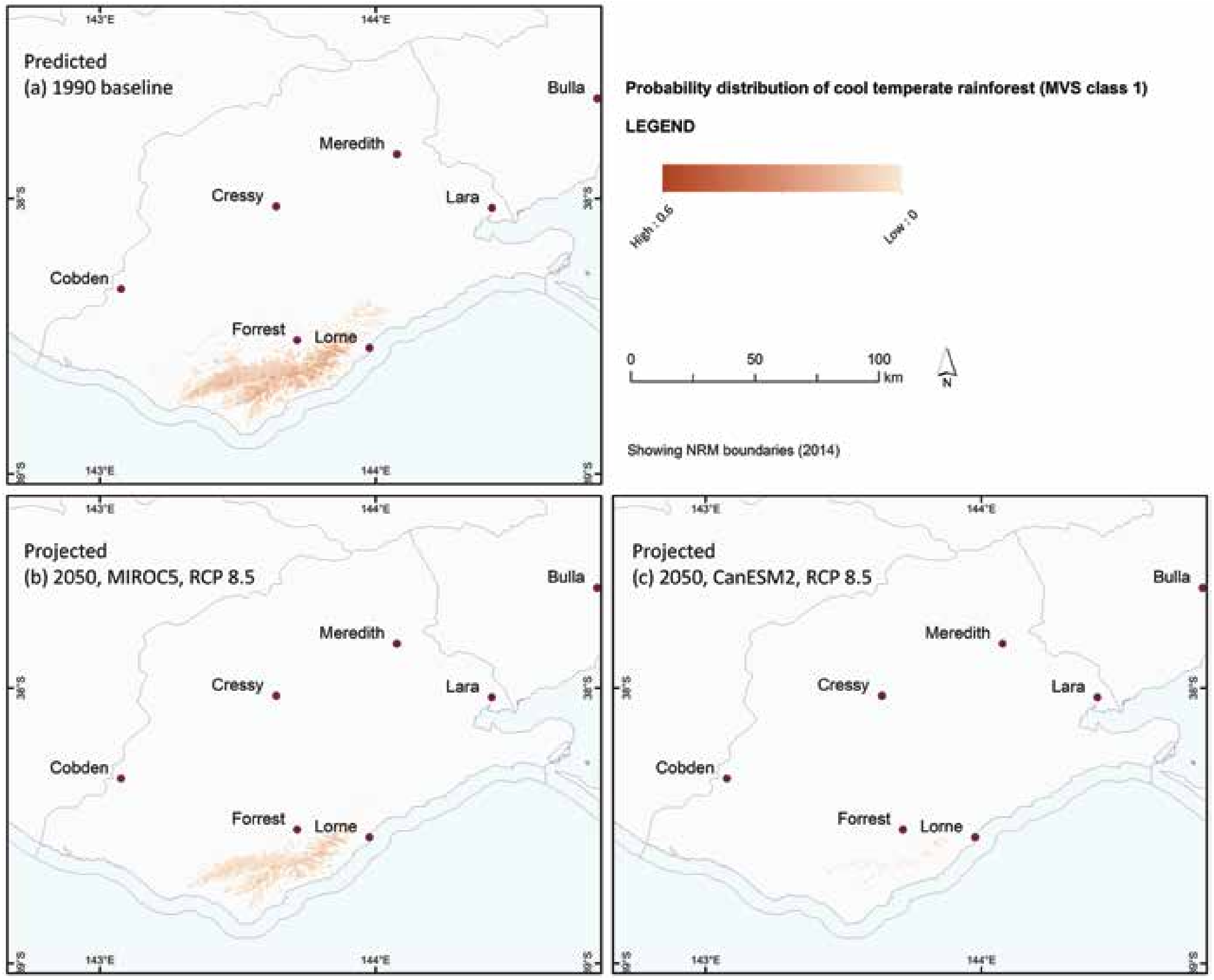
However, the *Banksia* trees themselves support animals such as black cockatoos which feed on *Banksia* cones and other woody fruits. Priority might therefore focus on *Banksia*-dependent species for more costly relocation or habitat augmentation options.

Image Below: *Banksia* woodlands are an iconic ecological community of the Perth region. Source: Suzanne Prober.

BOX 7

Shifts in *Cool temperate rainforest* in Corangamite CMA

The Corangamite Catchment Management Authority (CMA) region in Victoria currently contains remnants of *Cool temperate rainforest* that is unique to the region, stretching southwest from Lorne through Great Otway National Park (see (a) in the figure below). These remnants have high value, both for biodiversity and for tourism and a sense of regional character. However, the *projected distribution of vegetation types* results for this NVIS sub-group (see (b) and (c) in the figure below) suggest that *Cool temperate rainforest* is likely to become even more restricted by 2050 and would virtually disappear from the region based on the high emissions' *hot CanESM2* climate scenario.



Predicted probability of *Cool temperate rainforest* occurrence for the baseline (1990) climate (a) and projected occurrence for 2050 under the high emissions' *mild MIROC5* (b) and *hot CanESM2* (c) climate scenarios.

A variety of ecological similarity measures and additional information can be used collectively to give a more complete picture of what this change could entail. The colour (generalised) maps of vegetation types into the future (see main text) suggest that Eucalypt forest may dominate, with either a tree-fern or a grassy understory. But they also suggest that, particularly under the *hot CanESM2* climate scenario, the new vegetation type will continue to be unique in the region, showing stronger affinities with parts of eastern Victoria than the rest of the Corangamite region.

Exploration of the measures introduced in ***Implications of Climate Change for Biodiversity*** for vascular plants also show that the overall *potential degree of ecological change* in the region is not exceptionally high, that these environments are not likely to disappear from a continental perspective, and that the environments that exist in the future will not necessarily be novel. While *Cool temperate rainforest* may be lost from the region, this may be accomplished through change in a moderate subset of the species present. Although the newly assembling vegetation type may not be unique from a continental perspective, it may still retain a unique character within the region.

Local expert opinion and other sources of information can be used to refine and further explore these interpretations. For example, in an expert workshop hosted by Chris Pitfield of Corangamite CMA, Prof. Peter Gell from Federation University suggested that changes to fire regimes in surrounding vegetation may have the greatest impact on *Cool temperate rainforest*. Combining these insights with the community-level measures, fire regime changes could influence whether or not a tree-fern or a grassy understory comes to dominate and/or may act to accelerate the changes to cool temperate rainforest projected by the analyses.

The options available to the CMA and its stakeholders to manage this change will also depend on the new principles and strategic goals for biodiversity conservation that they may choose to adopt (Section 2). For example:

'Optimise ecological processes' – If this is a core principle, one goal could be to help nature take its course by minimising other stressors and maintaining connectivity into the areas that currently support *Cool temperate rainforest*.

'Maintain unique regional character' – If this is a core principle, analyses suggest these areas are likely to retain unique regional values so one goal could simply be to promote the assembly of the new vegetation type with native species, focusing on monitoring and management of potential transformer species that might threaten that unique character.

'Promote cross-sectoral adaptation planning' – If this is a core principle, one goal could be to ensure that any changes to adjacent land uses do not further contribute to changed fire regimes that may accelerate loss of *Cool temperate rainforest*.

Image Right: Forest scene in the Tarra-Bulga National Park near Cyathea Falls
Source: Michael Barnett/

Benefits of revegetation

SECTION 4

This section describes a measure that indicates benefits of increasing habitat area through revegetation, and how this potentially supports the persistence of present-day biodiversity under climate change.

Image Below: Revegetation activities
Source: Northern Agricultural Catchments Council

Revegetation, the re-establishment of vegetation in cleared or degraded landscapes, is one of the most common ecological restoration actions undertaken in Australia's agricultural regions. Many native trees and shrubs are planted on cleared land each year, and some land use changes can also promote natural regeneration.

Revegetation may be designed to achieve a variety of benefits, one of which is to increase available habitat area to support native species. Increasing habitat area and the effectiveness of that habitat will become even more important under climate change, for example, in counteracting climate-induced habitat losses and supporting the principle: to 'Minimise species loss nationally'. Further, we can expect changes in where the greatest benefits of revegetation are likely to accrue, depending on how climate change alters the extent of different ecological environments.

REVEGETATION

is a common ecological restoration activity in Australia's agricultural regions

REVEGETATION

to increase habitat area may be increasingly important under climate change.

4.1 Estimating revegetation benefit

Revegetation benefit is an indicator of how many more contemporary species the landscape is likely to sustain as a result of revegetation at a location (see Technical Note 3). The measure is relative, indicating the benefit of a revegetation action in the focal cell compared with the benefit of a similar action in other cells. It should not be interpreted as an estimate of the absolute gain in species numbers or proportions, because this depends on the quality and extent of the revegetation practice.

Our analysis focuses only on cleared natural areas using data compiled by the Australian Government[3]. In these locations, we represent the proportion of clearing that has occurred in a grid cell by aggregating the 100m source data to match our resolution.

Our calculation of *revegetation benefit* is based on the observation that within natural ecosystems, the number of species generally increases with area of available habitat, but at much greater rates when area is limited. This empirical relationship is known as the 'species-area curve' (Figure 4). We use this classic curve to relate change in the area of available habitat as a result of revegetation to the potential proportion of species likely to benefit from that revegetation.

REVEGETATION BENEFIT

is an indicator of how many more species the landscape is likely to support as a result of revegetation at a location.

THE MEASURE

is relative - the benefit of a revegetation action in a location is compared with the benefit of a similar action in other locations.

THE BENEFIT OF REVEGETATION

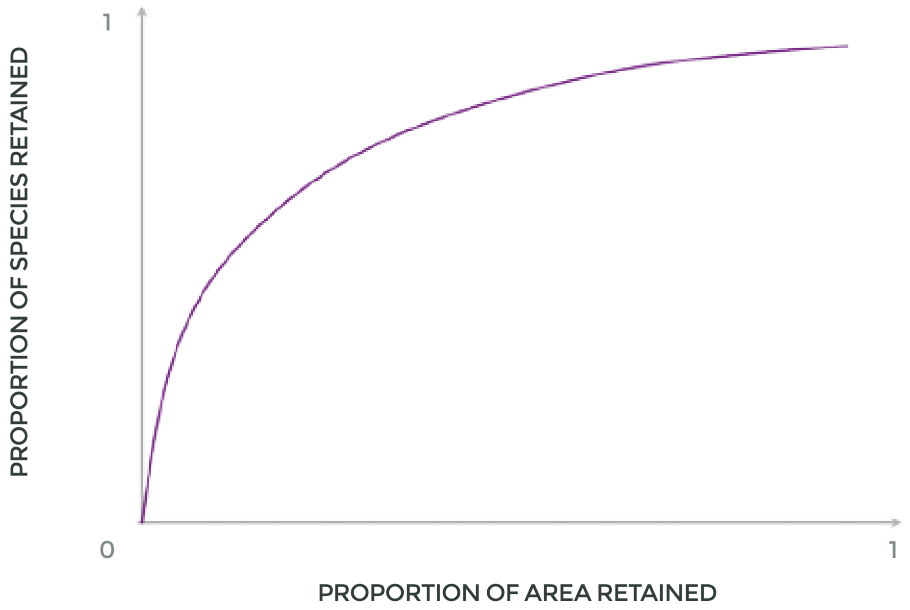
is assumed to be greatest for ecological environments that are or will become rare, either naturally or due to human influences.

[3] Search for 'natural areas of Australia' at
http://www.environment.gov.au/fed/catalog/main/home.page

FIGURE 4

This measure assumes the benefit of revegetation is greatest for ecological environments that are or will become rarer, relative to a hypothetical pre-clearing natural state at baseline, due to human influences such as land clearing and/or climate change.

The species-area curve describes how the number or proportion of species (S) increases with available habitat area (A), described by the formula $S = cA^z$. The shape of the curve is described by the exponent known as z, which is commonly set at 0.25; *c* is a constant that can be ignored if using proportions as we do here.



The calculation of *revegetation benefit* uses the concept of *change in effective area of similar ecological environments*, a measure introduced in ***Implications of Climate Change for Biodiversity***. This estimates change in the availability of ecological environments similar to the focal cell caused by factors such as clearing or climate change, compared with a hypothetical pre-clearing natural state at baseline (e.g., 1990).

We apply this measure:

- to baseline (1990) ecological environments, to indicate the relative benefits of revegetation in cleared landscapes without accounting for climate change.
- using future (e.g., 2050) climate scenarios, showing the relative benefits of revegetation for the biota of the baseline (1990) ecological environment given the additional influences of climate change.

We can also show the difference between these two measures to reveal the degree to which climate change alone alters the benefits of revegetation in different places (see example in Technical Note 3). Note that benefits for future biota assembling under future ecological environments are not considered in this particular measure of *revegetation benefit*.

Importantly, the contribution of revegetation to *change in effective area of ecological environments* under climate change is dependent on the similarity of the baseline (1990) focal cell to its future self. At low similarity (i.e., if the ecological environment becomes very different), the contribution will be low because the cell will no longer be very suitable for baseline (1990) biota (see Technical Note 3).

On the other hand, if the focal cell remains similar under climate change but the total area of similar ecological environments is projected to decline compared with the baseline period (1990), this can increase the importance of a contemporary revegetation action using baseline biota in that cell.

We emphasise that other potential benefits of revegetation such as reduced salinisation or enhanced connectivity are not accounted for in this measure. More integrated approaches that consider a wider range of benefits from conservation actions beyond just revegetation, are being developed (e.g., see the report for south-eastern mainland Australia – ***Biodiversity Management Under Future Climate***).

More broadly, in common with any index of conservation benefit, the revegetation index is intended to be used along with other information supporting decision making, such as social values, economic constraints, iconic species, and additional environmental benefits.

Image Previous Page: South Cape York Catchments volunteers reconnecting riparian corridors with trees grown from local seed.
Source: South Cape York Catchments
Source: Jason Carroll

THE ESTIMATION

of revegetation benefit uses the measure of change in effective area of similar ecological environments.

THE SIMILARITY

of a location to its future environment will impact upon the benefits of revegetation for the present-day biota because low similarity means the location will decline in suitability over time for present-day biota.

THERE ARE ADDITIONAL

benefits of revegetation not included in this measure, such as management of salinity and erosion.

THE BENEFITS OF

revegetation for vascular plants appear greater compared to other biological groups, under both climate scenarios.

4.2 Revegetation benefit – the national context

The national pattern of *revegetation benefit* for vascular plants is illustrated in Figure 5, comparing the baseline (1990 climates) with the high emissions' *mild MIROC5* climate scenario (2050).

The measure only applies to cleared natural areas, elsewhere no benefit is shown. These are most prominent in the eastern and south-western agricultural zones, where differences in benefit are evident as lighter (lower benefit) and darker (higher benefit) shades of red. The greatest benefits of revegetation at the broad scale accrue in parts of the south-east from the Yorke Peninsula to the NSW south-west slopes, and in the Geraldton area of Western Australia, concurring with some of the most highly cleared regions.

For vascular plants we see an increase in *revegetation benefit* from baseline (1990) to the high emissions' *mild MIROC5* climate scenarios. This reflects a decline in the overall area of the 1990 ecological environments (increased rarity) and hence greater importance if revegetated.

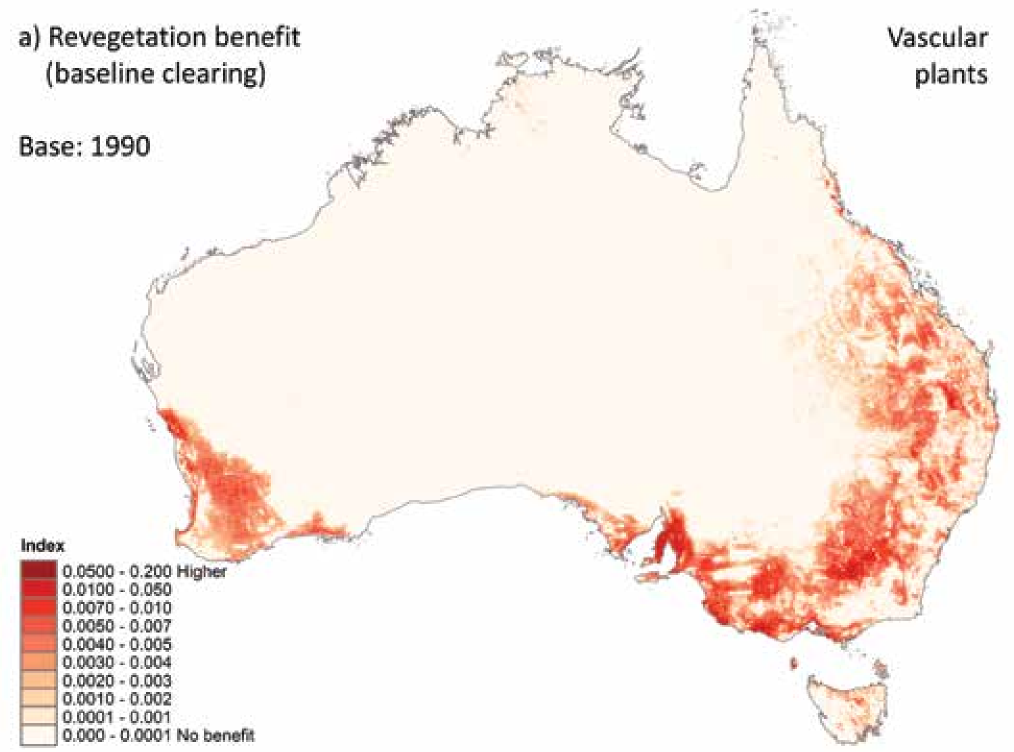
A visual comparison of differences in *revegetation benefit* between the biological groups is given in Figure 6 for the two high emissions' climate scenarios. In these cases, benefits of revegetation consistently increase with climate change, and with severity of the climate scenario. Broad spatial patterns are similar across biological groups but the magnitude of benefit tends to be higher in groups such as vascular plants with higher overall diversity and therefore often greater local rarity.

Image Left: South West Catchments Council officer partnering with Department of Parks and Wildlife officer in on-ground biodiversity projects, Source: South West Catchments Council, Credit: Tim Swallow

FIGURE 5

Revegetation benefit for baseline (1990) vascular plant species under the (a) baseline (1990) climate and (b) high emissions' *mild MIROC5* future climate scenario (2050). Darker colours signify higher overall benefit; lighter colours signify less benefit. While the legend shows 10 classes, the data itself is continuous. The difference between (a) and (b) is given in Technical Note 3 showing how revegetation benefits change with climate.

