Assessing the ecological representativeness of Australia’s terrestrial National Reserve System: A community-level modelling approach

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Cover photograph

Acacia spp. growing along drainage lines in stony soils at the foot of a mesa in Bladensburg National Park, Western Queensland, merging to form patches of gidgee woodland in the black cracking clays of the native grasslands (image: Dan Metcalfe, CSIRO).
Foreword

The Department of the Environment and Energy has commissioned CSIRO to undertake an analysis of the relative levels of biodiversity protection (representativeness) within the National Reserve System (NRS), Australia’s network of protected areas, under current and future climates. This project was undertaken in three parts with specific deliverables set out below.

1. Assessment of the representativeness of the current terrestrial National Reserve System
This part provides an analysis of the relative and effective level of protection for biodiversity within the terrestrial National Reserve System.

2. Assessment of the representativeness of the National Reserve System under different climate scenarios
This part builds on part 1 to examine the effective ecological representativeness of the National Reserve System under alternative plausible climate change scenarios.

A total of four climate change scenarios are examined comprising two emission scenarios and two climate change models for the change period 1990-2050. 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)—were used to project ecological change by 2050 under two greenhouse gas emission scenarios (using representative concentration pathways 4.5 and 8.5 Wm\(^{-2}\) radiative forcing which equate to approximately 1.4 and 2°C of global warming respectively by 2050).

3. Discussion on the potential application of the representativeness analysis to inform future decisions
This part reflects on the findings of parts 1 and 2, and considers what further work is needed to help identify gaps in representativeness and inform future decisions by government and other potential stakeholders.
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Indigenous Protected Areas were included in this analysis. In using this dataset (current to 31 October 2015), we acknowledge the Environment Branch, Indigenous Employment and Recognition Division, Department of the Prime Minister and Cabinet and the Environmental Resources Information Network (ERIN), Department of the Environment and Energy.

The Australian Protected Areas database used in this analysis (CAPAD14) is supplied by States and Territories of Australia to the Commonwealth for compilation. Custodianship rests with the source agencies: Australian Antarctic Division (DoE); ACT Territory and Municipal Services Directorate; Australian Government Department of the Environment and Energy; NSW Lord Howard Island Board; Forestry South Australia; Forestry Commission of NSW; NSW Office of Environment and Heritage; Parks and Wildlife Commission of the NT; Queensland Department of Environment and Heritage Protection; Queensland Department of National Parks, Recreation, Sport and Racing; South Australian Department of Environment, Water and Natural Resources; Tasmanian Department of Primary Industries, Parks, Water and Environment; Victorian Department of Environment and Primary Industries; Western Australian Department of Parks and Wildlife.

Lakes shown on the maps in this report derive from those specifically named in Geoscience Australia’s Topographic map data 1:250,000 series 31 (2004).

This project has been conducted in collaboration with officers of the Department of the Environment and Energy in the Biodiversity Conservation and Science Divisions who provided feedback on the approach as it was developed and contributed to the narrative and interpretation of results with regard to the policy context. In particular we thank Jacqui Doyle, Lalage Cherry, Rebecca Thomson, Alex Hulme, Ben Jobson, Peter Lyon and Randal Storey. Thanks also to Suzanne Prober and Ian Cresswell for their insightful comments that improved a draft version of this report.

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Executive summary

The National Reserve System is Australia’s network of protected areas, comprising Commonwealth, State and Territory parks and reserves and Indigenous and private protected areas. It conserves examples of Australia’s natural landscapes and native plants and animals which is important as our environment is under pressure from future land-use and climate change.

Australia has obligations under the International Convention on Biological Diversity including to meet Aichi Target 11, which requires that at least 17 per cent of terrestrial land be conserved through an ecologically representative and well connected system of protected areas by 2020. Over 17 per cent of Australia’s landmass is now included in the National Reserve System (NRS), however this does not mean that the NRS fully protects the complete range of ecological environments.

This study provides a different analysis to those previously conducted on how well the National Reserve System represents the full range of ecological environments in Australia, both now and under future climate change scenarios. That is, how well do existing protected areas represent the diversity of biologically-scaled ecological environments occurring across Australia, and how might this level of representation change as a result of climate change?

The results provide an indication of how well positioned the reserve system is to protect Australia’s biodiversity from future threats and may inform future conservation efforts, such as identifying and mapping ecological environments that are poorly represented in the National Reserve System.

Key Findings:

- Although over 17 per cent of Australia’s landmass is included in the NRS, the full range of distinct ecological environments is not equally represented.
- 28 of the 86 bioregions in the Australian continent have achieved an average 17% representativeness across the ecological environments they contain.
- Around 63% of Australia’s distinct ecological environments are below 17% protected.
- While there is no formal target for representing distinct ecological environments, this analysis provides a framework for defining the term ‘ecologically representative’ under the Convention on Biological Diversity’s Aichi Target 11 and as a basis for applying the minimum 10% protection threshold at the bioregional scale within Australia. The question

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2 See, https://www.cbd.int/sp/targets/rationale/target-11/
CBD Strategic Goal C: To improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity. Target 11: By 2020, at least 17 per cent of terrestrial and inland water areas and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscape and seascape.