A
(1990)



B
(2050)

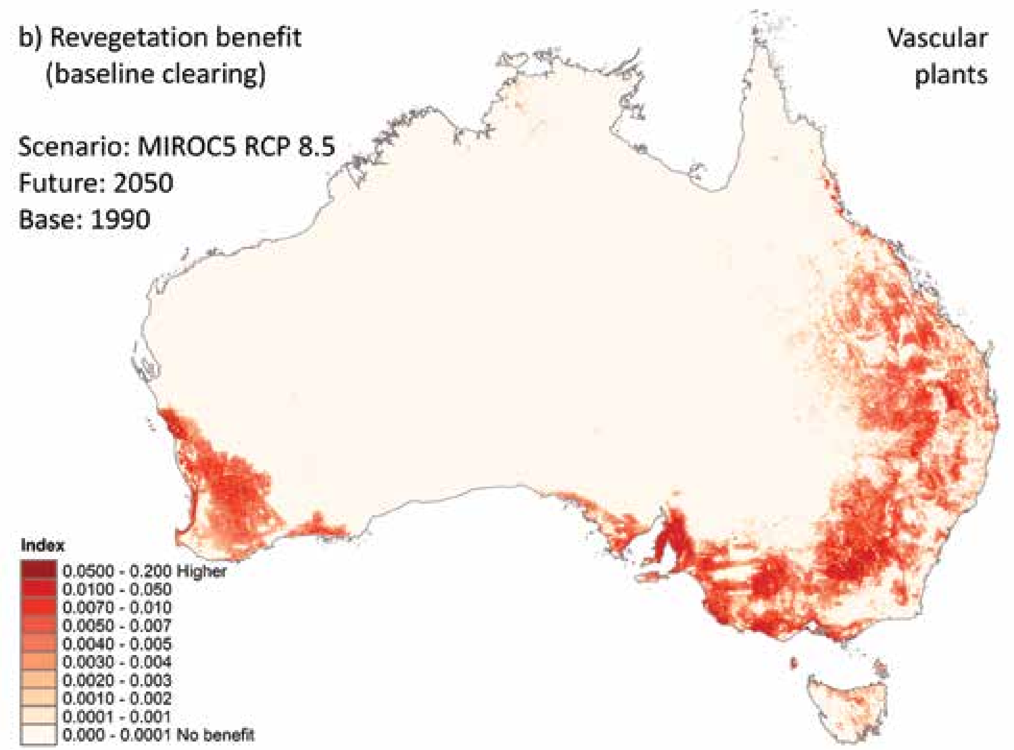
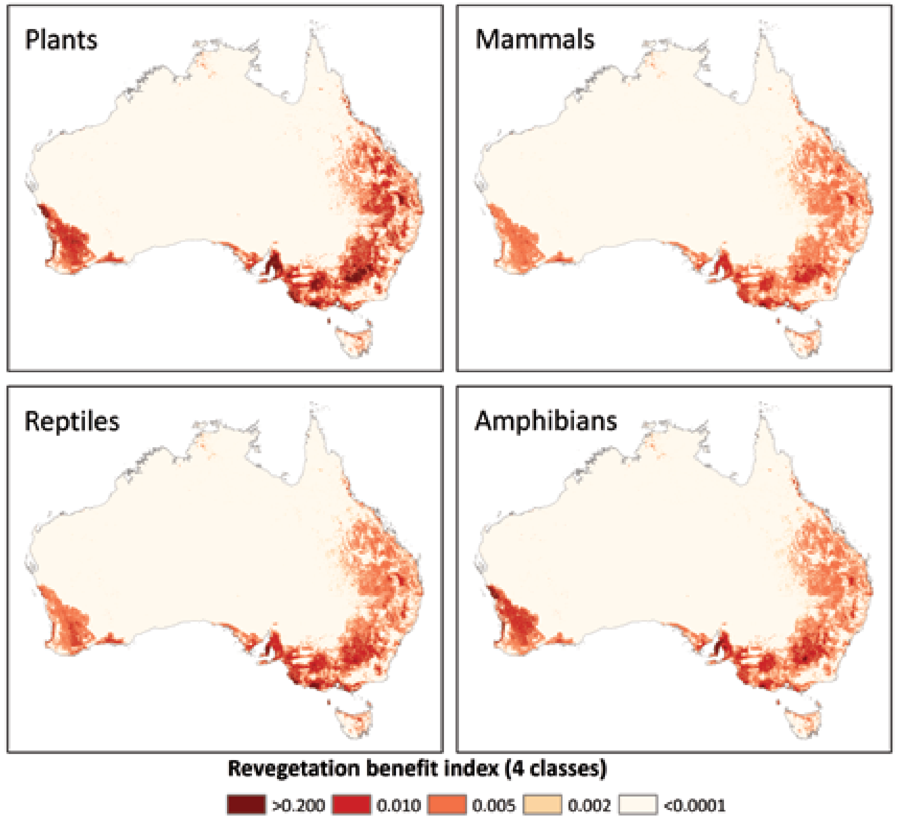


FIGURE 6

Revegetation benefit for the biota of the baseline environment (1990) under two scenarios of climate change by 2050, for four biological groups. Darker colours signify higher overall benefit; lighter colours signify less benefit. While the legend shows five categories for ease of visual comparison, the data itself is continuous.

MIROC5

(1990-2050 RCP 8.5)



CanESM2

(1990-2050 RCP 8.5)

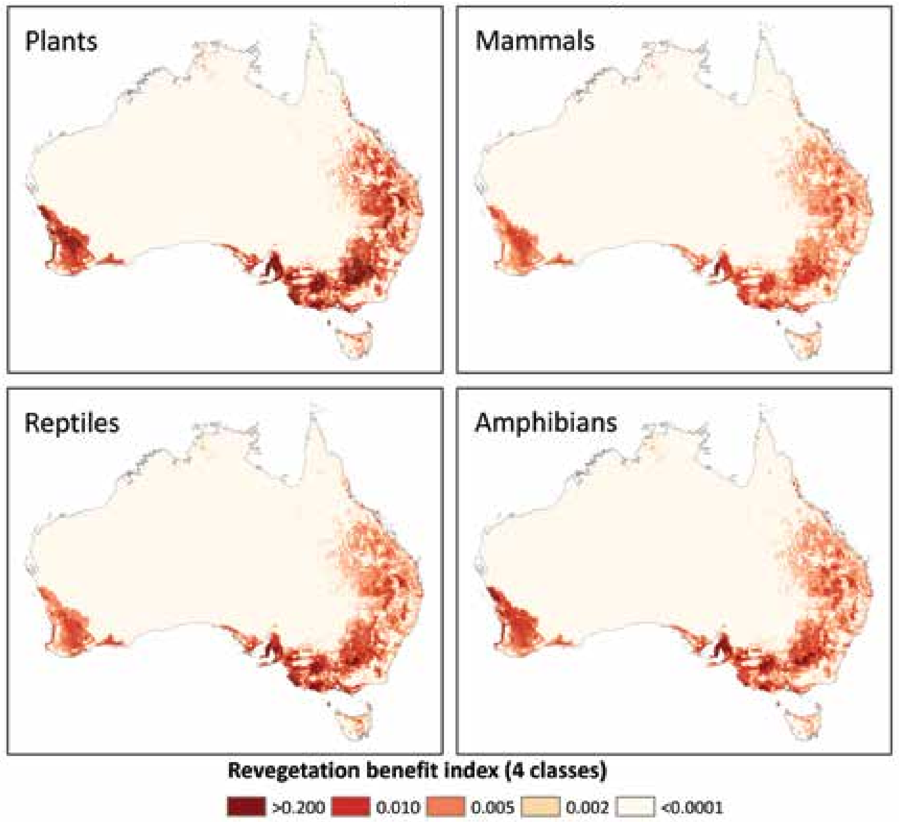


Image Below: Yandin Hill, Source: Suzanne Prober

BENEFITS OF REVEGETATION

can vary between different locations at the regional scale.

4.3 Revegetation benefit – a regional focus

Viewing *revegetation benefit* at a finer scale can facilitate regional or local-scale prioritisation of revegetation investments.

For mammals in south-western Australia, *revegetation benefit* varies moderately across the region under the baseline climate (1990) (Figure 7a). Without considering climate change, investments appear to have the greatest benefit in some coastal zones and in the central parts of the wheatbelt, for the criteria considered in our measure.

Image Below: NSW Central Tablelands Local Land Services, Source: Suzanne Prober

As we saw from the national overview maps, the *revegetation benefit* for mammals tends to increase by 2050 under the high emissions' *hot CanESM2* climate scenario (Figure 7b). However, the gain in benefit differs among locations (Figure 7c), and hence incorporating climate change into planning might modify the way we prioritise areas for revegetation. While the coastal areas and central wheatbelt remain important priorities, the wheatbelt fringes to the northwest show some of the strongest gains, and might now be considered high priority as well.

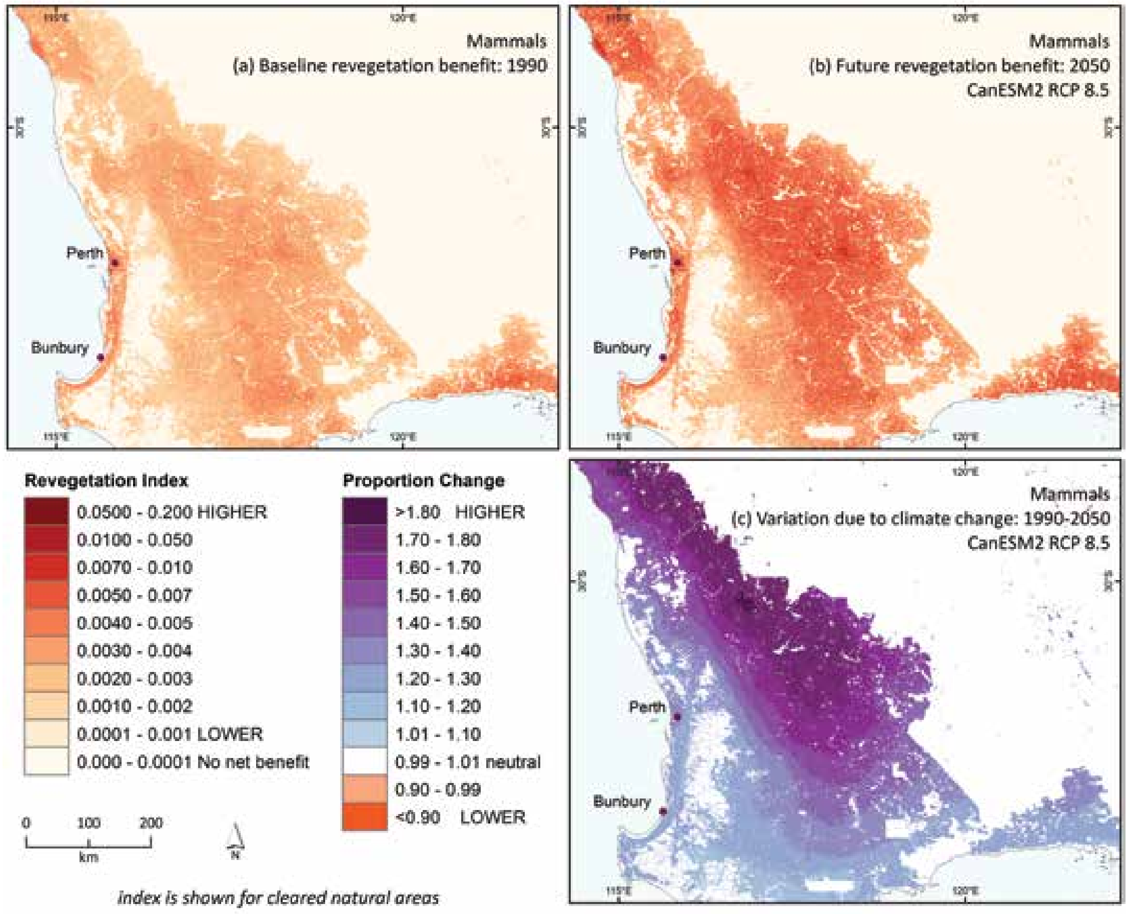
By contrast, there are two potential reasons for low gains (or reductions) in benefits of revegetation under future climate scenarios.

- Change in benefit will be low if ecological environments similar to the focal cell do not substantially change in area, and the ecological environment of the focal cell in the future (e.g., 2050) remains similar to the baseline (1990), or
- Change in benefit can be low or negative if the environment of the focal cell in 2050 is highly dissimilar to its baseline (1990) ecological environment (i.e., there is a low similarity to self).

Examining *potential degree of ecological change* and *change in effective area of similar ecological environments,* provided in *Implications of Climate Change for Biodiversity*, suggests the former applies in the Esperance and south-west wheatbelt areas that have low change in benefit.

FIGURE 7

Revegetation benefit with regard to present-day ecological environments for mammals in the south-west agricultural zone (a) under the baseline (1990) climate, (b) for 2050 under the high emissions' *hot CanESM2* climate scenario, and (c) showing proportional change in accrued benefit under the future climate (calculated as b/a). A reduction in benefit due to climate change could also occur but none is evident here. This would suggest either an increase in available effective habitat area, or a low similarity between the baseline (1990) ecological environment and the future environment of the focal cell. More examples of the proportional change in accrued revegetation benefit are given in Technical Note 3.



BOX 8

Revegetation for multiple benefits in Tasmania

Revegetation is usually conducted with multiple aims in mind, so our *revegetation benefit* measure will almost always need to be combined with other information to guide priorities for placement of revegetation in the landscape. At the moment, most prioritisations incorporate some measure of current biodiversity benefits. Our measure of *revegetation benefit* estimates benefits for biodiversity of the baseline climate (1990) under future climate scenarios. This could substitute for current benefit layers to explore how priority areas might shift. Because revegetated areas will take decades to mature and begin to provide the full biodiversity benefits intended, prioritising areas that will continue to benefit biodiversity *into the future* is particularly critical.

For example, the NRM regions in Tasmania (NRM North, NRM South and Cradle Coast NRM) have collaborated to produce a multi-criteria analysis of where revegetation might best serve multiple purposes within the state. They considered carbon sequestration, soil protection and amelioration, and current biodiversity benefits in their analysis, as well as areas where the greatest opportunities may exist due to minimal agricultural use. To include biodiversity benefits, they used an analysis of biodiversity hotspots produced by the Tasmanian Resource Management Council (TRMC). Specifically, the spatial layer was a single metric that summed ratings according to eight criteria:

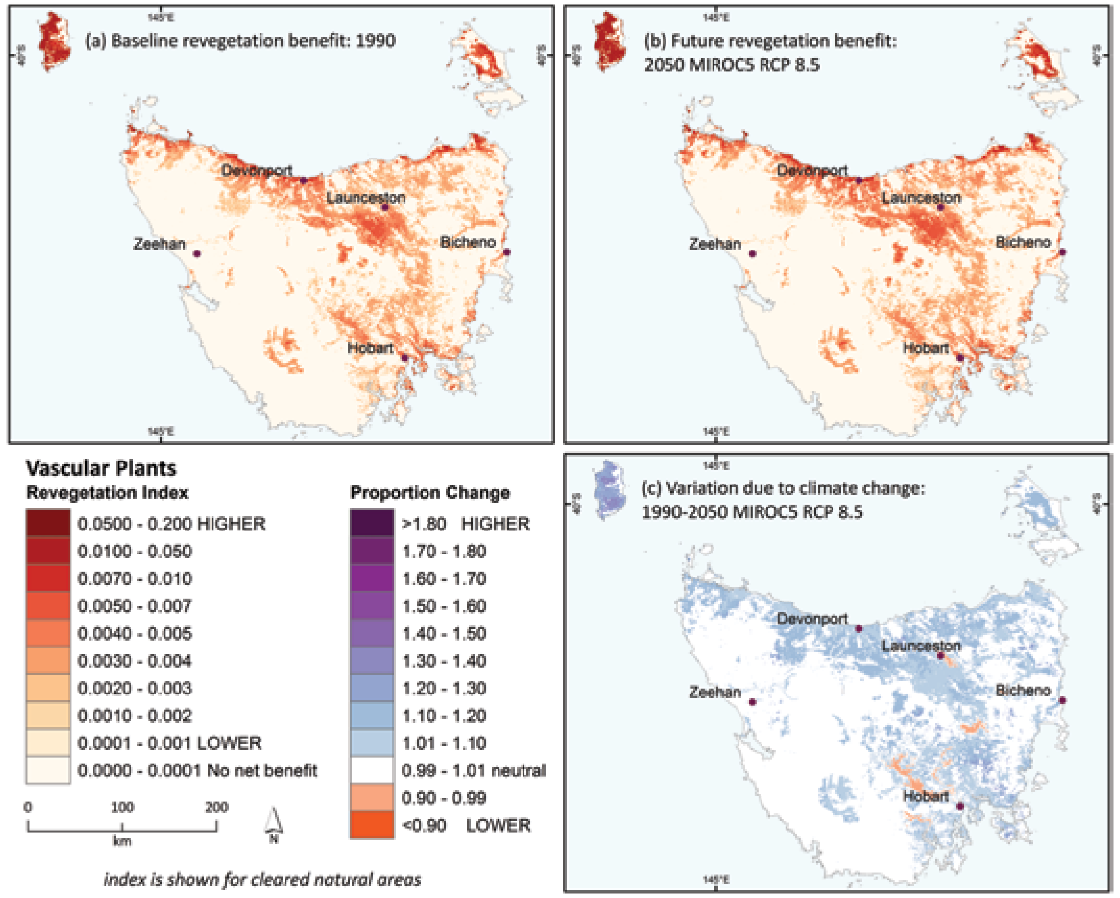
- Biogeographic distinctiveness
- Distinctiveness of areas of threatened and uncommon plants
- Conservation and reservation status of vegetation communities
- Native vegetation in bioregions with <10% in the reserve system
- Fire and disease refugia
- Glacial refugia
- Important bird habitat
- Freshwater ecosystems

Note that the first two of these criteria place importance on areas that are currently distinctive, particularly in terms of plants, as these areas may disproportionally contribute to state or national scale biodiversity. Our *revegetation benefit* measure is based on the same principle but under a changing climate. It places importance on revegetating areas that will be rare and distinctive *in the future* to best support the full range of national diversity in the long term. To adjust the existing Tasmanian analysis to plan for future biodiversity benefits, the TRMC biodiversity metric could be disaggregated and *revegetation benefit* for vascular plants substituted for the first two criteria. Further, *revegetation benefit* for mammals, reptiles, and amphibians could be incorporated as measures of future importance for faunal habitat.

As this is only one component of a multi-criteria analysis that incorporates many different spatial layers, it would be reasonable to think that updating the existing analysis with these new *revegetation benefit* layers might not yield very different results. However, an exploration of the layers along with an understanding of how the multi-criteria results will generally be used suggests that adding future *revegetation benefit* could make a small but significant difference.

The original Tasmanian analysis identified limited opportunities for revegetation – riparian buffers in the northwest and a few more substantial areas in the midlands around the margins of irrigation pivots. But our analysis of *revegetation benefit* for vascular plants, shown below under the high emissions' *mild MIROC5* climate scenario, suggests that some of the best opportunities for biodiversity benefits in the future exist along most of the north coast. These areas are more important in the future than at present (panel (c)), and the existing Tasmanian analysis suggests there are also localised opportunities for change due to patches of minimal agricultural use and potential for carbon benefits and soil improvement as well.