To meet the target [Aichi Target 11] several conditions need to be met: The area conserved should: “be ecologically representative – protected area
Assessing the ecological representativeness of Australia’s terrestrial National Reserve System: A community-level modelling approach
of precisely how 10% protection at the bioregional scale should be interpreted, and implemented is a future policy question.

- Under future climate change scenarios, very low levels of present-day ecological environments will be protected within existing NRS boundaries. Of those that are retained, some may be diminished in extent within the NRS or generally in terms of their entire distribution, while others may have expanded their range.
- Further work may be needed to protect current ecological environments and help manage the transition to new environments that may develop under climate change.
- This analysis can serve as a key input to identifying areas outside the NRS that are important for conservation. However, to prioritise future activity across the broader landscape, these results need to be integrated with additional information on land condition, land use and future threats.
- There is potential to extend the analytical framework employed in this project to inform prioritisation and evaluation of investment in protection and restoration of habitat across entire landscapes.

A different method for measuring representativeness

Previous methods for reporting on the representativeness of the NRS have used the proportion of land mass covered by formal protected areas within a given land classification (such as bioregions) and the proportion of broad vegetation types included.

The approach developed by CSIRO uses modelled “ecological environments” as a surrogate for the extent and variety of natural ecosystems. The method of representativeness assessment is consistent with the new model-based indicators developed by CSIRO for global reporting against progress towards Aichi Target 11 under the Convention on Biological Diversity.

Ecological environments for vascular plants were developed by comparing all available records of plant species to the environments where they are found. The differences in plant communities from site to site were calibrated to the differences in environments at those sites, to produce a fine scale continuous representation of ecological distinctiveness. The method is called generalised dissimilarity modelling, or GDM. The result provides a continuous view of “ecological environments”, and importantly, how these environments are related to one another in terms of varying levels of distinctiveness in species composition.

In this study, the ecological environments of vascular plants are being used to gauge the ecological representativeness of the NRS.

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systems should contain adequate samples of the full range of existing ecosystems and ecological processes, including at least 10% of each ecoregion within the country;” [1 of 5 listed objectives].

x | Assessing the ecological representativeness of Australia’s terrestrial National Reserve System: A community-level modelling approach
The current representation of ecological environments in the NRS

Figure 1 shows the current level of protection of ecological environments in the NRS. For convenience of interpretation there is a colour break between the shades at 17%. The green shades indicate ecological environments represented in the NRS at greater than 17%. Figure 2 of Tasmania is an example of the detail provided by the data when viewed at more detailed map scales. Figure 3 depicts the spread of representativeness when broken into classes of “proportional protection” based on the national data shown in Figure 1.

Figure 1 Current level of protection of ecological environments (scaled by vascular-plant composition) within NRS properties (as at 31 October 2015).
Greens indicate environments for which the minimum 17% threshold representation has been achieved. Legend classes and colours follow Figure 3. The NRS properties used in this analysis are shown in Figure 6.
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Figure 2 Current level of protection of ecological environments (scaled by vascular-plant composition) within NRS properties (as at 31 October 2015), shown for Tasmania (other states and territories are presented in appendices). Greens indicate environments for which the minimum 17% threshold representation has been achieved. Legend classes and colours follow Figure 3. The NRS properties used in this analysis are shown in Figure 6.

Figure 3 Histogram depicting the frequency of ecological environments (scaled by vascular-plant composition) achieving different levels of proportional protection within the NRS.

Combining all the ecological environments represented above 17% results in approximately 37% meeting this threshold. In other words, approximately 63% of ecological environments are represented at less than 17% in the NRS.
Future of ecological environments in the NRS under climate change

There are several ways to view how the National Reserve System may represent biodiversity under climate change. This analysis considers only the extent to which present-day ecological environments will potentially still be represented somewhere within the National Reserve System under climate change.

Four climate change scenarios were examined, comprising two greenhouse gas emissions scenarios and two climate change models for the change period 1990-2050. The two climate models (MIROC5 and CanESM2) are a relatively mild and a relatively hot scenarios respectively, each with moderate rainfall change. The two emissions scenarios (Representative Concentration Pathways (RCPs) 4.5 and 8.5 Wm$^{-2}$ radiative forcing) equate to approximately 1.4 and 2°C of global warming respectively by 2050.

The results of the four scenarios are shown in Figure 4. In general, they show that very low levels of familiar, present-day ecological environments will be represented in 2050 within the NRS boundaries of 2015.

These results have not considered how well the NRS may represent future ecological environments that develop as the climate changes. However previous work by CSIRO has found that the level of representation of the continent’s future environments show a similar pattern to the current representation of today’s environments. This suggests that the NRS will continue to include about the same amount of diversity of the continent’s environments of the day in the future as it does presently.

![Figure 4 Proportional (%) protection of present-day ecological environments (scaled by vascular-plant composition) within NRS properties (as at 31 October 2015) in the future (2050 climate scenarios). Greens indicate environments for which the minimum 17% threshold representation has been achieved. The NRS properties used in this analysis are shown in Figure 6.](image-url)
Further work to inform future conservation actions and policy decisions

This report provides information on the representation of current ecological environments within the NRS and what that might look like in the future, assuming there is no change to the present-day NRS boundaries.

The findings suggest that further efforts may be required to protect current ecological environments and help manage the transition to a new suite of environments that may develop under climate change. While this does not answer the question of precisely where these efforts should be focussed, areas identified as poorly represented in the NRS provide a first lens of priority.

Not all under-represented ecological environments are depleted, threatened or in poor condition. Priority should be further guided by information on the condition, land-use and future threats to ecological environments outside the current NRS estate. Such an analysis could be repeated at regular intervals to measure progress and re-adjust priorities as the climate and land-use patterns change.

A whole-landscape approach to conservation prioritisation and evaluation would allow these additional considerations to be taken into account. This could be achieved using CSIRO’s existing analytical techniques for projecting future retention of biodiversity. Conservation and investment priorities could then be assessed in terms of current and future habitat condition across the entire distribution of ecological environments, not just the proportion of each environment included within the NRS.

While these additional components of a whole-landscape approach to conservation investment will require extra effort, they are feasible given the advanced development stage of an integrated modelling system. The amount of effort then required for any particular application will depend on the level of rigour and sophistication to apply in each instance.
Definitions

- *Ecological environments* are biologically-scaled environments derived from using the GDM method of community-level modelling, and used as a surrogate for the extent and variety of ecosystems within a specified analysis domain, and often also for a particular biological group (e.g., vascular plants). Ecological environments are not discrete classes, and the continent is therefore not divided up into a finite set of these environments, unlike what would be the case for discrete vegetation types or ecosystem types. Rather the ecological environment associated with each individual location (grid cell) is viewed as being potentially unique, and exhibiting a variable (sliding scale) level of environmental, and therefore biological, similarity with all other locations.

- *Proportional protection* of a given ecological environment is the proportion of the total distribution of a given ecological environment (i.e. the proportion of all cells with a similar environment to that of a particular location) included within formal reserves (for a specified analysis domain).

- *Protected-area representativeness* of all ecological environments is a collective property derived from the levels of proportional protection for a whole set of environments – either expressed as a geometric mean of these proportions (varying from 0 to 1), or as a proportion of environments that have achieved some threshold level of proportional protection (e.g. at least 17%).

- An *Ecologically representative* protected area network is inclusive of the variety of habitats and species and their natural dynamics within local areas to ensure sufficient genetic options exist for evolutionary processes to function without the need for intervention.

- An *Ecologically comprehensive* protected area network is inclusive of examples of all the native biota and natural landscapes that are characteristic of a region in which they have evolved.

- An *Ecologically adequate* protected area network is inclusive of sufficient amount and configuration of good quality habitat within a managed landscape to maintain the integrity of meta-populations, species and ecological communities through intrinsic ecosystem processes (e.g., regeneration regimes, population dynamics, food web interactions).

- The *Ecological representativeness* of a protected area network is the degree to which the original extent of species, ecosystems and ecological processes characteristic of a realm or a jurisdiction occur within protected areas in sufficient quality or quantity to persist *in situ* over the long term.

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*4 For other definitions, technical terms and acronyms, refer to the Glossary at the end of this report.*
Acronyms

AR5 – IPCC Assessment Report 5
CanESM2 – The Canadian Centre for Climate Modelling and Analysis Earth System Model (Mk 2)
CAR – Comprehensive, Adequate Representative
CBD – Convention on Biological Diversity
CSIRO – Commonwealth Scientific and Industrial Research Organisation
DAP – Data Access Portal
GDM – Generalised Dissimilarity Modelling
IBRA – Interim Biogeographic Regionalisation for Australia
IPCC – Intergovernmental Panel on Climate Change
MIROC5 – Model for Interdisciplinary Research on Climate version 5
NRS – National Reserve System
RCP – Representative Concentration Pathway
Introduction

The National Reserve System is a network of protected areas, conserving examples of Australia’s natural landscapes and native plants and animals for future generations. It is made up of Commonwealth, State and Territory parks and reserves, Indigenous and private protected areas. Amongst other things, it is a ‘safety net’ to ensure the maintenance of species and evolutionary processes under pressure from global change (climate and land use), and a foundation for whole of landscape conservation and management.

Global objective

Australia as signatory to the Convention on Biological Diversity supports the Strategic Plan for Biodiversity 2011–2020⁵, which reaffirms the importance of protected areas as a core component of international efforts to address biodiversity loss. Target 11 of this plan aims at ensuring that: “By 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes”.