The NRM groups plan to use the analysis to identify focal areas for more detailed regional analysis, including evaluation of potential landholder uptake of revegetation opportunities. The addition of our future *revegetation benefit* layer in a revised version of the analysis could help identify additional focal areas worthy of further exploration, like the north coast east of Bridport.



Revegetation benefit for present-day ecological environments for vascular plants in Tasmania (a) under the baseline (1990) climate, (b) for 2050 under the high emissions' *mild MIROC5* climate scenario, and (c) showing proportional change in accrued benefit under the future climate (calculated as b/a).

Finally, as these multi-criteria analyses are often constructed using means-ends diagrams, it is worth considering new principles for biodiversity conservation (Section 2) in the context of defining the 'ends', and then working backwards to define the means to map/model them. The Tasmanian approach in general and the specific use of *revegetation benefit* aligns primarily with the potential new principle of minimising species loss nationally, through prioritising 'distinctiveness'. If additional new principles are adopted, they should be considered as 'ends' and might result in different approaches to a revegetation analysis. For example, if new principles adopted include optimising ecological processes and maintaining key services, additional layers representing landscape connectivity to support species' movements and ecosystem services beyond soil protection could be incorporated. Explicitly recognising the principles underlying the 'ends' can lead to greater clarity about the means needed to perform such analyses to actually benefit biodiversity into the future.

Need for assisted dispersal

SECTION 5

As the climate changes, some species will not be able to reach suitable habitat on their own. Assisted dispersal offers one of the few options for helping such species to adapt.

Image Below: Relocation programs are already common for iconic fauna such as the Numbat (*Myrmecobius fasciatus*), Source: © Stewart Macdonald / Ug Media

Climate change is expected to challenge the ability of many species to persist within their historic ranges, but suitable ecological environments may arise elsewhere. If these new habitats are too far away, these species may benefit from assisted dispersal. Assisted dispersal is defined here as the 'intentional translocation or movement of species outside of their historic ranges, in order to mitigate actual or anticipated biodiversity losses caused by anthropogenic climatic change'[4].

Assisted dispersal is a controversial climate adaptation option because of the risks associated with potential impacts on the recipient ecosystem. In particular, there are concerns that the target species could become invasive in its new habitat, and could result in negative consequences for other species.

Opportunities for assisted dispersal should thus be carefully weighed against potential risks, and considered in the context of a broader mix of potential adaptation options. Similarly application of assisted dispersal may involve trade-offs between principles to 'Minimise species loss nationally' and 'Maintain unique regional character' in our biodiversity (Section 2).

Here we present a measure, which we call *need for assisted dispersal,* to help inform decisions about assisted dispersal. The measure estimates how far an organism might need to move from its current location to find an ecological environment that is at least 50% similar to the ecological environment it currently occupies. The threshold choice of ecological similarity is arbitrary, and other thresholds could be used.

[4] Hewitt et al. (2011)

UNDER CLIMATE CHANGE

some species may find it difficult to persist within their historical ranges.

IF SUITABLE HABITATS

exist only across great distances, a species may benefit from assisted dispersal.

AS WITH MANY

management decisions, there are risks associated with assisted dispersal that need to be considered.

NEED FOR ASSISTED DISPERSAL

is a measure that estimates how far an organism may need to move to find an ecological environment that is at least 50% similar to its current location.

Image Below: Red-necked pademelon (*Thylogale thetis*)
Source: © Stewart Macdonald / Ug Media

TO ESTIMATE A NEED FOR ASSISTED DISPERSAL

we look into the future and find the closest location within Australia that is at least 50% similar to the baseline ecological environment. The distance to that location is the measure for *need for assisted dispersal*.

ZERO OR LOW VALUES

for *need for assisted dispersal* indicate similar ecological environments in the future will be located in the local region.

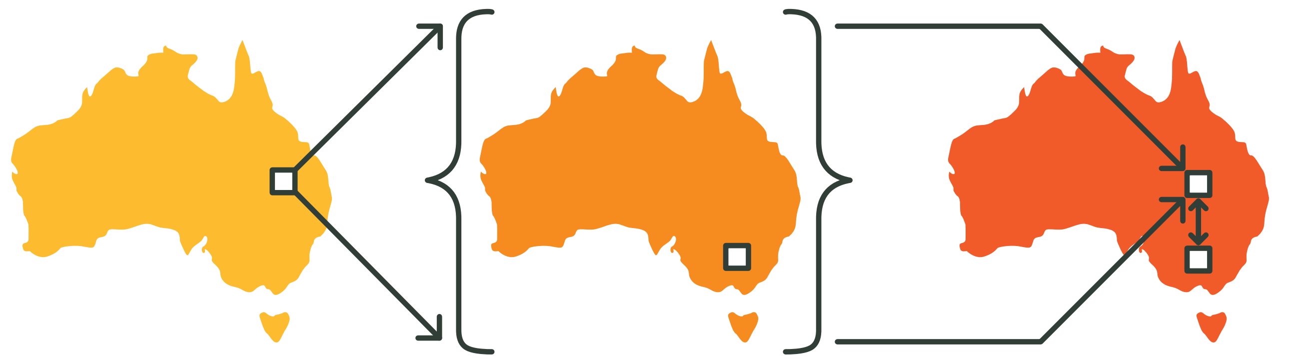
5.1 Estimating need for assisted dispersal

The calculation of *need for assisted dispersal* is relatively simple. For each location we look into the future, to find the closest location anywhere in Australia that has an *ecological similarity* of at least 0.5 (i.e., 50%) to the baseline (1990) ecological environment. The geographic distance to that location in kilometres is the measure, *need for assisted dispersal* (Figure 8).

Where the *ecological similarity* between the baseline (1990) and the future is 50% or more within a location, the closest location will be the baseline location itself; i.e., *need for assisted dispersal* will be zero. In many cases, there will be a location within the local region which remains at least 50% similar in the future, leading to low distances for *need for assisted dispersal*. However, where local change is high, similar ecological environments may only be found a lot further away.

FIGURE 8

Schematic describing the calculation of *need for assisted dispersal*, which is reported in units of distance (e.g., km) and uses a threshold for projected ecological similarity to match places (e.g., 50%).



In some cases, no future locations may be found within the ecological similarity threshold. An arbitrary maximum distance of 10,000 km is given to these locations. These extreme distances are similar in concept to *disappearing ecological environments* described in *Implications of Climate Change for Biodiversity*.

The threshold for *projected ecological similarity* of 50% used in this calculation means that around half the species present at a location would be expected to persist there into the future. This threshold is arbitrary, and the calculation can be applied to any threshold. It may be useful to explore higher thresholds of *ecological similarity* to support a particular planning scenario (e.g., 70%), recognising that fewer locations will meet this criterion. This may be useful for targeting likely successful translocations for high priority species or ecological communities. More generous thresholds (lower *ecological similarity*) mean there is less chance for a species to survive in the destination location (e.g., 35%).

HIGHEST VALUES

for *need for assisted dispersal* are similar in concept to *disappearing ecological environments*.

5.2 Need for assisted dispersal – the national context

The national pattern of *need for assisted dispersal* for vascular plants is illustrated in Figure 9 for the high emissions' *hot CanESM2* climate scenario (2050).

The light greens and yellows on the map suggest that a significant proportion of vascular plants across large parts of inland Australia are likely to need to disperse moderate to long distances (50-400 km) to find similar ecological environments under this climate scenario (projecting 60 years of change since 1990). A more limited number of locations are presently more than 500 km from potentially similar ecological environments in the future (oranges).

These distances are likely to be beyond the dispersal capacity of many plant species. For example, dispersal of *Eucalyptus* seed is generally poor (thought to be similar to the height of the tree). A study of *Eucalyptus cladocalyx*[5] showed successful colonisation rates equivalent to only about one metre per year.

Locations where similar ecological environments are expected to be found in abundance in the future could be considered worthy of further investigation for assisted dispersal opportunities. Further investigations might include identifying potential priority species from the source locations that have special value to society, evaluating which species are less likely to be able to disperse across the distances involved, and identifying environmentally suitable places where relocation is supported by local communities.

VASCULAR PLANTS

are likely to need to disperse moderate to long distances to find similar ecological environments in the future.

THESE DISTANCES

are beyond the known dispersal capacity of many species.

[5] Ruthrof et al. (2003)

THERE ARE ALSO MANY PLACES

where similar ecological environments for vascular plants may be found within 50 km so assisted dispersal may not be a priority under these scenarios.

Figure 9 also shows locations for which no potential habitat analogues of at least 50% *ecological similarity* are likely to exist on the continent by 2050 under the high emissions' *hot CanESM2* climate scenario (grey areas). These are similar to *disappearing ecological environments* introduced in ***Implications of Climate Change for Biodiversity***. In these areas, *ex-situ* conservation approaches might be considered.

Further, the map suggests there are many places where future ecological environments of at least 50% *ecological similarity* may be found within 50 km. In these locations, assisted dispersal may be a lower priority, especially for plants with effective dispersal mechanisms.

It is important to remember however, that not all species would be likely to survive in ecological environments that may be as little as 50% similar to baseline. The measure should therefore be treated as indicative only. Analyses using different *ecological similarity* levels, e.g. 70%, could also be undertaken.

The overview maps in Figure 10 show *need for assisted dispersal* for all four biological groups under the two scenarios of climate change. It is notable that under the high emissions' *mild MIROC5* scenario, the maps are mostly green, indicating habitat of >50% *ecological similarity* in 2050 is likely to be found within relatively close proximity (<50 km) across much of the continent. On the other hand, *need for assisted dispersal* appears to be significantly greater under the high emissions' *hot CanESM2* scenario across all groups.

FIGURE 9

National-scale view of *need for assisted dispersal* for vascular plants by 2050 under the high emissions' *hot CanESM2* climate scenario. This measure indicates distance in kilometres to the nearest ecological environment that is projected to be at least 50% similar to the baseline (1990) ecological environment of each cell. Grey areas (no similar cells) show where there is no match with a baseline ecological similarity of 50%. The legend is shown in categories, but the data itself is continuous.

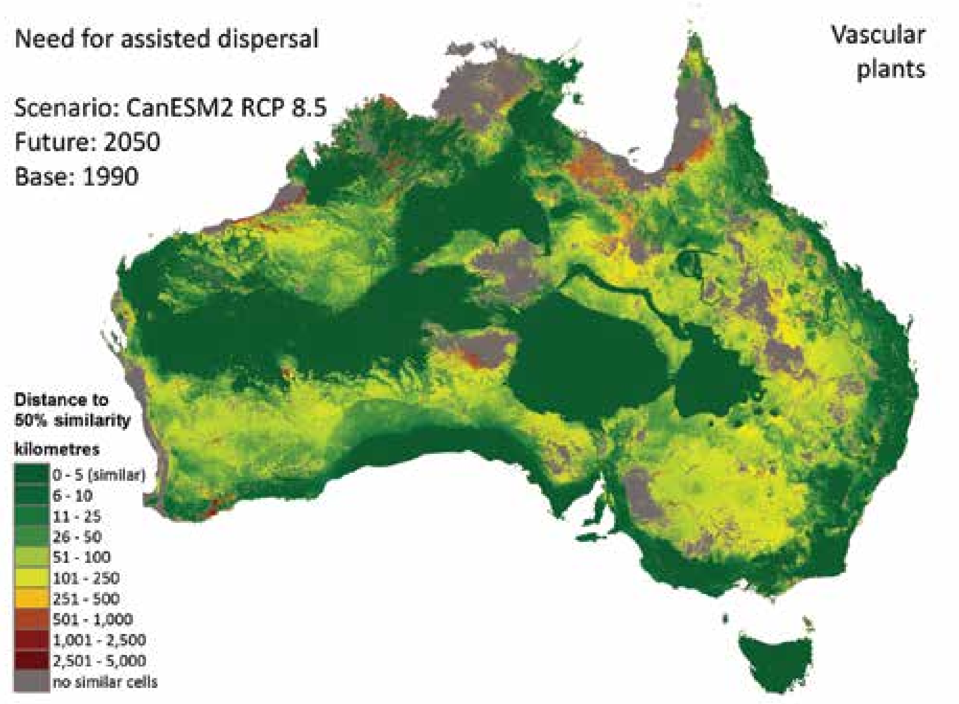
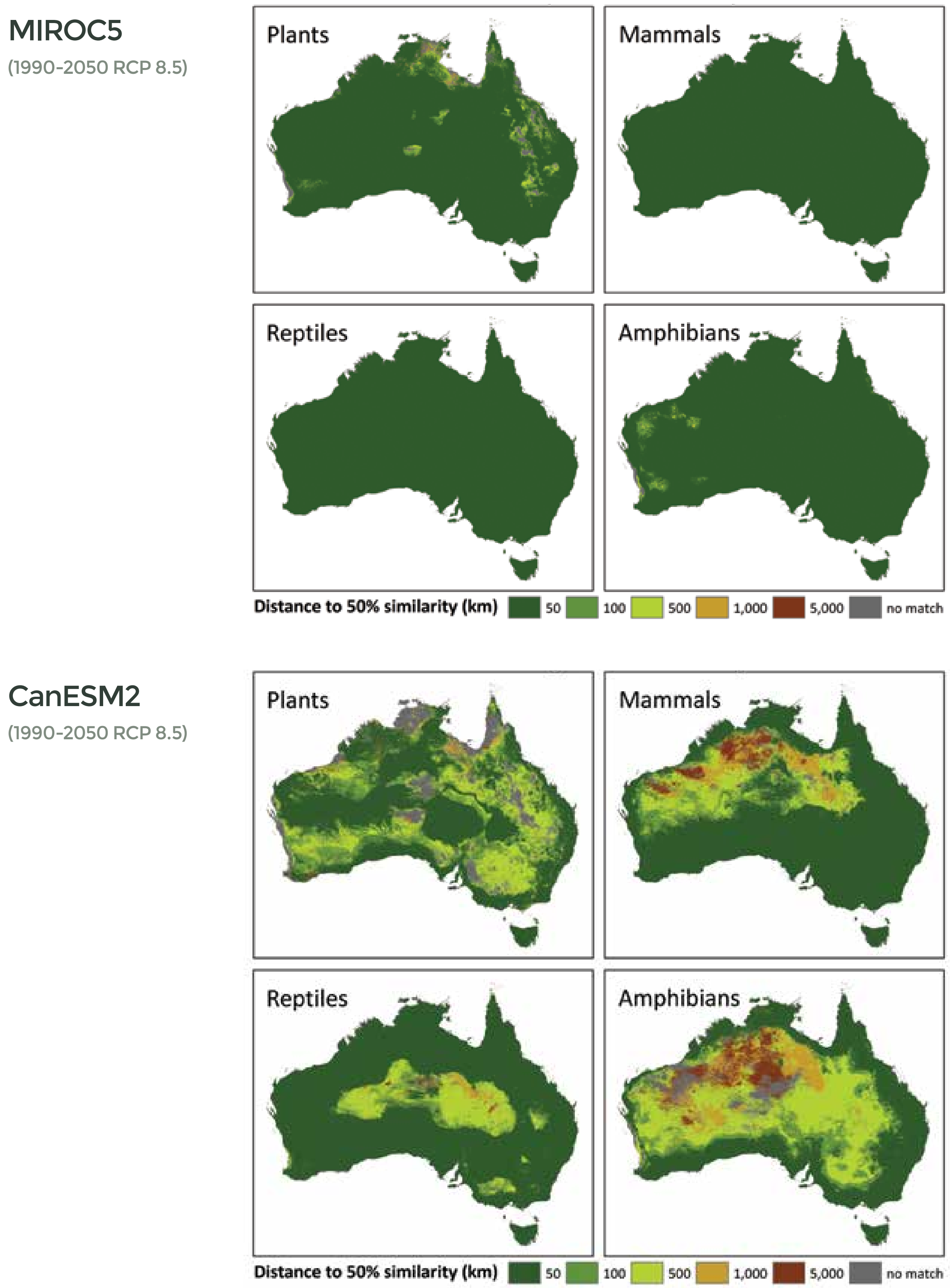


FIGURE 10

Need for assisted dispersal potentially experienced by the biota of the baseline environment (1990) under two scenarios of climate change by 2050, for four biological groups. Green colours signify less pressure, browns signify higher levels of *need for assisted dispersal* and grey areas signify places where there are no matching ecological environments with at least 50% similarity. The legend shows a few categories for ease of visual comparison, but the data itself is continuous.



5.3
Need for assisted dispersal – a regional focus

Closer examination of projected *need for assisted dispersal* can suggest places that may benefit from monitoring for sudden or significant declines in population abundance of climate-sensitive species. These could herald the need for immediate action such as assisted dispersal or *ex situ* conservation.

For example, Figure 11a shows parts of northern Australia where mammals are projected to experience highly variable *need for assisted dispersal* by 2050 under the high emissions' *hot CanESM2* climate scenario. There is a clear geographic disjunction south of Katherine where the measure shifts from low (greens) to high (oranges) *need for assisted dispersal*, reverting to low again around Tennant Creek.

Many of the small mammals occurring in this semi-arid, north western region were historically distributed across a wide range of rainfall and temperature regimes. The areas with long distances to potentially suitable environments (oranges) may represent places where species are already likely to be approaching their thermal maxima. Here, the measure highlights potential areas for monitoring and further investigation of options for assisted dispersal.

At baseline, the average temperatures of the warmest month are around 38°C in the more extreme orange and brown areas (39°C for the grey areas) in Figure 11a. Under the high emissions' *mild MIROC5* climate scenario by 2050, average temperatures are expected to have increased by 2°C to 40°C, and under this projection ecological environments of at least 50% ecological similarity for mammals are expected to remain close-by (within 50km, Figure 10).