National objectives

Australian Governments have laid out a strategy for achieving a National Reserve System that secures Australia’s biodiversity assets in their landscape setting and ensures they are effectively managed (Australia’s Strategy for the National Reserve System 2009–2030). The Strategy identifies priority actions to provide a nationally coordinated approach to protected area management, including the following national targets for a National Reserve System:

- examples of at least 80 per cent of all regional ecosystems in each bioregion by 2015;
- examples of at least 80 per cent of all regional ecosystems in each subregion by 2025;
- core areas for the long-term survival of threatened ecosystems and threatened species habitats in each of Australia’s bioregions by 2030; and
- critical areas for climate change resilience, such as refugia, to act as core lands of broader whole of landscape scale approaches to biodiversity conservation by 2030.

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Current status

At the time of writing, over 17 per cent of Australia’s landmass and inland waterways are permanently protected in the National Reserve System (NRS). This is made up of over 10,000 properties and includes Commonwealth, state and territory reserves, Indigenous Protected Areas (IPAs) and protected areas on private properties.

The Australian Government has asked CSIRO to provide a more detailed analysis than those previously conducted on the current ecological representation of the NRS and the representation of current ecosystems under future climate change scenarios. This work will increase the Australian Government’s understanding of how well the NRS captures the current diversity of ecological environments and will assist with prioritising future conservation efforts.

CSIRO’s community-level modelling infrastructure

Over the past five years, CSIRO has been building the technical and analytical infrastructures needed to evaluate the status and trend of Australia’s biodiversity at relatively fine scales nationally using modern methods of measurement and synthesis (Ferrier, 2002; Ferrier et al., 2002; Ferrier et al., 2009; Ferrier et al., 2004).

An earlier collaborative project with the Department of the Environment and Energy detailed the development of this infrastructure (Williams et al., 2010) followed by specific applications (Mackey et al., 2012; Williams et al., 2012), including a preliminary assessment of the NRS performance under climate change (Dunlop et al., 2012a; 2012b; Ferrier et al., 2012), and refugial potential (Reside et al., 2013). These developments were further refined, documented in two guide books provided with the datasets to support climate-ready NRM planning (Prober et al., 2015; Williams et al., 2014).

What to expect in this report

The main body of this report is presented in three parts:

1. An analysis of the present level of protection for biodiversity within the terrestrial NRS.
2. A preliminary examination of the effective ecological representativeness of the NRS under future alternative plausible climate change scenarios.
3. Discussion of further work needed to inform future decisions about the design of the NRS.

Detail about the methods applied in parts 1 and 2 is provided in Appendices.
Assessing the representativeness of the current National Reserve System (NRS)

Conceptual framework for assessing ecological representativeness

Biodiversity, or biological diversity, is the variety of all life on Earth, where variety can be observed at all levels of organisation from the gene to the ecosystem. It is constantly changing and evolving in response to interactions with the environment over the long and short-term (National Biodiversity Strategy Review Task Group, 2010; Secretariat of the Convention on Biological Diversity, 2011).

While methods for observing and recording biodiversity are rapidly advancing, we are still a long way from being able to accurately measure and map the occurrence and dynamics of biodiversity at all levels of organisation everywhere. Gaps in information about the spatial distribution of biodiversity will continue to be a challenge for regional conservation planning in many parts of the world, requiring a surrogates, or proxy, approach to biodiversity assessment (Ferrier, 2002).

The different approaches to biodiversity surrogates broadly fall into two types: 1) species-level and 2) community-level (Figure 5). Species-level approaches rely on the use of data for individual species to guide conservation planning with the expectation of conserving broader biodiversity (e.g., Rodrigues and Brooks, 2007). This approach requires comprehensive knowledge about the species of interest and is therefore often limited to well-known or iconic species for which sufficient data are available or can be modelled. Each species is treated as equally distinct in conservation assessments of how locations complement or represent each other in their occurrences.

Community-level approaches aim to address more of biodiversity as a whole, by classifying or representing observable patterns of variation in the composition of whole communities to act as surrogates for similar biodiversity. These patterns can be expressed by discrete classes, such as vegetation maps or environmental classifications where the relationships between classes may or may not have been considered; or continuously where the biotic relationships between all individual locations are characterised, without grouping these locations into discrete classes (Ferrier et al., 2009; Ferrier and Guisan, 2006).

There are two important challenges associated with using discrete classes for conservation assessment: a) accounting for varying levels of overlap between classes in the composition of species occurring within those classes (i.e. many species will be distributed across more than one class); and b) accounting for internal environmental and biological heterogeneity within classes (i.e. many species will occur only in particular parts of a given class).

As the number of discrete classes become more finely divided to address internal heterogeneity, it becomes increasingly critical to account for levels of compositional overlap between these subdivisions. For example, how well the species associated with a vegetation class are represented within reserves will depend not only on the level of protection of this particular class, but also on
the extent to which related vegetation classes (sharing species with the class of interest) are represented.

The ultimate level of subdivision addressing environmental and biological heterogeneity is to treat every individual location (e.g., grid cell) as a separate unit, containing a combination of species that exhibit varying levels of overlap (commonality) with the species occurring in other cells. In this “continuous approach” assessment is driven completely by estimated proportions of species shared between individual locations. The continuous approach avoids the need to choose an arbitrary cut off (in terms of similarity in species composition) in defining discrete classes (such as vegetation types). CSIRO is applying the continuous approach in assessing representativeness of protected areas.