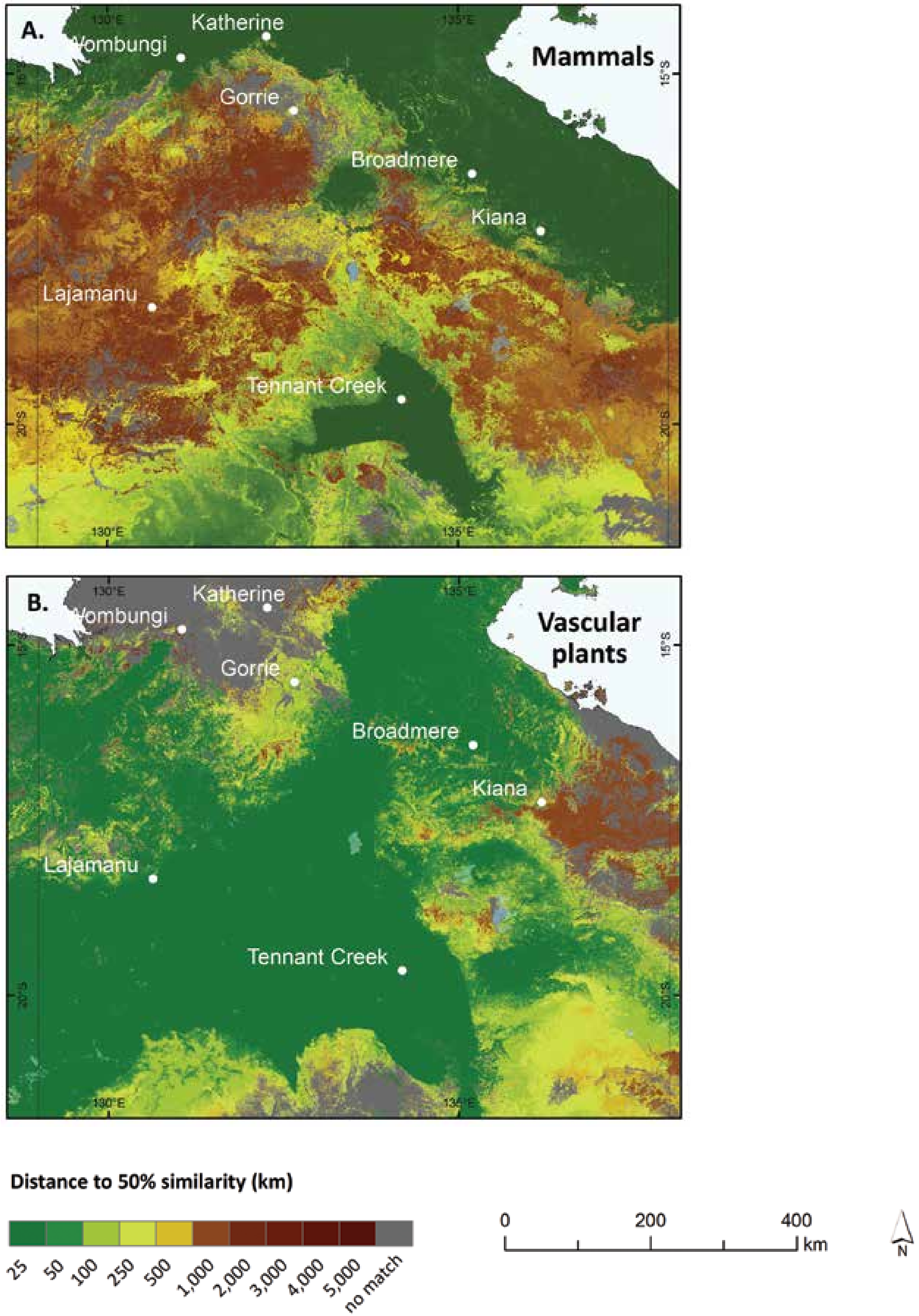
However a step-change in response is apparent between the high emissions' *mild MIROC5* and the *hot CanESM2* scenario (compare Figure 11a with scenarios for mammals in Figure 10), corresponding with average temperature increases to up to 42°C under the *hot CanESM2* scenario. These future average temperatures exceed that experienced across this region for at least 20,000 years[6]. The projected future ecological environments therefore represent conditions near the limits of climatic tolerance and may exceed the ability of some mammal species to adapt locally. Dispersal may be the only option for persistence, and the data suggest that some species would need assistance to disperse the significant distances required to find even moderately suitable habitat.

The persistence of suitable vegetation types for shelter and food will be a key factor in determining the outcome for small mammals with limited dispersal ranges. These dependencies are only indirectly represented in the biological models through their common relationship with climate, substrate and landform. Therefore it makes sense to consider the projected outcomes for vascular plants and mammals together (compare Figure 11a and b). This comparison suggests a more optimistic view for plant communities, although some of the northern areas that may remain climatically suitable for mammals may become novel ecological environments for vascular plants, with potential cascading implications for fauna.

Image Left: Lake Magenta, Source: Kevin R Thiele

FIGURE 11

Need for assisted dispersal for mammals (A) in parts of the Northern Territory under the high emissions *hot CanESM2* climate scenario by 2050, compared with the same scenario for vascular plants (B).



Potential for climate change refugia

SECTION 6

Protecting and managing refugia – places where biodiversity will retreat to and persist but be rarer than at present – may be one of the few ways to help some species and ecological communities to survive the changing climate.

Image Below: Locally moist environments in otherwise dry savanna landscapes provide current-day refugia for Kimberley rainforest species, Source: Suzanne Prober

Biological refugia can be defined in different ways. The measure we introduce falls within the increasingly accepted definition of refugia as 'habitats that components of biodiversity retreat to, persist in, and can potentially expand from under changing climatic conditions'[7]. For example, if the climate dries out, widespread species may retreat to and persist in wetter areas such as gullies. If the climate warms, species may move to and persist in rare cooler sites, at higher altitudes or on south-facing slopes.

Refugia can arise where the climate itself remains relatively stable compared with other places, so species are able to persist in those locations. Local areas of relative climatic stability until 2050 are evident from our measure of the *potential degree of ecological change*, provided in ***Implications of Climate Change for Biodiversity***. Areas projected to undergo low levels of ecological change under a future climate scenario are potentially valuable refugia for the biota they presently support.

Refugia can also be places that don't presently support a particular biological community, but become more suitable for it in the future. Areas that support biological communities that are locally common now but will be rare in the future are particularly important priorities for biodiversity planning, because they might be the last remaining places where these biological communities or their component species can survive.

To be effective as refugia under climate change, these also need to be places that species are likely to be able to reach through their own dispersal capabilities.

Here we describe an index termed *refugial potential* that aims to capture these attributes – expected future rarity of once more common ecological environments, and adequate proximity to present-day occurrences.

6.1 Estimating refugial potential

Our calculation of *refugial potential* uses the concept of *effective area of similar ecological environments* to estimate the baseline and future extent of an ecological environment. *Effective area of similar ecological environments* is introduced in ***Implications of Climate Change for Biodiversity***, but is adjusted here to look from the viewpoint of the future ecological environment of the location of interest.

To account for the limitations of dispersal, our calculation assumes that plants and animals of the baseline period (1990) will only be able to disperse 100km at most to access new areas that are becoming suitable for them by 2050 (i.e., over a period of 60 years in this case). We use a dispersal distribution in our calculations rather than this single limit – one which simulates a typical dispersal distance of 10km and allows for occasional greater distances up to 100km (see Technical Note 4).

[7] Keppel et al. (2012)

THE TERM REFUGIUM

refers to a habitat that species are able to retreat to, persist in, and expand from under climate change.

THE MEASURE

potential degree of ecological change indicates areas of relative climatic stability in the future. Places of low projected change may be valuable refugia.

REFUGIA

can also be areas that don't currently support a biological community, but will become more suitable for it in the future, particularly if these environments are rare in the future.

EFFECTIVE REFUGIA

need to be reached through species' own dispersal capabilities.

OUR NEW MEASURE,

refugial potential, is an index of future rarity of ecological environments and their proximity to present-day locations of those environments.

Two distinct attributes are considered in the estimation of *refugial potential*:

- First, we estimate how well the future (e.g., 2050) ecological environment of a location represents baseline (1990) ecological environments within the 100 km radius – the more similar cells within the radius, the greater the score for the location as a refugium for the biota of baseline ecological environments.

- Second, we estimate how rare the future (2050) ecological environment of the location may be within the 100km radius in the future (2050). We assume that rarer ecological environments will be more vulnerable to losses in biodiversity due to inappropriate management, and so will benefit from earlier intervention for their protection. Hence the rarer the ecological environment in the future, the greater the score assigned to refugial potential.

The result is a relative index, applied spatially, that shows areas that are likely to support ecological environments in the future that will have become much rarer locally than they were during the baseline period (1990).

More detail about how this index is calculated is provided in Technical Note 4.

6.2 Refugial potential – the national context

ACROSS THE BIOLOGICAL GROUPS

and climate scenarios, higher *refugial potential* is projected for areas with high topographical relief, such as the Great Dividing Range.

The national pattern of *refugial potential* for amphibians is illustrated in Figure 12, for the high emissions' *hot CanESM2* climate scenario (2050).

This shows distinct areas with higher *refugial potential* (darker greens) concentrated in areas where there is greater topographic relief, especially around the eastern and northern coastal rim of Australia and across Tasmania. Some inland ranges also show distinctly higher *refugial potential*, particularly the MacDonnell Ranges in central Australia, and the Hamersley Range in the Pilbara region of Western Australia. These places have greater potential as refugia for a high proportion of the local amphibian biota.

Higher *refugial potential* in areas of high topographic relief would be expected because variation in elevation and aspect often contribute to local variation in temperature and moisture, which are typically important determinants of species distributions. This in turn often means that areas suitable in the future for present-day biological communities are more likely to be nearby.

Image Above Left: Giant Burrowing Frog (*Heleioporus australiacus*)
Source: © Stewart Macdonald / Ug Media

Locations with low *refugial potential* (white and lighter greens) reflect future ecological environments that are projected to be more common in 2050 than they were in the baseline (1990) climate, within the 100km radius. This could result because:

- the projected future (2050) ecological environment is relatively uncommon within 100 km in the baseline period (i.e. the numerator is small), or

- the projected future (2050) ecological environment is projected to be relatively common within 100 km in 2050.

A visual comparison of *refugial potential* across the biological groups is given in Figure 13 for the two high emissions' climate scenarios. Areas with relatively high *refugial potential* across most climate scenarios and biological groups include the Great Dividing Ranges, Tasmania, and coastal North Queensland between Townsville and Cairns. Other areas of high *refugial potential* appear only for some biological groups or climate scenarios.

FIGURE 12

Index of *refugial potential* for amphibians under the high emissions' *hot CanESM2* climate scenario. Darker greens indicate greater potential as refugia for more of the local biota. The legend is shown in categories, but the data itself is continuous.

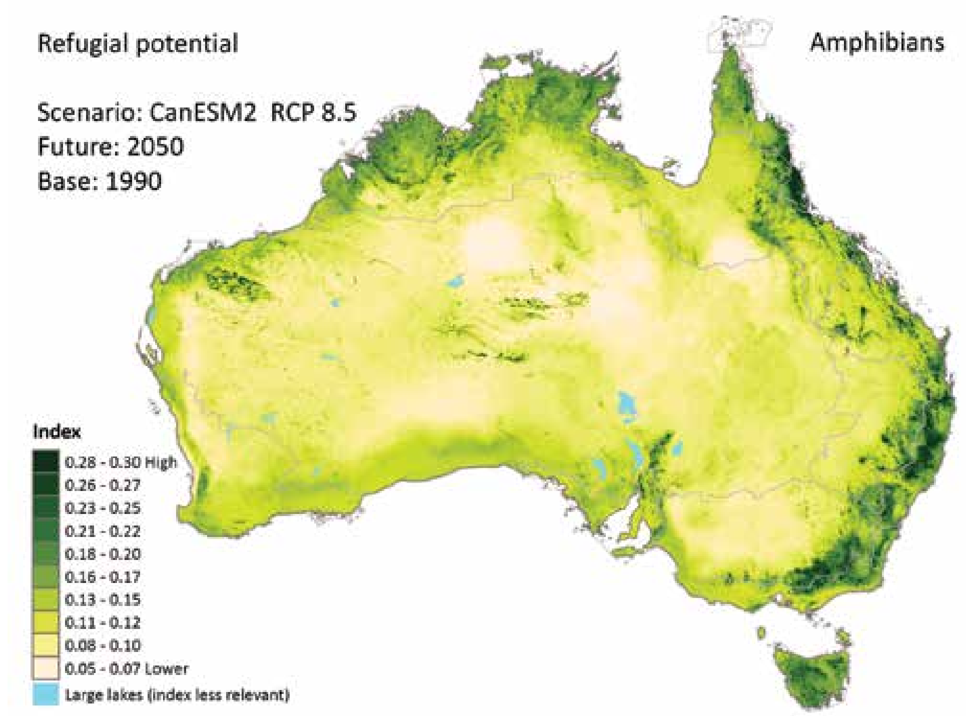
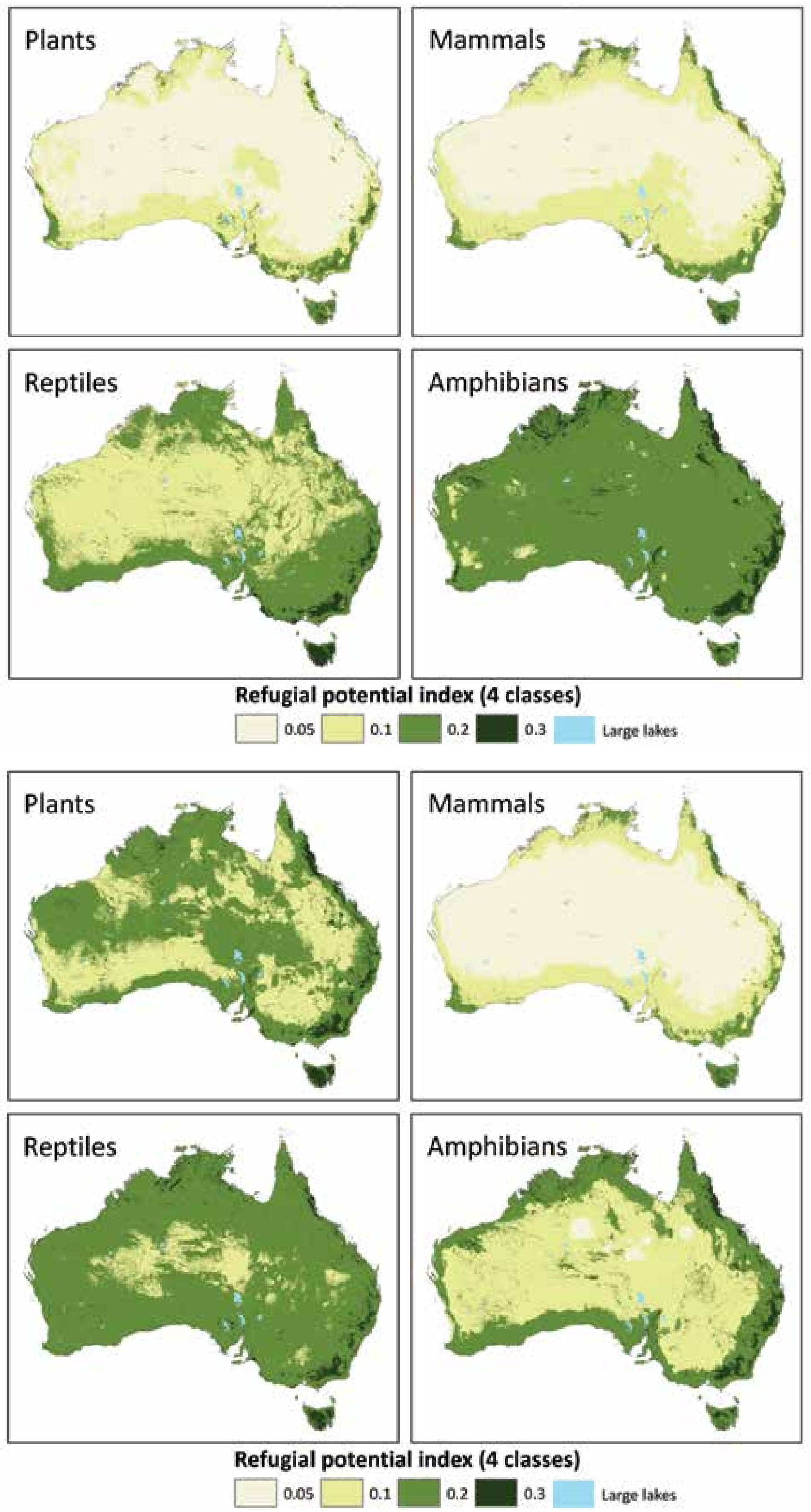


FIGURE 13

Index for *refugial potential* under two scenarios of climate change, for four biological groups. Darker colours signify higher *refugial potential*; lighter colours signify lower scores. While the legend shows four categories for ease of visual comparison, the data itself is continuous.

MIROC5
(1990-2050 RCP 8.5)

CanESM2
(1990-2050 RCP 8.5)



6.3 Refugial potential – a regional focus

Compared with areas of low *refugial potential* observed across the extensive, subdued landscapes of inland Australia (Figure 13), this region appears to highlight an opportunity for conserving reptile diversity in an arid environment.

The Channel Country is a region of very low rainfall (<200 mm annually), characterised by its broad, slow-flowing drainage systems that receive water from rain falling higher in the catchments of western Queensland. Owing to the minimal topographic relief, the water spreads widely from the main river channels during times of flood. It is likely this creates local gradients in moisture availability (the equivalent of topographic effects in more mountainous areas), potentially providing future local refugia for reptiles that are better adapted to baseline (1990) ecological environments.

We continue to see patterns of moderate *refugial potential* related to the river channels under the high emissions' *hot CanESM2* scenario, but there is some variation (Figure 14b). For example, the *refugial potential* of the broad flood plains and channels south-west of Windorah tends to decline, while many of the tighter river channels retain or increase in *refugial potential.*

We have seen from the national context maps (Figure 12 and Figure 13) that areas with high *refugial potential* are more commonly found in areas of high topographic relief, due to the local presence of many different microenvironments.

In Figure 14, which depicts the Channel Country, we see a more unusual pattern in *refugial potential*. For reptiles under the high emissions' *mild MIROC5* climate scenario, moderate *refugial potential* is apparent on the major floodplains, with intervening areas of lower potential.

REGIONAL VIEWS OF THE DATA

reveal that *refugial potential* can be associated with other types of diverse microenvironments like gradients in moisture availability across inland floodplains.

Image Right: Striped Possum (*Dactylopsila trivirgata*),
Source: © Stewart Macdonald / Ug Media

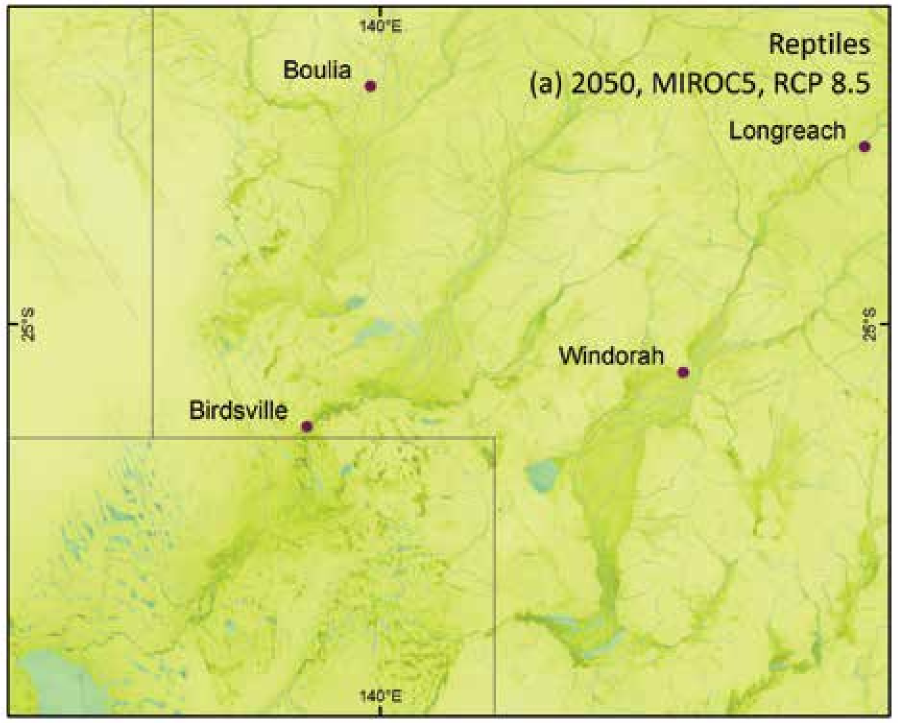
Image Below: Coopers Creek floodplain, Source: Suzanne Prober

FIGURE 14

(a) *Refugial potential* for reptiles in the Channel Country at the intersection of the Queensland, NSW and South Australian borders, under the high emissions' *mild MIROC5* climate scenario; and (b) *hot CanESM2*. Image shows baseline lakes and drainage lines in blue for context.