Figure 5. Different approaches to biodiversity surrogates for conservation assessment and planning showing where continuous surrogates (used by CSIRO) relate to other approaches.

The analysis of ecological representativeness in this report uses generalised dissimilarity modelling (GDM) of vascular plants as a surrogate measure for continuous variation in biodiversity across whole landscapes (Figure 5). This measure provides a more consistent indicator of regional ecosystem patterns and relationships than aggregated mapping of broad vegetation types.

Previous methods for reporting on representativeness used the proportional coverage of formal protected areas within a given land classification, such as bioregions, as an overall measure of achievement, and the number of broad vegetation types represented as an indicator of ecological diversity captured within each bioregion (National Reserve System Task Group, 2009). CSIRO’s approach simultaneously considers the amount and proportional coverage of ecological representation at local and regional scales, as well as for the whole continent. Continuous measures allow for reporting of both the number and extent of ecosystems represented within protected areas for any given land class (e.g., a bioregion) or for the entire continent; effectively combining the measurement of comprehensiveness and adequacy with the measurement of representativeness (see glossary for definitions).

The analysis requires two primary data inputs, as follows:

1. Protected area boundary representing the NRS
2. GDM model of predicted vascular plant compositional turnover
Details of the approach are given in Appendix A and summarised below.

**Approach**

The protected area boundaries for this analysis derive from CAPAD14 (Department of the Environment, 2014a) and Indigenous Protected Areas declared up to and including October 2015 (Department of the Environment, 2015) (Figure 6).

![Figure 6](image)

**Figure 6** The extent of the terrestrial National Reserve System as at 31 October 2015, used in the analysis of ecological representativeness.

A model\(^6\) depicting present-day patterns of vascular plant variety was used to indicate extent and diversity of pre-1750 ecological environments (Williams et al., 2013) for this analysis of protected area representativeness. Figure 7 shows the compositional patterns predicted by this model

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\(^6\) The same model has been used in two AdaptNRM modules (Prober et al. 2015; Williams et al. 2014), a biodiversity forecasting analysis (Drielsma et al. 2015), and to assess gaps in biological surveys for the Bush Blitz program (Williams et al. 2015).
derived by finely classifying the continuous variation and using colour to depict the relationships between classes.

![Figure 7](image)

**Figure 7** Examples of the modelled continuous variation in vascular plant composition between locations derived by classifying predicted ecological similarity (continental and 3 bioregional examples). The full spectrum colour depicts relationships between classes in each case. Locations with similar colours are predicted to have high ecological similarity, while locations with very different colours are predicted to be highly dissimilar ecologically.

To explain precisely how this model of continuous variation in ecological environments is used to assess representativeness, a convenient starting point is provided by the more traditional approach based on discrete mapped classes. When assessing protected-area coverage using IBRA regions, each location on the continent (e.g., each 250m grid cell in the case of this study) is viewed as belonging to a single region. The protected-area coverage of this region can be

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7 This colouring is achieved by associating the red, green and blue colour bands with the first three axes of a metric multidimensional scaling of predicted dissimilarities between grid cells (Belbin et al., 1983).
calculated simply as the proportion of all cells in the region that fall within protected areas. This proportion is then assigned to each and every cell within the region, regardless of whether this particular cell is itself protected or unprotected. In other words, in a map depicting protected-area coverage of IBRA regions, all cells within a given region will be mapped in the same colour, indicating the region’s overall level of protection.

The approach to assessing representativeness employed in this study is underpinned by the same basic principle of estimating and mapping the proportional coverage of protected areas. Here, however, each grid cell is viewed not as belonging to a homogeneous set of cells forming a discrete region, but rather as sitting within a continuum of environmental variation (Figure 5). In other words, the ecological environment of this cell exhibits varying levels of similarity with the ecological environments of other cells across the continent (both within and beyond the IBRA region or subregion within which it lies). The spatial resolution (grain) and patterning of this ecological variation is determined directly from modelling the biological variety (based on vascular plants in the present study).

In this approach, the coverage of protected areas relative to the ecological environment associated with a given grid cell (the “focal cell”) is calculated in terms of the proportional protection of other cells predicted to have similar ecological environments to that cell (Figure 8). The contribution any other cell makes to the calculation of proportional protection for a given cell is weighted according to the similarity in biological composition between those two cells—ranging from 1.0 for a cell predicted to have identical species composition to the focal cell, through to 0.0 for a cell predicted to share no species with the focal cell. Given the nature of this weighting, the resulting value for a given grid cell, or a given region, can be interpreted as estimating the mean proportional protection of the original extent of the habitat for a randomly chosen species associated with that cell or region (i.e., prior to any degradation of habitat condition).