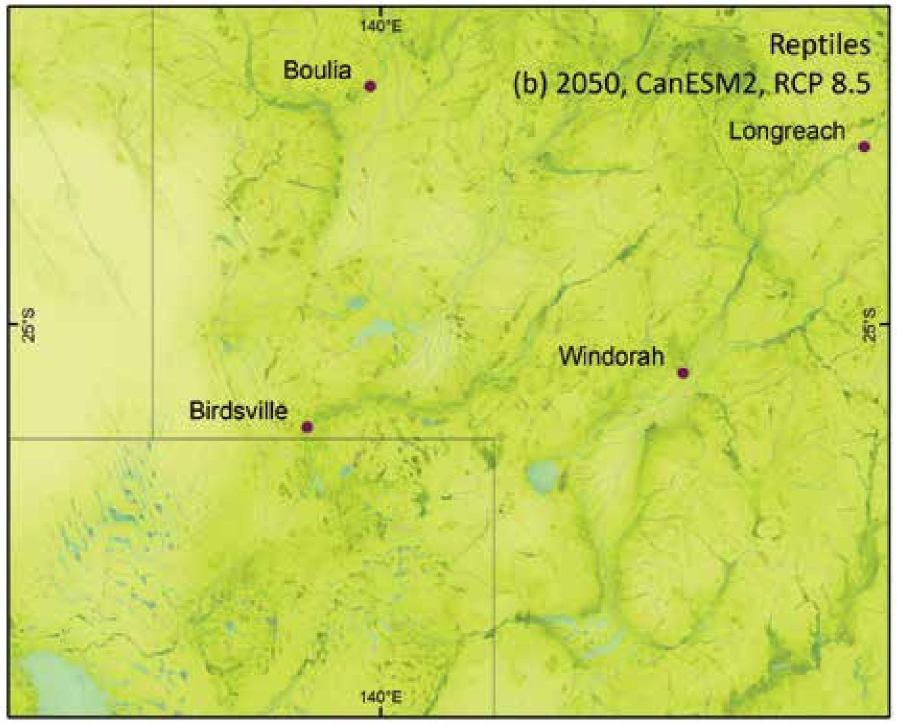
MIROC5

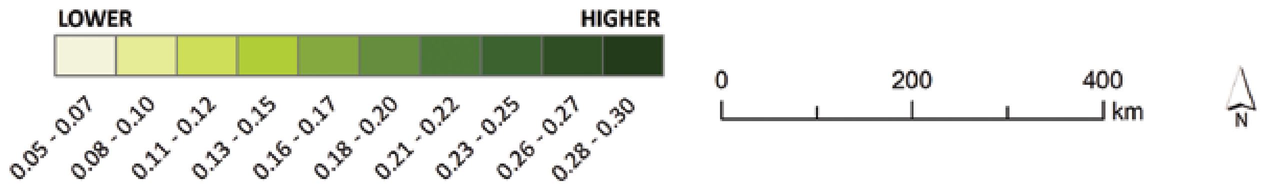
(1990-2050 RCP 8.5)



CanESM2

(1990-2050 RCP 8.5)





Planning for biodiversity in a changing climate: a summary

SECTION 7

Across the two AdaptNRM Biodiversity Guides *Implications of Climate Change for Biodiversity* and *Helping Biodiversity Adapt*, we proposed new principles and strategic goals to underpin biodiversity conservation decisions in a changing climate, and introduced a suite of novel climate adaptation planning tools and datasets that can help inform these decisions.

Image Below: Reflections on the lake at the Hunter Wetlands Centre
Source: Sarah Stuart-Smith, Credit: ©Department of the Environment

The inevitability of change in the composition and structure of ecological communities with climate change challenges current approaches to biodiversity conservation. The two biodiversity modules aim to help natural resource managers incorporate climate change perspectives into biodiversity conservation planning, by providing projections on potential changes in biodiversity and potential benefits of intervention options, supported by new principles to help set biodiversity conservation goals.

7.1 The biodiversity projections and tools in brief

The first AdaptNRM Module in the biodiversity series, ***Implications of Climate Change for Biodiversity***, explains the key concepts underpinning the community-level modelling approach used to estimate change for biodiversity as a whole. It introduced a suite of measures comparing baseline and future ecological environments, as follows (defined in Box 1):

- the *potential degree of ecological change* at a location; as a simple measure of the potential for future persistence of biodiversity within that location
- the potential for extreme ecological outcomes *(novel ecological environments* and *disappearing ecological environments*), where present-day environments may disappear in the future, and where novel environments may arise from a biotic viewpoint
- the concept of change in *effective area of ecological environments*, for measuring change in the capacity of future landscapes to support their original biodiversity, including interactions with natural area clearing patterns
- *composite ecological change*; an integrated measure that combines the implications of *potential degree of ecological change, novel environments and disappearing environments* to identify five general types of change that may need different strategic planning approaches

This second AdaptNRM Module in the series, ***Helping Biodiversity Adapt***, introduces four tailored measures that aim to inform these adaptation options:

- *projected distribution of vegetation types* is a measure of how the pattern of present-day vegetation communities may alter spatially with climate change
- *revegetation benefit* is an index highlighting where revegetation using contemporary practice is potentially most beneficial in a changing climate

Image Right: Yellow-spotted monitor (*Varanus panoptes*),
Source: © Stewart Macdonald / Ug Media

- *need for assisted dispersal* indicates the geographical distance an organism may need to disperse to reach a potentially suitable environment under the projected future climate scenario, informing whether organisms may need assistance to disperse or other conservation support
- *refugial potential* is an index identifying where ecological refugia may be located within a local region under future climate scenarios

The Guides use two indicative climate scenarios to simulate change between a baseline period (1990) and a future (e.g., 2050). They assume continuation of recent trends in high rates of global greenhouse gas emissions signified by RCP 8.5. One future represents a relatively mild degree of change using the *MIROC5* global climate model, and the other is more extreme (hotter) using the *CanESM2* model. Projections are provided for four biological groups (vascular plants, mammals, reptiles and amphibians).

We chose the high emissions trajectory to demonstrate the possible outcome for biodiversity by 2050, indicative of the ecological potential to respond to the changing climate. The climate models selected are not necessarily the most extreme or mild for this scenario and vary in this respect regionally, across Australia. Scenarios other than the two presented here could be generated.

Data and maps are available through the ***CSIRO Data Access Portal***. The two Guides are intended to serve as an ongoing resource as we develop refined models and apply different scenarios over time.

7.2 Limitations to the tools

Through the two AdaptNRM biodiversity Modules we have highlighted limitations of the modelling approach that users need to be aware of. Many of these limitations are common to all modelling approaches. We can't know exactly what the future will hold, and models always make assumptions that may not turn out to be completely appropriate, so it will be important to avoid interpreting them too strictly or precisely. The resulting datasets provide insights into the degree and types of change that, on the balance of evidence at hand, are likely to be experienced.

We recommend using the datasets and maps in conjunction with the planning principles introduced in ***The NRM Adaptation Checklist***. These include planning for multiple futures, maintaining flexibility, preparing for likely future decisions, and strengthening the adaptive capacity of people and organisations.

7.3 Applying the datasets and maps to NRM planning

Our aim has been to explain the general concepts and principles underlying the datasets and maps provided, and to demonstrate how they might be used by natural resource managers in their own regions.

Planners can familiarise themselves with the different measures using the Guides, then choose their preferred approaches to help inform planning for biodiversity conservation and adaptation under climate change. Different measures may be used towards different types of objectives. In most cases it will be beneficial to base decisions on multiple measures combined with additional local knowledge and information.

To facilitate uptake of these new datasets, we discussed how they relate to a suite of emerging principles underpinning biodiversity conservation in a changing climate, and introduced ideas for further discussion. We then assembled a toolbox of potential adaptation options to which these principles can be applied (Section 2).

For example, the simple measure of *ecological similarity* between the present and a projected future (i.e., the *potential degree of ecological change*) indicates the imperative to change our expectations – and hence how much we shift the focus from conserving current species compositions, towards, for example, 'Optimising ecological processes' at the site scale and 'Minimising species loss' nationally.

For distinctly changing places (i.e., where we have low *ecological similarity* between the present and a future) or *novel ecological environments*, the principles of 'Maintaining the evolutionary character of the Australian biota' and 'Maintaining unique regional character', and the measure *projected distribution of vegetation types* can all help inform which species we focus on to help new ecosystems assemble.

For declining environments (with a high *change in effective area of similar ecological environments*) the principle to 'Minimise species loss nationally' could trigger greater protection of areas likely to represent these environments in the future, especially areas with high *refugial potential*. Further, the measure for describing the *revegetation benefit* indicates how revegetation can contribute to conserving biological communities of declining environments, and the measure for *need for assisted dispersal* provides an indication of where investments in assisted dispersal can contribute to this goal.

Integrating these multiple resources to arrive at a strategic approach is challenging, but the tools provided allow users to develop their own approaches tailored to their needs and resources. For example, Box 9 illustrates how the North West Local Land Services natural resource management region in NSW is planning to combine the new principles and measures to incorporate climate change considerations into their next planning process.

Image Right: Frilled Dragon (*Chlamydosaurus kingii*)
Source: © Stewart Macdonald / Ug Media

BOX 9

Integrated use of AdaptNRM information by North West Local Land Services

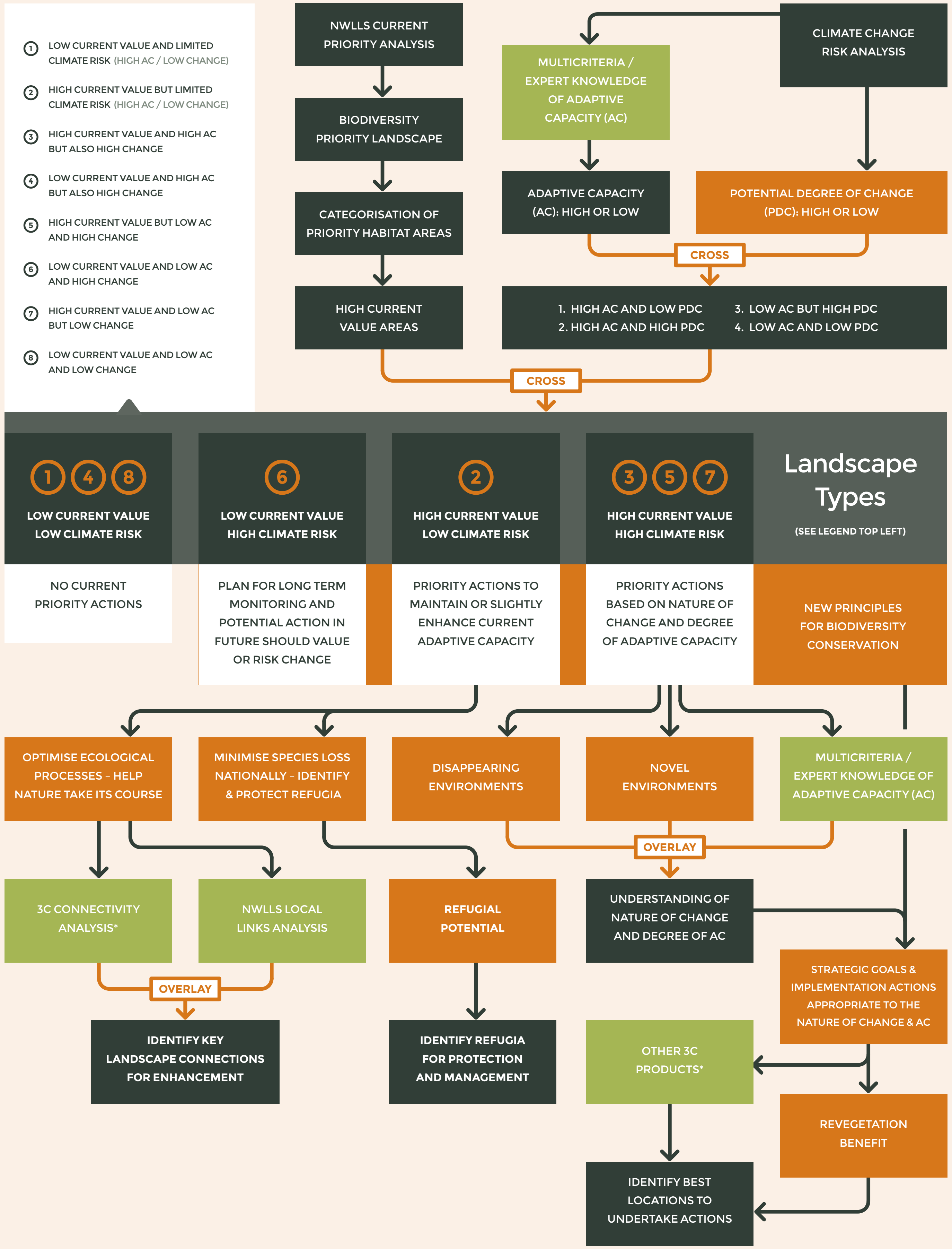
The approach to new principles for biodiversity conservation and the innovative new measures of impacts and potential adaptation options introduced in the two AdaptNRM biodiversity modules are intended to be viewed as a single set of tools to assist planning and management of our nation's biodiversity, especially at regional and local scales. While not all users will find all of our measures relevant, thinking of them as a single package can help to reduce 'information overload' and ensure they are used in concert, alongside other information, to facilitate the best outcomes.

One example of using the AdaptNRM information as a package, and integrating it with existing biodiversity analyses, comes from North West Local Land Services (NWLLS) in New South Wales. NWLLS are completing a multi-criteria analysis to identify priority areas for biodiversity conservation in their region. This analysis will assign scores for relative biodiversity priority to NWLLS landscapes, based on existing information on biodiversity assets and their values, but not yet incorporating climate change. NWLLS then intend to refine their priority landscapes and the associated actions that might be taken to support them using recently released climate change analyses on biodiversity impacts and adaptation options.

The AdaptNRM team scoped a draft process with NWLLS in a workshop in Canberra on the 15th April 2015, to understand where various products could best be used. While the final approach that will be used by NWLLS in their Biodiversity Prioritisation Plan process may be modified, this case study presents a draft conceptual framework discussed during the workshop. The full draft process is depicted in the following flowchart, in which AdaptNRM products are shown in orange. Its key features include:

- Using the *potential degree of ecological change* as a combined measure of exposure and sensitivity in a risk analysis.
- In that risk analysis, combining a binary layer of *potential degree of ecological change* with a binary layer of adaptive capacity to produce four risk categories.
- Crossing those risk categories with a binary layer of current value (from the existing biodiversity prioritisation analysis) to produce eight landscape types that differ in current biodiversity value, degree of potential ecological change, and existing adaptive capacity – low adaptive capacity and/or high potential change constitute a climate-related risk for areas with high current biodiversity value.
- Using those landscape types, combined with consideration of new principles for biodiversity conservation, to identify priority landscapes for three broad approaches – monitoring future change, maintaining adaptive capacity, and engaging in more advanced adaptation planning.
- For more advanced adaptation planning (for landscapes with high current value and high climate-related risk), using disappearing ecological environments and novel ecological environments as well as an understanding of adaptive capacity to consider not just the amount of risk but the nature of the risk as well.
- Using information on new principles, strategic goals, and potential implementation actions to target actions to the nature of the risk (e.g., where novel ecological environments are likely to arise but adaptive capacity may be low, support the assembly of new communities based on native species using connectivity restoration and assisted dispersal if necessary).
- Planning to implement actions based on spatial analyses of their effectiveness in the future.

This process might initially focus on using the AdaptNRM measures for vascular plants, but additional species groups could be included later. It should also be repeated for multiple climate scenarios with final decisions made based on the collective results. It may not be ideal, and other options are certainly possible, but multiple AdaptNRM products can be used alongside other information to create a consistent approach to climate-ready adaptation planning for biodiversity.



* Drielsma et al. (2014)

In conclusion

The AdaptNRM resources provided across the two biodiversity modules, underpinned by an emerging set of new principles and strategic goals for biodiversity conservation decisions, provide an opportunity to change the way we think about and plan for the future of biodiversity in a changing world. Australia's biodiversity - our biodiversity - will change. Yet we can plan for, support, and guide that change to ensure we will still live in a world full of the richness and wonder of biodiversity and be sustained by the services it provides.

Image Right: Landcare planting at Razorback, south western Sydney, Source: Greater Sydney Local Land Services, Credit: Esther Beaton

Image Below: Local flora in Kakadu National Park, Source: Michelle McAulay, Credit: ©Department of the Environment

Glossary of technical terms and definitions used in this Guide

Term Used In This Guide	Definition
Adaptation Pathways	Adaptation pathways aim to inform decision makers about integrating incremental actions on proximate causes with the transformative aspects of societal change, defined by Wise et al. (2014). Adaptation pathways concepts help inform robust decision making under uncertainty.
Alien species	A species occurring outside its natural past or present range and dispersal potential in the timeframe under consideration, its presence being due to human actions (either deliberate or accidental). The same meaning as non-indigenous, exotic and non-native (see AdaptNRM Module ***Weeds and Climate Change***).
Atlas of Living Australia	The ***Atlas of Living Australia*** contains information on all the known species in Australia aggregated from a wide range of data providers: museums, herbaria, community groups, government departments, individuals and universities. Data from the Atlas has been used in developing the biodiversity models for this Guide.
Assisted dispersal	The 'intentional translocation or movement of species outside of their historic ranges, in order to mitigate actual or anticipated biodiversity losses caused by anthropogenic climatic change' (Hewitt et al. 2011)
Biological refugia	'Habitats that components of biodiversity retreat to, persist in, and can potentially expand from under changing climatic conditions' (Keppel et al. 2012)
Bray-Curtis dissimilarity	Bray–Curtis dissimilarity is a statistic used to quantify the compositional dissimilarity between two different sites, based on counts at each site. The index varies from 0 (identical) to 1 (completely different).
CanESM2 climate model	Developed by the Canadian Centre for Climate Modelling and Analysis, and is the second generation of Earth System Models developed by that centre. The new model couples together an atmosphere-ocean general circulation model, a land-vegetation model and terrestrial and oceanic interactive carbon cycle. For more information see Chylek et al. (2011).
Change in effective area of similar ecological environments	The extent within a specified area to which a particular habitat may have changed in its suitability and therefore reduced or increased capacity to support its original biodiversity, for example due to climate change and/or land clearing patterns. If there is a loss of similar ecological environments, we expect a corresponding loss of original biodiversity, and vice versa.