Figure 8 Schematic showing how representativeness is estimated for each grid cell.
A value of proportional protection of ecological environments assigned to each and every grid cell across the continent results in a map showing the variation in ecological representativeness of the NRS from relatively poor (i.e., < 17%) to relatively good. The analyses underpinning this map also provide the raw materials for deriving summary statistics of representativeness for any defined region; for example an individual IBRA region, a state, or the entire continent. All statistical means reported here use the geometric mean (see Appendix A for a discussion of geometric vs arithmetic mean).

The mean representativeness of ecological environments within each IBRA region (and subregion) takes into account ecological relationships between locations. This allows for the contribution reserves in one region make to protection for the same or similar types of ecological environments found in other regions. In this way, the regional requirements for complementary protection are portrayed within a national context.

In this report we summarise NRS representativeness by IBRA subregion, IBRA region and the entire continent in three main ways:

- A frequency histogram showing the proportion of ecological environments falling within each class of proportional protection (as a percent). Alternatively portrayed by a cumulative frequency line showing the proportion of ecological environments achieving greater than a given threshold of proportional protection. The cumulative frequency plot allows assessment of the extent to which ecological environments achieve different proportional protection thresholds (e.g., 17%, 11%, 5%).
- Tables and maps showing the geometric mean of the proportional protection (as a percent) of ecological environments (see Appendix A for a definition of the geometric mean).
- Tables and maps showing the proportion of ecological environments that are below the 17% threshold for protection; and by way of contrast, the proportion of protected ecological environments (17% and above) can be calculated as 100 minus the given percentage.

Results and discussion

The resulting nationally continuous measure of protected area representativeness for vascular plants is shown in Figure 9 and in greater detail in Appendix C for each State and Territory. Of the 86 bioregions across the Australian continent, 28 have achieved a mean proportional representation of at least the 17% threshold, as have 112 of 411 subregions (Figure 10 and Appendix E - Table 5). As expected, representation is highest in regions and subregions where reserves are larger or more comprehensively represent biodiversity, and least in those parts of eastern and southern Australia where production or intensive land uses dominate.
Figure 9 Proportional (%) protection of ecological environments (scaled by vascular-plant composition) within the NRS, mapped at the resolution of individual grid cells. Greens indicate environments for which the minimum 17% threshold representation has been achieved. Class boundaries and colours match histogram bars in Figure 11.

The frequency of ecological environments achieving different levels of protection within the NRS is shown in Figure 11. The x-axis on the figure is in classes of proportional protection relative to the NRS. Green colours indicate threshold achievement of 17% or more protection and brown colours are below that threshold (i.e., < 17%). The y-axis is the proportion of ecological environments falling in each class (shown as a percent); and the shape of the histogram indicates how representativeness is distributed relative to environmental variation (scaled by vascular-plant composition) within the region of interest (here, nationally). In some parts of the landscape the proportional protection of ecological environments in the NRS exceeds 50% (histogram bars 49 to 50.9 and higher), wherein only a very small number of distinct ecological environments are so well represented (around 2% when summed over those bars as a proportion of the total number of ecological environments within the region). Elsewhere proportional protection is below 5% wherein only about 8% of ecological environments in that region have types that are so poorly represented in the NRS of 2015 (bars 3-4.9 and lower).
Figure 10 Geometric mean of % protection (in NRS) of ecological environments (scaled by vascular-plant composition) occurring in each IBRA bioregion. See Appendix E for the tabular data and Appendix D for comparison with standard areal measures. The NRS properties used in this analysis are shown in Figure 6.
Figure 12 conveniently shows the histogram as the cumulative proportion of ecological environments found within the NRS as of 2015 for different threshold classes of proportional protection. Ecological environments vary in their proportional protection across different parts of the landscape. The proportion of ecological environments in different classes of proportional protection for the NRS in 2015 can be determined by reading from the x-axis up to the line and then across to the value of the cumulative proportion on the y-axis. For example, 37% of distinct ecological environments have examples of their type within the NRS for a threshold of 17% proportional protection. If the threshold were just 11% proportional protection, given the current NRS boundaries, then the proportion of ecological environments with examples in the NRS is 67%; and for 5% proportional protection this is 92% (table and maps in Appendix E show this measure for each bioregion and subregion).

Aichi Target 11 specifies that by 2020, at least 17% of a nation’s terrestrial areas be conserved through ecologically representative reserves and other area-based conservation measures (sCBD, 2011). Further, a threshold of at least 10% of each ecoregion within a country is recommended for protected area systems to be ecologically representative—containing adequate samples of the full range of existing ecosystems and ecological processes.

The proportional protection of ecological environments derived using GDM-based methods, as shown here, provides a mechanism for adding, and assessing, additional levels to the target hierarchy to align with the intent of Aichi Target 11 (sCBD, 2011) and the CAR scientific framework (Commonwealth of Australia, 1992). The question of precisely how 10% protection at the bioregional scale should be interpreted, and implemented is a future policy question—i.e. would the aim be to achieve 10% for each and every ecological environment within the bioregion, or a geometric mean of 10% across these environments, or does the 10% apply just to the proportion of the bioregion represented, and the threshold for protecting ecological environments within this bioregion is lower again, such as 5% (thereby resulting in three cascading thresholds – 17% nationally, 10% for each bioregion and 5% for each environment)?