Term Used In This Guide	Definition
Climate adaptation services	The benefits to people from increased social ability to respond to change, provided by the capability of ecosystems to moderate and adapt to climate change and variability (Lavorel et al. 2014).
Climate Futures Framework	A new approach to exploring climate projections that reduces the level of complexity for the end-user. It allows the user to generate climate change projections tailored to their application, whether it is a general overview of climate change for a region, an investigation of likely threats and opportunities, or a detailed risk assessment using impact models. For more information see, *Climate Futures Framework*, Whetton et al. (2012) and Clarke et al. (2011).
CMIP5	The Coupled Model Intercomparison Project (CMIP) is a framework and the analogue of the Atmospheric Model Intercomparison Project (AMIP) for global coupled ocean-atmosphere general circulation models. *CMIP5* is the current (2010-2014) phase of the project, and will include more metadata describing model simulations than previous phases.
Community-level modelling	Combines data from multiple species and produces information on spatial pattern in the distribution of biodiversity at a collective community level. This approach contrasts with species-level modelling which models the pattern of distribution, one species at a time. Community-level modelling uses measures derived from multiple species occurrences, ideally from comprehensive survey data, such as the number of species at a site or a measure of compositional differences in species between pairs of sites (i.e., macro-ecological properties of the ecosystem). Ferrier and Guisan (2006) published a review of community-level modelling. Also see macro-ecological modelling.
Compositional dissimilarity	A measure of the differences in biological composition between two sites, termed beta diversity. The Bray-Curtis dissimilarity index is a statistic used to quantify the compositional dissimilarity between two different sites, based on counts at each site.
Compositional turnover	Sometimes used loosely as a synonym with compositional dissimilarity, but is not necessarily the same calculation. It is a measure of the replacement of species along a gradient, for example, how many times the species composition changes completely with distance between two locations.
Data access portal (CSIRO)	The *CSIRO Data Access Portal* provides access to data published by CSIRO across a range of disciplines. The portal is maintained by CSIRO to facilitate sharing and reuse of data held by CSIRO.
Disappearing ecological environments	Occurs where a present-day environment has a low similarity to its most similar environment in the future. It is estimated by comparing locations within a specified neighbourhood, such as the entire continent of Australia. The concept of novel and disappearing climates derives from Williams et al. (2007), and is applied here to projected ecological similarity. Disappearing ecological environments are scored on a scale of ecological similarity from 0 (completely different and disappeared) to 1 (identical and not at all disappearing).

Term Used In This Guide	Definition
Dispersal kernel	A probability distribution of the distance travelled by an individual
Dissimilarity	Is the inverse of similarity, where dissimilarity = 1-similarity
Ecological change	Refers to how different two places are in their biota, or how the biota at one place varies over time. Change refers to a comparison of some sort. Ecological refers to a measure of ecosystem properties of some sort. In this Technical Guide, the change comparison context is typically between a baseline climate (e.g. 1990) and a future climate scenario (e.g. 2050), and the ecological measure is ecological similarity. See, ecological similarity.
Ecological environments	
Ecological similarity	Ecological similarity is a term used to describe how similar two locations are in their predicted compositions, inversely related to the Bray-Curtis or Sørensen dissimilarity index. Similarity can vary from 0 (nothing in common) to 1 (effectively identical). Ecological similarity can be predicted within the same spatial and temporal domain for which the model was developed, or projected if applied to a future climate scenario. See also, projected ecological similarity.
Ecosystem function	The biological, geochemical and/or physical processes that occur within an ecosystem, including interactions between organisms and their environment, e.g. nutrient cycling, soil development.
Ecosystem service	The benefits that people obtain from ecosystems (Millennium Ecosystem Assessment, 2005)
Effective area of similar ecological environments	The proportional contribution that an area makes to overall biodiversity through habitat suitability. It is a measure of the relative capacity of any location to support all elements of its original (intact) biodiversity. If the effective habitat area is less than the original area, this indicates some loss in capacity to support all of the original biodiversity. For example, a 100ha plot of original suitable habitat may only contain 50 ha because of clearing or other driver of change. The effective area of suitable habitat within 100ha is therefore 0.5 x 100ha = 50ha. The change in effective habitat area is therefore 0.5.
Emissions scenario	Emissions scenarios describe future releases into the atmosphere of greenhouse gases, aerosols, and other pollutants and, along with information on land use and land cover, provide inputs to climate models. They are based on assumptions about driving forces such as patterns of economic and population growth, technology development, and other factors. Levels of future emissions are highly uncertain, and so scenarios provide alternative images of how the future might unfold. See representative concentration pathway.
Endemic	In relation to biota, restricted to a certain region or place.

Term Used In This Guide	Definition
Focal cell	The place, location or grid cell on the map layer (raster dataset) that is being scored for the calculation of interest.
Generalised Dissimilarity Model, GDM	A community-level modelling technique for relating compositional dissimilarity (based on species, for example) between pairs of locations to environmental distances. The compositional dissimilarity measure can be defined for any biotic phenomena including species, taxonomic or phylogenetic branch lengths, genetic entities, and so forth. Generalised Dissimilarity Modelling (GDM) was invented by S Ferrier and G Manion (Ferrier et al., 2007). It is a novel non-linear statistical method for assessing variation in the magnitude and rate of change in observations of biota along different environmental gradients.
Geographic Information System, GIS	A geographic information system (GIS) is a computer system designed to capture, store, integrate, manipulate, analyse, manage, share, and present all types of geographical data.
Grid cell	A grid cell is a location on a map layer or raster dataset that has a value representing some characteristic of that location.
Local similarity	When the projected ecological similarity is defined between the same location or focal cell at different times (i.e. the comparison is 'point on point') then the ecological similarity measure relates to the local effects of similarity. A contrasting case is when similarity of a location or focal cell is compared with other locations in a surrounding region (as is the case in defining novel and disappearing ecological environments).
Location	A non-specific term to indicate a place, site or grid cell, for which a geographic reference may be associated (e.g., longitude and latitude).
Macro-ecological modelling	Macro-ecological modelling refers to quantitative (usually statistical) methods applied in the study of relationships between organisms and their environment at large spatial scales aimed at characterising and predicting patterns of abundance, distribution and diversity. Macro-ecology is the study of the properties of the system as a whole, and such approaches are often termed 'top down'. Macro-ecological modelling is particularly valuable for highly diverse, poorly studied taxa, as it provides information relevant to all species: even those we know little about.
Macro-ecological properties	Ecosystem properties that may be observed and used in community-level or macro-ecological modelling usually related to measures of alpha, beta and gamma diversity. Most commonly modelled property is species richness (i.e., a measure of alpha diversity), either of a whole group (e.g. all vascular plants) or of a functional subgroup (e.g. annuals and trees). Many other macro-ecological properties (e.g. mean range size and endemism) can potentially be modelled. Compositional dissimilarity, as a measure of beta diversity, is also a macro-ecological property. See the review by Ferrier and Guisan (2006). See macro-ecological modelling.

Term Used In This Guide	Definition
Major Vegetation Sub-group (MVS)	The second level of classification within *Australia's National Vegetation Information System (NVIS)*. This includes 77 vegetation groups classified on the basis of key structural and floristic characteristics. NVIS is managed by the Australian Department of the Environment in partnership with State agencies.
Means-ends diagram	A means-ends diagram is a kind of conceptual model that visually shows the relationship between methodological alternatives (means) at one end and fundamental objectives (ends) at the other.
MIROC5 climate model	The MIROC5 climate model is the atmosphere-ocean general circulation model cooperatively developed in the Japanese research community. That research community is known as the Model for Interdisciplinary Research on Climate (MIROC). For more information see the article by Watanabe et al. (2010).
Multi-criteria decision analysis	Multi-criteria decision making is concerned with structuring and solving decision and planning problems involving multiple criteria. The purpose is to support decision makers facing such problems. Typically, there does not exist a unique optimal solution for such problems and it is necessary to use decision maker's preferences to differentiate between solutions.
Novel ecological environment	Occurs where a future environment has a low similarity to its most similar environment in the present. It is estimated by comparing locations within a specified neighbourhood, such as the entire continent of Australia. The concept of novel and disappearing climates derives from Williams et al. (2007), and is applied here to projected ecological similarity. Novel ecological environments are scored on a scale of ecological similarity from 0 (completely different and novel) to 1 (identical to contemporary analogues).
Potential degree of ecological change	Potential degree of ecological change is a term used in this Guide. In the context of climate change, it is an estimate of the projected ecological similarity between the same locations at different points in time, for example between a baseline period (e.g., 1990) and a future time (e.g., 2050). See also, projected ecological similarity and local similarity.
Prediction	We use the term 'predicted' or 'prediction' when referring to ecological similarity or other measures calculated using baseline climate data, for which we can validate the outcome. See also 'projection'.
Present-day	A term used in this Guide in referring to a baseline period against which change is referenced. Base or baseline is usually specifically defined in text and maps.
Pressure to change	The inverse of similarity (i.e., dissimilarity or 1-similarity) can be viewed as the potential for climate change to drive ecological change, i.e., a measure of ecological 'pressure to change'. See also projected ecological similarity and projected ecological change. These are all the same measures, simply viewed from different perspectives.

Term Used In This Guide	Definition
Projected ecological similarity	Projected ecological similarity measures how similar a single location is over two time periods in its predicted composition. Typically applied to a baseline (current) and future climate scenario. Similarity can vary from 0 (nothing in common) to 1 (effectively identical). The measure is inversely related to the Bray-Curtis or Sørensen dissimilarity index. See also 'projection' and 'prediction'.
Projection	We use the term 'projected' or 'projection' when referring to ecological similarity or other measures calculated using derived estimates of future climate. See also 'prediction'.
Proximity principle	Under climate change it may no longer be possible to use only local species in revegetation and restoration efforts. We propose using the 'proximity principle' to select species for use in these circumstances, i.e. select native species from as close-by as possible that are still likely to survive in future climates. This aims to help regions with unique biological character to remain unique even as the details of the species and communities they support changes.
Raster dataset	Spatial data is stored as a grid of cells (pixels) in a geographic information system, each with a defined location reference, where it is termed a 'raster' dataset, in contrast with other spatial data types defined by points, lines and polygons. Raster datasets represent geographic features by dividing the world into discrete square or rectangular cells laid out in a grid. Each cell has a value that is used to represent some characteristic of that location.
Representative concentration pathway (RCP)	Representative Concentration Pathways (RCPs) are four greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its *Fifth Assessment Report* (AR5). The pathways are used for climate modelling and research. They describe four possible climate futures, all of which are considered plausible depending on how much greenhouse gases are emitted in the years to come. The four RCPs, RCP2.6, RCP4.5, RCP6, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m^2, respectively). See also emission scenario. For more information see Jubb et al. (undated).
Revegetation	The re-establishment of vegetation on cleared or degraded land, through seed sowing, plantings or natural regeneration
Similarity	Used in this Guide to make macro-ecological comparisons between two locations at the same point in time or for the same location at two points in time. Note that similarity is the inverse of dissimilarity, where similarity = 1- dissimilarity. See also dissimilarity.
Sørensen dissimilarity	A statistic used for comparing the similarity of two samples, originally applied to presence/absence data. When index is used as a distance measure, 1–Similarity, it is identical to Bray-Curtis dissimilarity. See Bray-Curtis dissimilarity.

Term Used In This Guide	Definition
Spatial	Used in this Guide to refer to the geographic features of a dataset or a concept related to geographic locations or variability among many locations at once.
Species composition	Species composition refers to the number, type and if applicable, abundances and potentially other attributes of each species (e.g. phylogenetic relationships) described for a particular location or areas.
Temporal	Used in this Guide to refer to the variation over time, such as between baseline climates in 1990 and future scenarios by 2050 (i.e., different time periods).
Vascular plants	Vascular plant is a collective term for a group of highly evolved plants characterised by the ability to conduct water and minerals throughout the plant using lignified tissues (the xylem). In this Technical Guide, the models of vascular plants include species of fern, gymnosperm and angiosperms.

Biodiversity projection datasets and maps

Supporting materials and information about the community-level biodiversity models applied to climate change, and the derived measures, are available from the *CSIRO Data Access Portal*. Biodiversity projection datasets and map-posters are organised by biological group, climate change scenario and the type of measure.

We suggest that you initially access the smaller (~10Mb file size) map-posters relevant to your region for exploration while reading this Guide as these will be quicker and easier to download. You can then decide which map posters you wish to download and use for planning and/or printing (~50Mb file size, greater resolution) and which datasets (~1Gb in size) you wish to download and use with a Geographic Information System (GIS). The higher resolution map-posters (~25-50Mb) are provided to support closer examination of fine details using readily accessed image visualisation software should access to GIS be limited.

How to access datasets and map-posters on the Data Access Portal

1. Access the DAP at the following URL: *https://data.csiro.au/dap/* or search for 'CSIRO Data Access Portal' using your search engine. The link is also available on the AdaptNRM webpage, *www.adaptnrm.org*.

2. Use the search engine to locate datasets and maps you are after (see tables below for what is available). Below is a list of search terms we recommend you use.

   a. 'adaptnrm': results in all AdaptNRM products, including those associated with *Weeds and Climate Change*, *Implications of Climate Change for Biodiversity* and *Helping Biodiversity Adapt*.

   b. 'adaptnrm biodiversity': results in all AdaptNRM biodiversity products, including *Implications of Climate Change for Biodiversity* and *Helping Biodiversity Adapt*.

   c. 'adaptnrm biodiversity' plus any of the biological groups or measures of change in the table below will limit your search to more specific datasets and maps. For example, entering 'adaptnrm biodiversity assisted dispersal mammals' will result in datasets and maps for "…need for assisted dispersal for Mammals 1990:2050 CanESM2…" and "…need for assisted dispersal for Mammals 1990:2050 MIROC5…".

3. Once you have selected and clicked the map or dataset you would like to access, you will come across two tabs – the first containing a description of that data set, and the second ('data') containing links to download data. Select the files you would like to download, then click 'download selected files as ZIP archive'. The files are not always immediately available. If files cannot be selected for download by ticking the 'boxes', then a request for the data will need to be submitted. To submit a request, enter your email address in the form provided and click 'request files'. A notification and link to the data will be sent to this email address when the files have been made available. A similar process is required for accessing large collections, and additional instructions will appear in the data tab/window when applicable.

4. Map-posters are provided at a medium resolution A0 size (picture files .png) for printing as posters (~50Mb file size per poster) to use in planning if you do not use GIS datasets. The map- posters are also provided at a lower resolution (pdf files .pdf) for initial exploration (~10Mb file size each). Further information on how to use the datasets is available under the 'description' tab.

5. More information on how to use the Data Access Portal is available on *www.adaptnrm.org*, and help can be accessed from the portal at *https://wiki.csiro.au/confluence/display/dmsdoc/Find+Data*.

Map-posters available on the *CSIRO Data Access Portal*

The map–posters cover *eight broad groupings of NRM regions* based on the clusters defined in consultation with the Department of the Environment. Map-posters are provided in PNG image format at moderate resolution (300dpi) to suit A0 printing as well as in PDF format to suit initial printing and exploration at A3 size.

Each map-poster contains four dataset images coloured using standard legends. Each series is provided in two parts: part 1 shows the two climate scenarios for vascular plants and mammals and part 2 shows reptiles and amphibians, except for *projected distributions of vegetation types*. Annotation briefly outlines the topics presented in the Guide so that each map-poster stands alone as a quick reference guide.

Guide Section	Map series (continued from Implications of Climate Change for Biodiversity)	Monsoonal North	Wet Tropics	Rangelands	Central Slopes	Murray Basin	East Coast	Southern Slopes	Southern & Flatlands	National
3.2	7.(1-77). Probability distributions of each of 77 vegetation types for a) 1990 baseline, and b) 2050 scenarios									✓
3.3	8.1 Generalised projected distribution of vegetation types for a) 1990 baseline, and b) 2050 scenarios	✓	✓	✓	✓	✓	✓	✓	✓	✓
4.2	9.1 Revegetation benefit for vascular plants and mammals (1990-2050)	✓	✓	✓	✓	✓	✓	✓	✓	✓
4.2	9.2 Revegetation benefit for reptiles and amphibians (1990-2050)	✓	✓	✓	✓	✓	✓	✓	✓	✓
5.2	10.1 Need for assisted dispersal for vascular plants and mammals (1990-2050)	✓	✓	✓	✓	✓	✓	✓	✓	✓
5.2	10.2 Need for assisted dispersal for reptiles and amphibians (1990-2050)	✓	✓	✓	✓	✓	✓	✓	✓	✓
6.2	11.1 Refugial potential for vascular plants and mammals (1990-2050)	✓	✓	✓	✓	✓	✓	✓	✓	✓
6.2	11.2 Refugial potential for reptiles and amphibians (1990-2050)	✓	✓	✓	✓	✓	✓	✓	✓	✓

Example citation: Williams KJ, Raisbeck-Brown N, Harwood T, Prober SM (2014) An index of *refugial potential for vascular plants and mammals (1990-2050)*, A0 map-poster *11.1 – Monsoonal North NRM regions*. CSIRO Land and Water Flagship, Canberra. Download from *https://data.csiro.au/dap/*.

Datasets available on the *CSIRO Data Access Portal*.

Guide Section	Measure of change in biodiversity	Biological Group				Climate Scenario
		Amphibians	Mammals	Reptiles	Vascular Plants	
3	Projected distribution of each of 77 vegetation types at a) 1990 baseline, and b) 2050				✓	1990
					✓	CanESM2
					✓	MIROC5
3	Generalised projected distribution of vegetation types for a) 1990 baseline, and b) 2050 scenarios				✓	1990
					✓	CanESM2
					✓	MIROC5
4	Revegetation benefit, 1990:1990	✓	✓	✓	✓	1990
4	Revegetation benefit, 1990:2050	✓	✓	✓	✓	CanESM2
		✓	✓	✓	✓	MIROC5
4	Climate-driven proportional change in revegetation benefit, 1990:2050 (packaged within Revegetation benefit, 1990:2050)	✓	✓	✓	✓	CanESM2
		✓	✓	✓	✓	MIROC5
5	Need for assisted dispersal, 1990:2050	✓	✓	✓	✓	CanESM2
		✓	✓	✓	✓	MIROC5
6	Refugial potential, 1990:2050	✓	✓	✓	✓	CanESM2
		✓	✓	✓	✓	MIROC5

The data layers have been developed at approximately 250m resolution across the Australian continent (9 second grids) to incorporate the interaction between climate and topography, and are best viewed using a geographic information system (GIS). Each GIS dataset is provided as an ESRI binary export grid (float file format: *.flt; *.hdr) in *GDA94*, Australian geographic coordinate system, and is a 1 gigabyte raster file.

GDM-based *projected distribution of vegetation types*

Modelling vegetation classes

Predictive models of vegetation classes were derived using the two-step process originally developed for individual species distribution modelling, using presence and absence observations with GDM (described in Elith *et al.* 2006). The first step uses a Generalised Dissimilarity Model (GDM) of vascular plants (as described in *Implications of Climate Change for Biodiversity*) to derive a set of scaled environmental variables for current (e.g., 1990 baseline) and future climates (e.g., 2050). The second step applies this data in a kernel regression to predict the probability of the presence of each vegetation class using training data derived from the pre-European mapping of 77 Major Vegetation Sub-groups version 4.1 of the National Vegetation Information System database (DSEWPaC, 2012). An overview of this process is shown in Figure 1.

The training data comprised 150,000 locations defined by randomly sampling within each vegetation class, proportional to their originally mapped areal extent. These locations were then attributed with the baseline values of the GDM-scaled environmental variables. Separate kernel regressions were then run for the baseline and future climate scenarios using the same baseline training data. In this way, the future distribution of each vegetation class was projected based on its affinity with present-day ecological environments.

How kernel regression works

At any location (grid cell), the kernel regression considers the surrounding relative density (in environmental space) of training sites of the target vegetation class as a proportion of other types and generates a predicted probability for that class for the focal grid cell. A probability surface for the predicted proportions, varying from 0 to 1, is generated for each of the 77 mapped Major Vegetation Sub-groups. This method is infrequently used in ecology because of the need first to scale and reduce the dimensionality of the predictor variables (Lowe, 1995). The GDM step does this – it reduces dimensionality by choosing the variables to use and scales the predictor variables using similarity-decay functions which equate to the multivariate distances expected by kernel regression. The kernel regression thus incorporates interactions by modelling ecological distances and vegetation class densities within a truly multivariate predictor space, with no assumption of additivity.

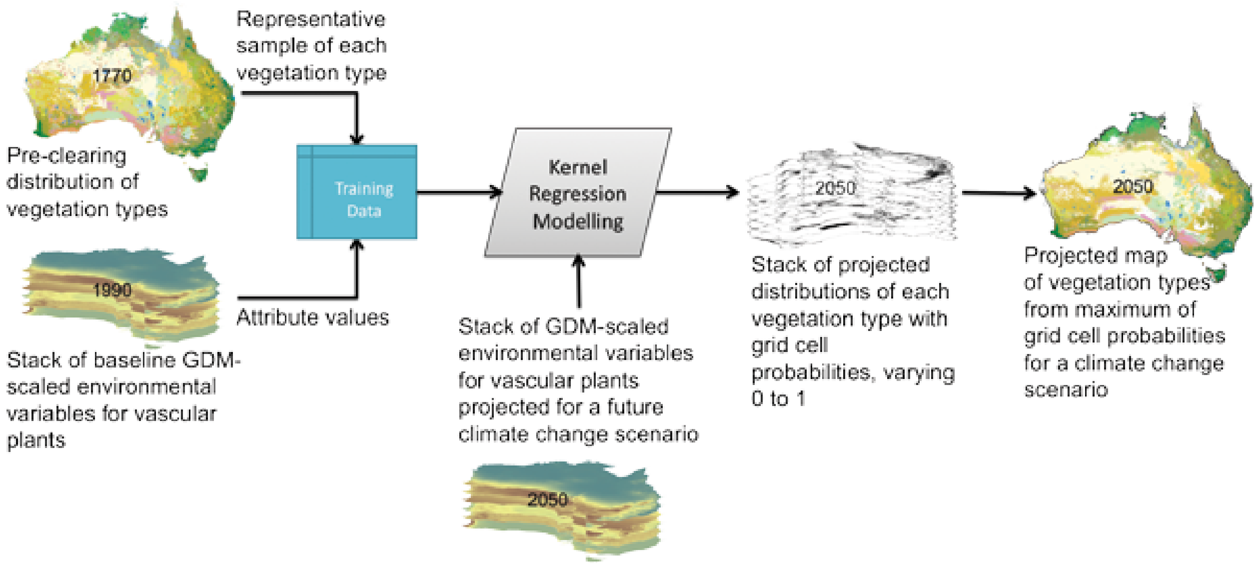


Figure 1. An overview of how the baseline distributions of vegetation types are projected using kernel regression for a climate change scenario. If the predicted 1990 baseline GDM-scaled environmental variables are also used in the kernel regression, then the outputs are baseline predicted distributions of each vegetation type.

Sensitivity of prediction to the historical areal extent of the vegetation type

Kernel regression aims to predict the probability of occurrence of each vegetation class at each location as accurately as possible. However, if there is relatively high uncertainty associated with the occurrence of rarer types (e.g. their occurrence is in reality affected by environmental variables not discerned in the modelling, or by more stochastic, and therefore unpredictable, processes) then these types will tend to be predicted with lower levels of probability than more common (widespread) types. Cell by cell, the class with the maximum probability selected to represent spatially varying vegetation class mosaics on a single generalised map (essentially one dimension) can thus be biased towards more common types, at the expense of locally rare and nationally rare types, that may be in reality equally suited. Therefore, to inform planning, it is important to view the individual probability distributions for each vegetation type as well. These reveal where the rarer vegetation types have a greater likelihood of persistence. Higher probabilities associated with other vegetation types at the same location can be viewed as a measure of the extent to which species inherent to them may compete. Any outcome, at least in the medium term, may be strongly influenced by the extant occurrence of ecosystems and the ability of their constituent species to persist under marginal conditions.

Figure 2 shows how the maximum probability for a grid cell varies, and is often lower, when many vegetation types are predicted to occur at the same grid cell. Up to 25 of the 77 vegetation types are predicted to potentially occur at any single grid cell. The highest probability for a vegetation type to be mapped in a grid cell may only be marginally greater than one or more other vegetation types. Alternative rules can be developed for deciding which among the vegetation types with potential to occur at a grid cell, to actually represent there. For example, local knowledge of vegetation types and their ability to cope with disturbance or exist in fine-scale mosaics could be used to decide. These local considerations will be more relevant to planning than the generalised projected vegetation patterns using the maximum probability rule. In some cases, low probabilities may be indicative of places where novel ecosystems may be assembling.

Continuous versus classed data

Vegetation naturally occurs in a continuum across the landscape, but for planning purposes we typically use classes to facilitate communication and decision making. This leads to a simplification of the continuous patterns modelled directly using ecological similarity. The process of classification reduces detail, and therefore it is important to consider these outputs in conjunction with the additional detail provided by the continuous measures described in ***Implications of Climate Change for Biodiversity***. When the outputs are viewed as individual probability surfaces, much of this continuous pattern is captured (in 77 dimensions of vegetation type). When collapsed into a single dimensions (e.g. using the maximum probability), much of this information is discarded. The generalised map therefore provides a quick reference to the probability distributions for individual vegetation types to use in planning.

Accessing the data

Further details about the method and the individual probability distributions (1990 predictions and 2050 projections) for each vegetation class under the two climate scenarios are provided for each of Australia's 77 Major Vegetation Sub-groups via the ***CSIRO Data Access Portal*** (details are provided in Technical Note 1).

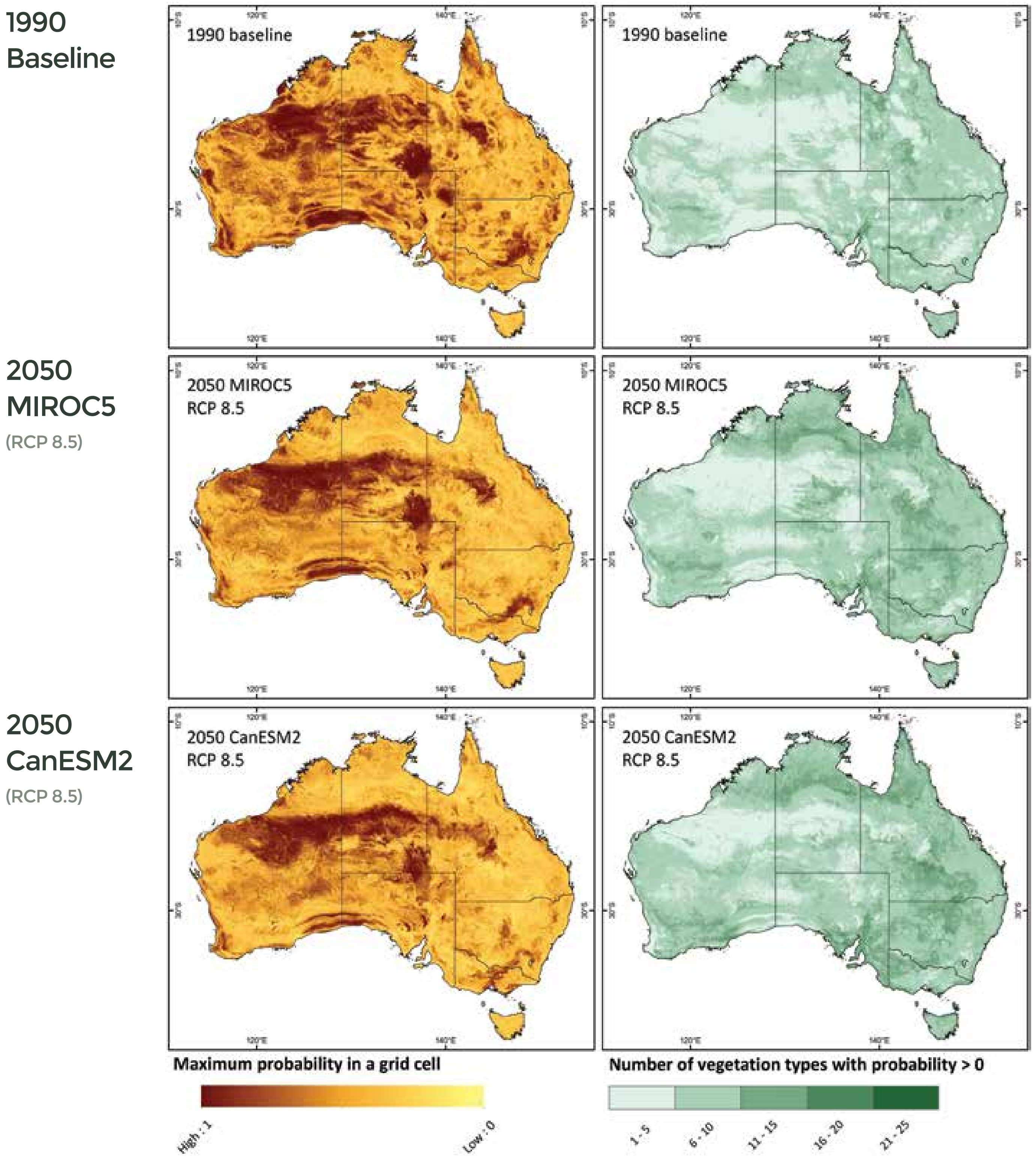


Figure 2. Maximum probability for each grid cell used to assign general vegetation class (left column, brown-yellow maps) and the number of vegetation classes with a probability score >0 for each grid cell (right column, blue-green maps); for baseline and projected climates. Where the maximum probability is low, this is often because many other vegetation types are predicted to potentially occur there too (up to 25 possibilities).

An index of *revegetation benefit* for contemporary biodiversity

The index, *revegetation benefit*, was described in Section 4.1 of this Guide. Here we provide a more detailed description of the measure.

Revegetation benefit indicates the relative benefit of revegetating a focal cell compared with revegetating other cells. It can be calculated for baseline (1990) ecological environments, to indicate the relative benefit of revegetation without accounting for climate change, or for future climate scenarios. When calculated using future (e.g., 2050) climate scenarios, the index shows the future benefit for the biota of the baseline (1990) ecological environment.

Our metric specifically accounts for the benefit associated with increasing the habitat area, i.e. additional *effective area of similar ecological environments* (a concept introduced in ***Implications of Climate Change for Biodiversity***). We benchmark change against a hypothetical uncleared Australia under the baseline (1990) climate, and calculate *revegetation benefit* only for cells with some degree of clearing.

As outlined in Section 4.1 of this Guide, this index uses the species-area curve to relate the increase in *effective area of similar ecological environments* resulting from revegetation at a location to the maximum potential proportion of species likely to benefit. Figure 1 shows how this relationship works. At small areas (i.e., low proportions of the 'original' *effective area of similar ecological environments* – the X-axis), increases in area have more effect on the proportion of species that can persist than similar increments for larger areas. The 'original' area, as noted above, assumes all areas are uncleared and in their hypothetical natural state under the baseline (1990) climate scenario, and the proportion of original area of habitat (i.e., change) is determined from the change due to clearing and/or a future climate scenario.

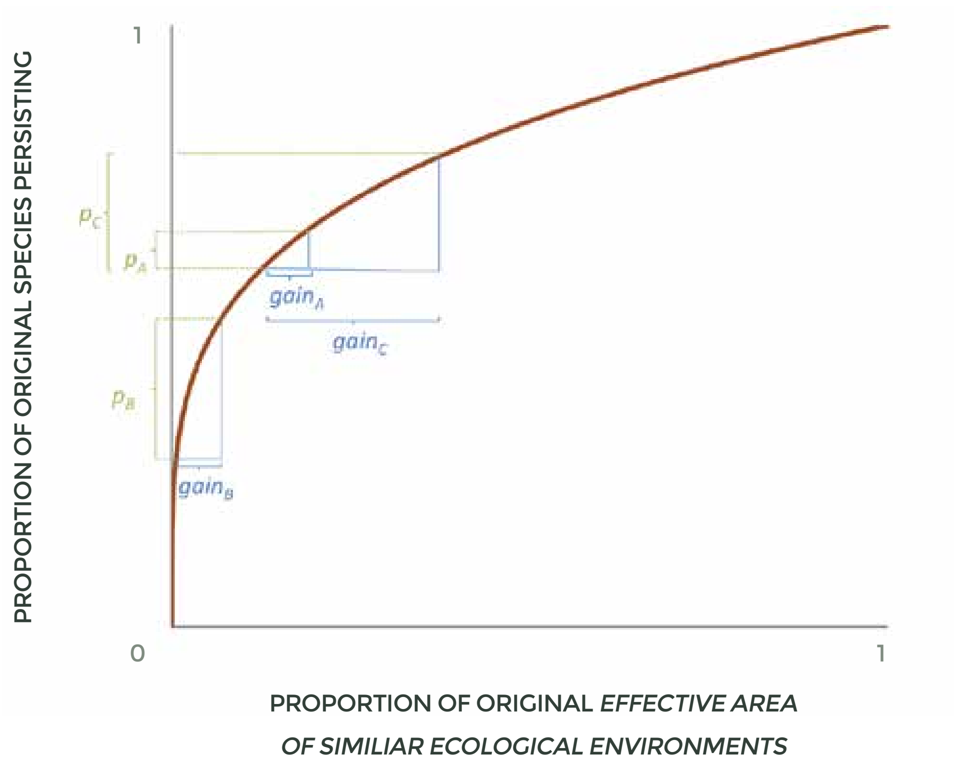


Figure 1. *Revegetation benefit* (*p*) due to revegetation (*gain*) in the context of the species-area curve for three locations, A, B and C. The (unspecified) amount of revegetation at each location is assumed to be the same, and quality is assumed to be optimal (accurately replicates the hypothetical natural state). The original (pre-clearing) *effective area of similar ecological environments* for A and B is the same (not shown), so a given amount (area) of revegetation results in the same proportional increase in *effective area of similar ecological environments* for these two locations (shift on X axis). However the ecological environment associated with B has suffered much greater proportional loss than that associated with A. In this case, a similar amount of revegetation results in a larger increase in expected proportion of species persisting (*p*) for B than for A. Conversely, the ecological environments associated with A and C exhibit the same proportional loss (proportion cleared) – but the environment associated with C was originally much rarer than that associated with A (not shown). In this case, the same amount of revegetation results in a larger increase in expected proportion of species persisting (*p*) for C than for A, due to a larger proportional increase in *effective area of similar ecological environments*.

Along these lines, the *revegetation benefit* index is calculated using *change in effective area of similar ecological environments* (outlined in ***Implications of Climate Change for Biodiversity***), rescaled according to the species area relationship (i.e.,z using the generally applicable exponent of 0.25), as shown schematically in Figure 2.

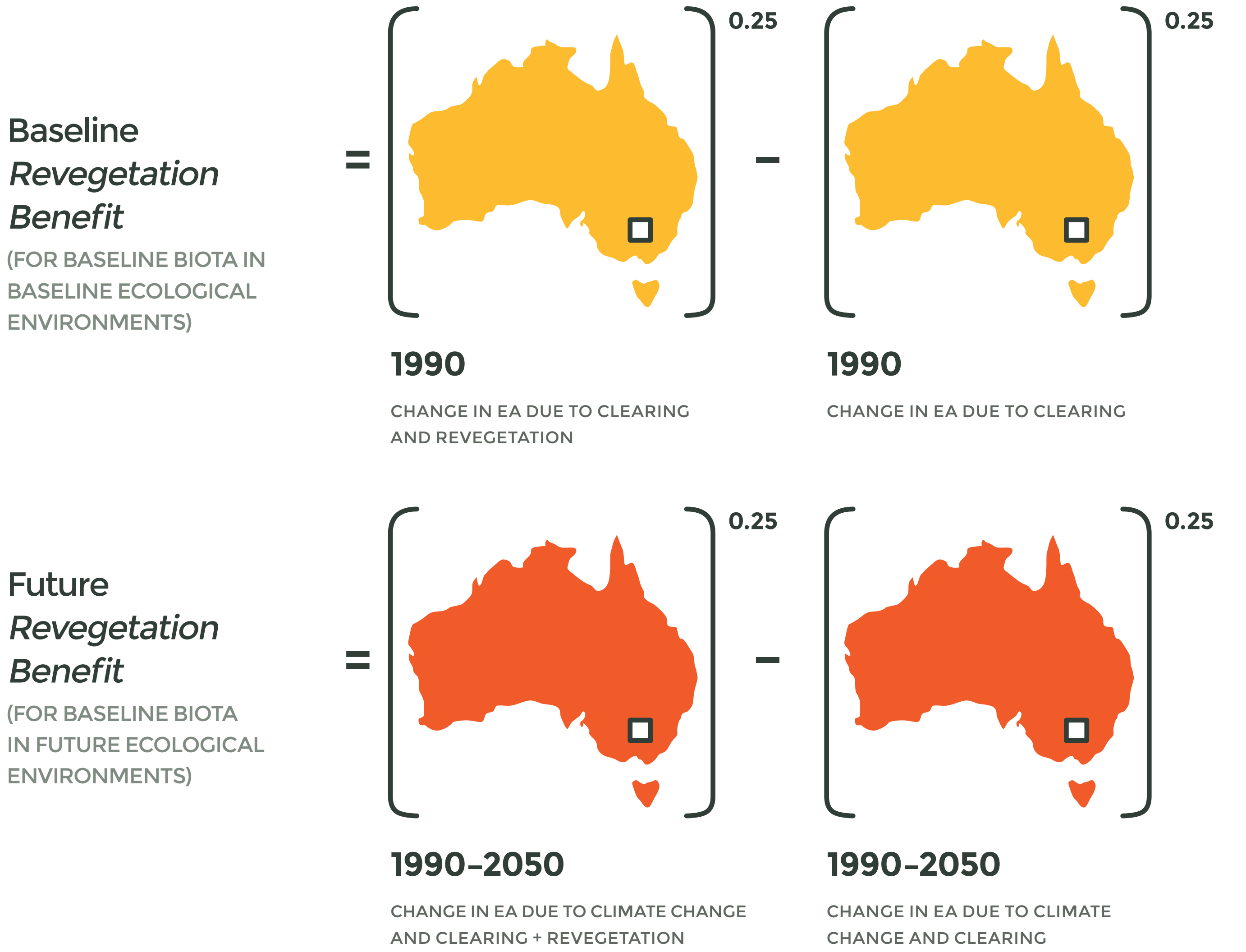


Figure 2. Schematics showing how the *revegetation benefit* index is calculated using *change in effective area* (EA) *of similar ecological environments* and applying the species-area curve with the generally applicable exponent of 0.25. The upper example shows the baseline (1990) benefit of revegetating cleared areas (current revegetation benefit) and the lower example shows how the calculation is modified to also take climate change into account (future revegetation benefit).