![Figure 11 Frequency distribution, across Australia, of ecological environments (scaled by vascular plant composition) achieving different levels of % protection within the NRS.](image-url)
The variation in protection among ecological environments within individual regions is particularly apparent when viewing contrasting bioregions. Within the Arnhem Land bioregion, for example, about 7% of its characteristic ecological environments are below 17% protection (Figure 13). This includes the contribution of reserves in surrounding bioregions that protect similar ecological environments (Figure 14).

![Diagram](image)

Figure 12: Cumulative frequency plot showing the extent to which ecological environments are not included in the NRS of 2015 for different proportional protection thresholds (e.g., 17%, 11%, 5%).

![Diagram](image)

Figure 13: Frequency distribution, for the Arnhem Coast bioregion (ID = 1), of ecological environments (scaled by vascular-plant composition) achieving different levels of % protection within NRS2015 reserves. Proportional protection is mapped in Figure 14.
The Tasmania West bioregion, with 56% mean proportional protection (Figure 10 and Appendix E - Table 5) is the only region for which all of its characteristic ecological environments for vascular plants achieve at least 17% protection (Figure 15). None are below the 17% threshold (Figure 16). By contrast, in the Desert Uplands bioregion of north Queensland (Figure 18) virtually all characteristic ecological environments are below the 17% protection threshold (99.3%, Figure 17) for a regional average proportional representation of 6% (the geometric mean, Figure 10 and Appendix E - Table 5). The extensive Darling River Plains bioregion (comprising more than 10M ha in New South Wales and extending into Queensland) has the lowest regional average proportional representation of 4.1% (geometric mean), closely followed by the Brigalow Belt North bioregion with 4.8% (over more than 13M ha, Appendix E - Table 5). As expected, the proportion of poorly reserved ecological environments (below the 17% threshold) within a region increases as the level of proportional representation declines (see Appendix E - Figure 42).
Figure 15 Frequency distribution, for the Tasmania West bioregion (ID = 84), of ecological environments (scaled by vascular-plant composition) achieving different levels of % protection within NRS2015 reserves.

Figure 16 Proportional (%) protection, for the Tasmania West bioregion (ID = 84), of ecological environments (scaled by vascular-plant composition) within the NRS, mapped at the resolution of individual grid cells. Greens indicate environments for which the minimum 17% threshold representation has been achieved. Class boundaries and colours match histogram bars in Figure 15. The NRS properties used in this analysis are shown in Figure 6.
Figure 17 Frequency distribution, for the Desert Uplands bioregion (ID = 23), of ecological environments (scaled by vascular-plant composition) achieving different levels of % protection within NRS2015 reserves.

Desert Uplands Bioregion

Proportion (%) of ecological environments falling in each class

Class of proportional protection (%) of ecological environments within the NRS of 2015

< 17% threshold: 99.3% of ecological environments in 2015 have no examples in the NRS

≥ 17% threshold (green bars): NRS in 2015 includes examples of 0.7% of distinct ecological environments

Figure 18 Proportional (%) protection, for the Desert Uplands bioregion (ID = 23), of ecological environments (scaled by vascular-plant composition) within the NRS, mapped at the resolution of individual grid cells. Greens indicate environments for which the minimum 17% threshold representation has been achieved. Class boundaries and colours match histogram bars in Figure 15. The NRS properties used in this analysis are shown in Figure 6.
These results demonstrate that a continuous measure of proportional protection can usefully provide information for reporting on the status of Australia’s biodiversity against both the National target of 17% and regional targets to represent examples of at least 80% of ecosystems.

The CSIRO approach is a substantial improvement over previous methods because it accounts for (1) ecological heterogeneity at relatively fine spatial scales and (2) ecological relationships between locations, such that representation in one region can support representation in neighbouring regions. While vascular plants are generally considered a good surrogate for other types of biodiversity, they may not represent all biological groups in exactly the same way. We would expect to see some variation in spatial patterns of representation for different biological groups, such as for vertebrates or invertebrates. Alternative patterns of representation could be tested using different community-level models for biological groups of conservation interest.

The continuous measure of NRS representativeness, shown here for vascular plants, takes into account variation in the extent of different ecological environments within Australia assuming all such environments are intact. With additional information about the remnant extent and quality (condition) of habitats, this measure could be used to indicate where additional effort is needed regionally to protect Australia’s unique flora. It is important to recognise that this analysis in its current form is only dealing with representativeness, and does not take into account where ecological environments have been replaced by other land uses or otherwise degraded habitats, where representing examples of the majority of Australia’s regionally distinct and unique ecosystems is no longer possible without restoration. Intactness, among other ecological, social and economic criteria becomes important when considering how this measure can be used in prioritisation analyses.