Specifically, to calculate *revegetation benefit* in the baseline (1990) period without accounting for climate change, we subtract the *change in effective area of similar ecological environments* due to past clearing alone, from the *change in effective area of similar ecological environments* due to past clearing *and* revegetation. Both of these terms are adjusted according to the species area relationship (i.e. using the exponent of 0.25) before subtraction, as shown in Figure 2.

To indicate *revegetation benefit* under a future climate scenario, climate change is accounted for in both terms (Figure 2): i.e., we subtract the *change in effective area of similar ecological environments* due to past clearing *and* climate change, from the *change in effective area of similar ecological environments* due to past clearing, climate change *and* revegetation (again, both adjusted first for the species-area relationship).

This is expressed mathematically for each cell *i* under a "test" climate scenario as:

$$Benefit_i = \left[\frac{\sum_{j=0}^{j=n} s_{ij}^{1990\_test} h_j^{current} + s_{ii}^{1990\_test}}{\sum_{j=0}^{j=n} s_{ij}^{1990\_1990}}\right]^{0.25} - \left[\frac{\sum_{j=0}^{j=n} s_{ij}^{1990\_test} h_j^{current}}{\sum_{j=0}^{j=n} s_{ij}^{1990\_1990}}\right]^{0.25}$$

Where s_{ij} is the similarity of the focal cell i to each other cell in Australia j with condition (here estimated as the proportion of a cell uncleared) h_j.

The $s_{ii}^{1990\_test}$ term is the similarity of the ecological environment of the focal cell to itself. It reflects the contribution of revegetation of that cell to *change in effective area of ecological environments*. If calculating benefit under the baseline (1990) climate, this term (similarity to self) will equal 1, but under future climate scenarios is likely to be less than 1. If the future ecological environment is very different this will lead to a low score for *revegetation benefit* because the environment will no longer be suited to biota of the baseline (1990) ecological environment. For example, if $s_{ii}^{1990\_test} = 0$, then *revegetation benefit* = 0. Conversely, a low score may suggest the need for other measures to assess the benefit of revegetation using species more-suited to future ecological environments. These decisions may be guided by this measure in combination with others, such as the potential future *(projected) distribution of vegetation types* (Section 3).

In practice, revegetation of a whole cell with vegetation or habitat of original (pre-clearing) quality is unlikely to be achievable. Therefore we use the metric as a relative measure, rather than attempting to estimate the absolute number of species that benefit from a revegetation action. Direct comparison between cells is still possible, if we assume a revegetation action of comparable area and quality is undertaken in the cells compared.

Visualising climate-driven revegetation benefit

The ratio of the future to baseline revegetation benefit indices (i.e., 2050:1990) depicts the climate-driven biodiversity benefit of revegetating areas using contemporary local species. Figure 3 shows this proportional change in revegetation benefit for vascular plants under the high emissions' *mild MIROC5* climate scenario. This supplementary index for adaptation planning helps by distinguishing where the benefits of revegetation continue to accrue with climate change, separate from the general benefits to biodiversity of revegetating cleared land.

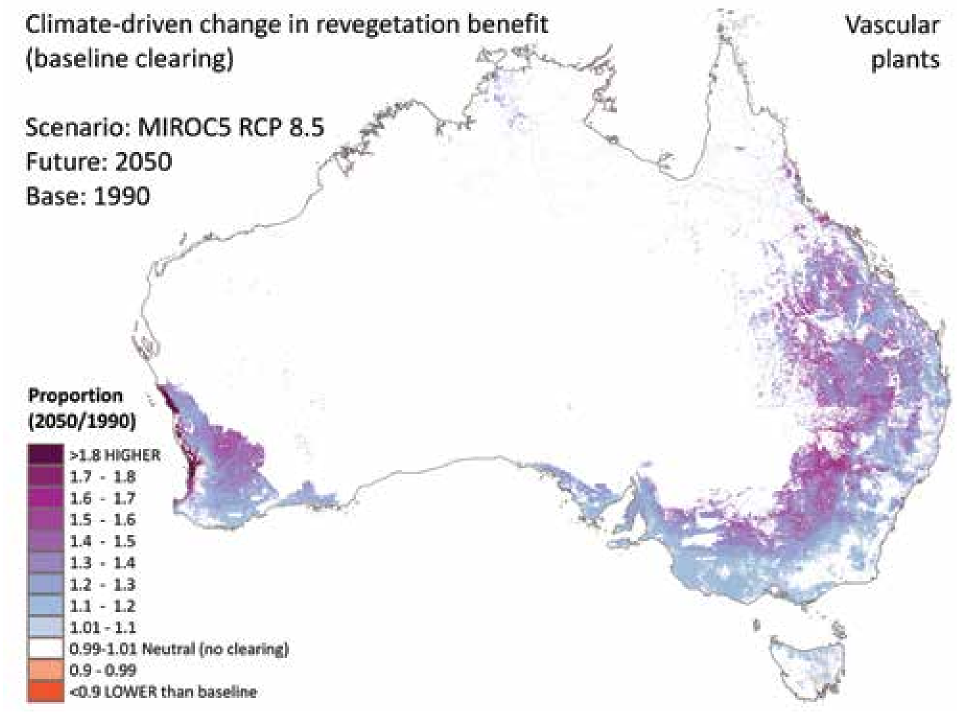


Figure 3. Climate-driven proportional change in *revegetation benefit* for vascular plant species under the high emissions' *mild MIROC5* future climate scenario (calculated as the ratio, 2050:1990). Darker colours signify higher overall benefit; lighter colours signify less benefit. While the legend shows 10 classes, the data itself is continuous.

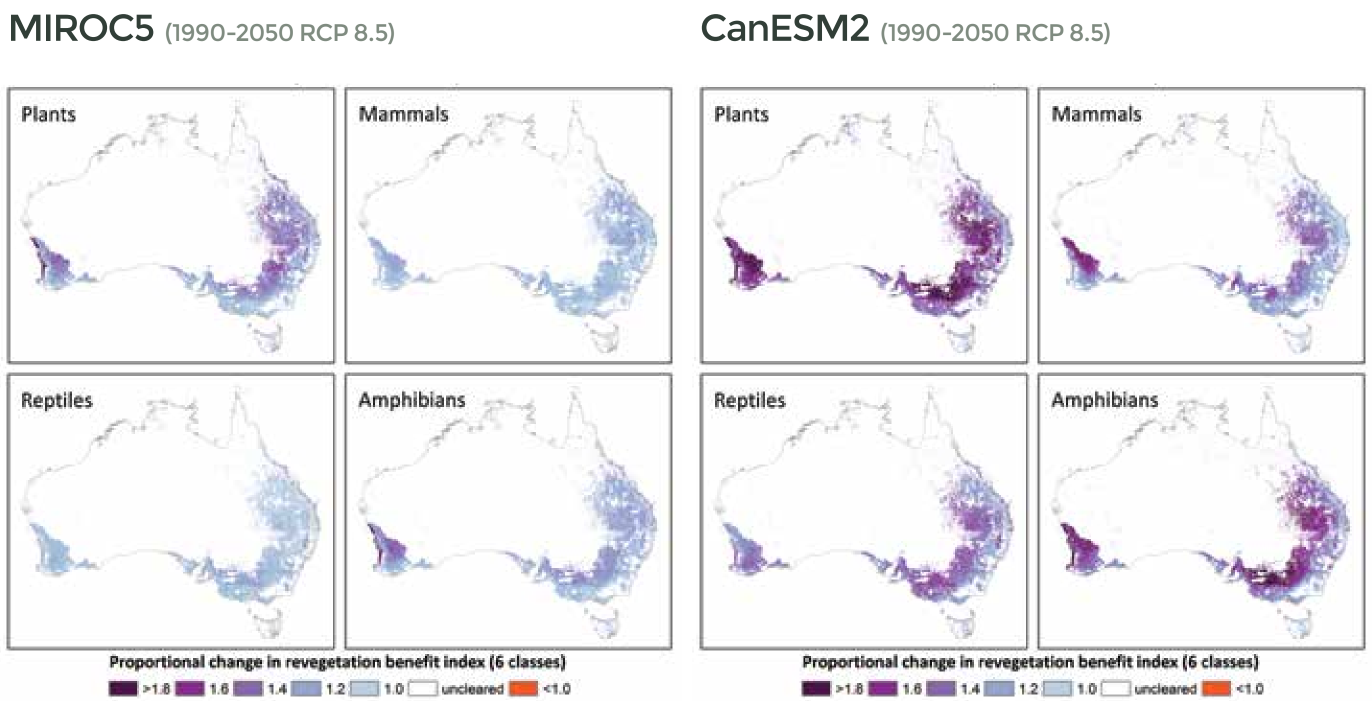


Figure 4. Climate-driven proportional change in *revegetation benefit* (calculated as the ratio, 2050:1990) under two scenarios of climate change by 2050, for four biological groups. Darker colours signify higher overall benefit; lighter colours signify less benefit. While the legend shows five categories for ease of visual comparison, the data itself is continuous.

Calculating the index of *refugial potential*

To calculate *refugial potential*, we use modifications of *effective area of similar ecological environments,* previously described in ***Implications of Climate Change for Biodiversity***. The calculation is made from the perspective of the ecological environment of a focal cell under a future climate scenario, in our case in 2050.

There are two main parts to the calculation of the index (see Figure 1 schematic).

First, we estimate the *effective area of similar ecological environments* looking from the future (2050) to the baseline period (1990). A high score for this part of the calculation indicates that the focal cell in the future represents an environment that was common in the baseline period, and hence it has greater potential as a refugium for widespread species.

We then adjust this score by dividing by (the square of) the *effective area of similar ecological environments* looking within the future (i.e., looking from the focal cell in 2050 to other similar cells in 2050). The more extensive the ecological environment in 2050, the less rare it is and therefore the lower the *refugial potential*. This denominator is squared in order to emphasise rare refugial environments in the future.

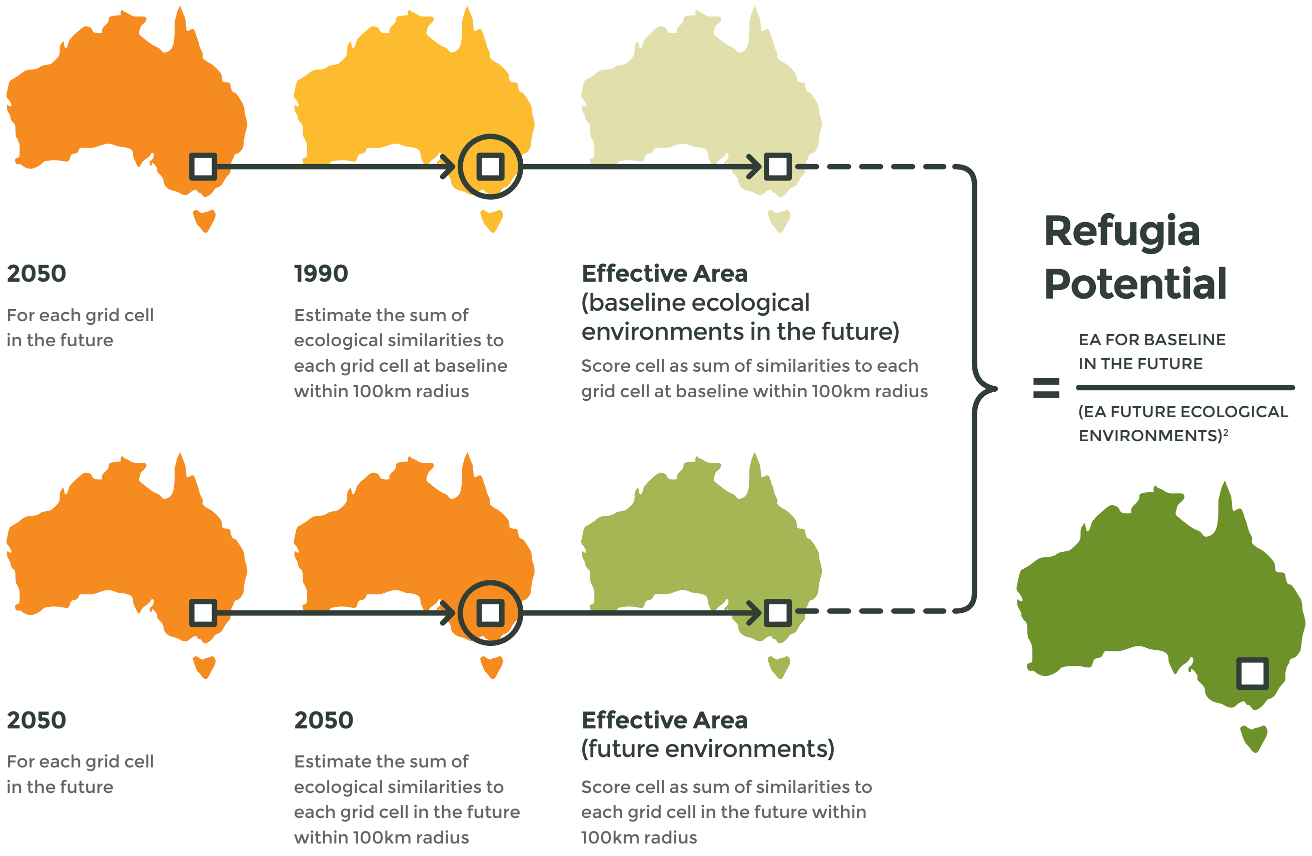


Figure 1. Schematic indicating how the index of *refugial potential* is calculated using *effective area* (EA) *of similar ecological environments*, a measure that was described in Section 5 of AdaptNRM Module ***Implications of Climate Change for Biodiversity***.

To account for local dispersal capacity, these calculations are performed within a limited 100km radius of each cell. We use 30,000 sample points distributed according to a half-Cauchy (negative square power law approximation) dispersal kernel with median dispersal distance of 10km (see Figure 2). This simulates a typical dispersal distance of 10km related to the 60 years of change (1990-2050) and allows for occasional greater distances up to 100km. The calculation is adjusted for sampling variation in coastal areas where the 100km radius around the focal cell extends into the ocean.

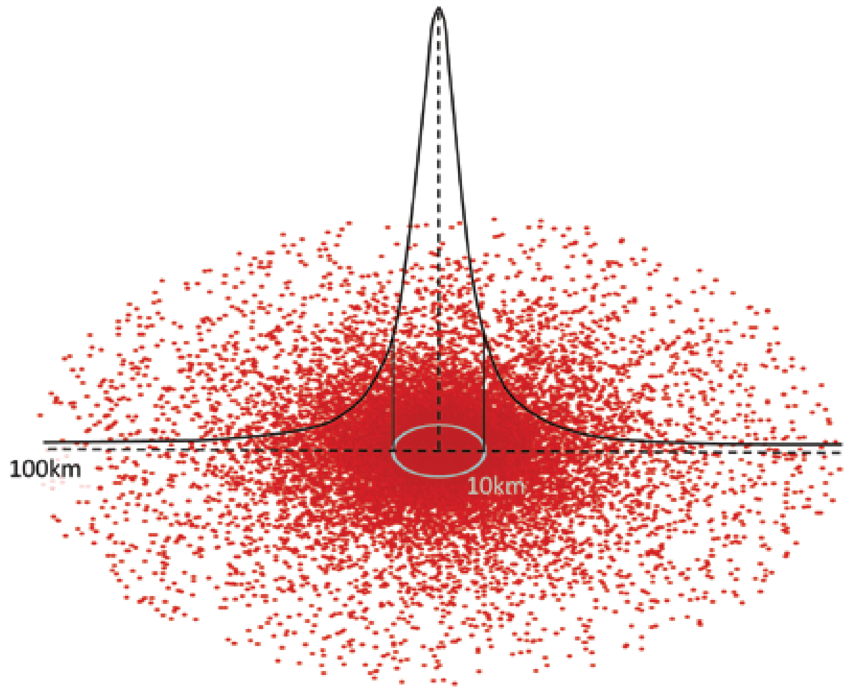


Figure 2
Sampling strategy for estimating *refugial potential* under an assumption of 10km median dispersal distance (over the 60 year period). Sampling points (red) are drawn from a half-Cauchy (negative power law) distribution (black) with a median distance of 10km. Half the samples fall within 10km of the focal cell, ensuring full spatial coverage within a radius of approximately 25km, with decreasing density out to 100km.

While we use a general dispersal parameter for comparison and to demonstrate the index in this Guide, these parameters can be customised for different biological groups and change periods, where sufficient knowledge about dispersal rates exist. We note that sensitivity analyses suggest that increasing the mean dispersal distance does not substantially change the results, probably due to a tendency for similar ecological environments to be nearby even under climate change.

The resultant equation for the *refugial potential* index is:

$$r_i = \frac{A^{2050\_1990}\sigma}{\left(A^{2050\_2050}\right)^2} = \frac{\sum_{j=1}^{j=n} s_{ij}^{2050\_1990}\sigma_{ij}}{\left(\sum_{j=1}^{j=n} s_{ij}^{2050\_2050}\right)^2}$$

where *A* is the *effective area of similar ecological environments* for the specified time comparisons, lower case sigma is a sampling correction, and s_{ij} is the similarity of cell i to each other cell j in the 100 km radius. The scores for this index are very low, and are consequently rescaled by multiplying by a factor of 3000 to approximately bring them into a range varying from 0 to 1, although in practice most scores range between 0.1 and 0.3.

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ABOUT ADAPTNRM

The National AdaptNRM Impacts and Adaptation Project is a multidisciplinary endeavour that brings together a diverse group of scientists working with NRM practitioners.

While the project itself consists of researchers from CSIRO and NCCARF, our output and initiatives have been shaped and informed through the generous input of NRM practitioners across Australia as well as a multitude of researchers, state and federal government stakeholders.

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