Further discussion of these extensions to the analytical framework to inform prioritisation and evaluation of investment in protection and restoration of habitat across entire landscapes is provided in Section 3 (from page 41).
The representativeness of the National Reserve System under different climate scenarios

Different ways to view the implications of climate change for the NRS

There are three ways to view how well the National Reserve System represents biodiversity when considering the dynamics of ecological systems interacting with climate:

1. The proportional protection of present-day ecological environments within the National Reserve System under present climatic conditions (i.e., present – present)
2. The proportional protection of present-day ecological environments within the National Reserve System under future climatic conditions (i.e., present – future)
3. The proportional protection of future ecological environments within the National Reserve System under future climatic conditions (i.e., future – future)

The first of these views is the baseline analysis presented in the previous section. [Note: The fourth combination (i.e., future – present) is implausible.]

The second and third views are reasonable scenarios for consideration. These were first explored by Ferrier et al. (2012) as a component of a larger assessment (Dunlop et al., 2012a; 2012b). They compared the extent to which present and projected future ecological environments for vascular plants and five other biological groups might be represented within the NRS (CAPAD 2006).

Here we consider only the second view, where we reflect on the present-day ecosystems and consider how well these are represented in the future, within the present land boundaries of the NRS (i.e. present – future). This analysis substantially updates the previous work. In considering the application of the results, we include a discussion of this update and the previous work.

Climate change approach

The major steps in evaluating how well contemporary ecological environments are represented by the National Reserve System under different climate scenarios are explained in Appendix F (Figure 44 and Figure 45).

Four climate change scenarios were examined comprising two greenhouse gas emission scenarios and two climate change models for the change period 1990-2050 (c.60 years). The two climate models (MIROC5 and CanESM2) are a relatively mild and a relatively hot climate scenario with moderate rainfall change, respectively. These represent the spectrum of ‘maximum consensus’ plausible futures for Australia (Whetton et al., 2012). The two emission scenarios—representative concentration pathways (RCPs) 4.5 and 8.5 Wm⁻² radiative forcing—equate to approximately 1.4 and 2°C of global warming respectively by 2050 (van Vuuren et al., 2011). RCP 4.5 is a mid-range IPCC scenario whereas RCP 8.5 is a high-end scenario (see Appendix F - Table 6).

The biodiversity model and future climate scenarios are the same as those used in the AdaptNRM modules projecting change in ecological environments (Prober et al., 2015; Williams et al., 2014).
This assessment of NRS representativeness under climate change therefore provides additional measures that complement the existing data series in support of climate-ready NRM planning.

The analysis of proportional protection of ecological environments within reserves uses the same basic formulation as previously outlined (Appendix A – Equation 6). The baseline remains the same, i.e. the area of similar ecological environments which would be present in a pre-1750 landscape (under present-day average climates, assumed before the onset of rapid climate change). However for representativeness, we now calculate proportional protection for projected extents of similar ecological environments found within reserves under future climate (Figure 19).

Figure 19 Schematic showing how proportional protection of present-day ecological environments, found to occur in the NRS under future climatic conditions (i.e., present – future), is estimated for a given reporting region.

Results and discussion

The measures of future proportional protection for present-day ecological environments (scaled by vascular-plant composition) using the two emission scenarios are shown in Figure 20 (for climate model MIROC5) and Figure 21 (for climate model CanESM2). Figure 20 presents the mildest scenario of the four examined (MIROC5, RCP 4.5), and Figure 21 is the most extreme (CanESM2, RCP 8.5). These results are generally reminiscent of the proportional protection patterns at baseline (Figure 9). They indicate the present location of ecological environments that are likely to retain reasonably high levels of proportional protection under future climate change, even if the location of these environments are redistributed elsewhere within the NRS.

In deriving this analysis of representativeness, we considered only where the present-day ecological environments might be located in the NRS in the future assuming protected areas remain intact. We have not given consideration to the condition or intactness of surrounding areas, or the ecological processes of adaptation, dispersal, establishment, interactions and survival that ultimately determine the variety of species that coexist locally.
Figure 20 Proportional (%) protection of present-day ecological environments (scaled by vascular-plant composition) within NRS properties (as at 31 October 2015) in the future (2050, MIROC5, RCP 4.5 and 8.5). Greens indicate environments for which the minimum 17% threshold representation has been achieved. The NRS properties used in this analysis are shown in Figure 6.
Figure 21 Proportional (%) protection of present-day ecological environments (scaled by vascular-plant composition) within NRS properties (as at 31 October 2015) in the future (2050, CanESM2, RCP 4.5 and 8.5). Greens indicate environments for which the minimum 17% threshold representation has been achieved. The NRS properties used in this analysis are shown in Figure 6.
Across the four contrasting scenarios the same trends are apparent and increasingly extreme as the climate scenario worsens (from the relatively mild MIROC5, RCP 4.5 to the relatively hot and high emissions CanESM2m RCP 8.5). In general we find very low levels of familiar, present-day ecological environments represented within existing NRS boundaries due to the altered climatic conditions and changing future locations of environments capable of supporting them. Under climate change the NRS is likely to still include relatively high proportions of familiar ecosystems currently occurring in parts of central and western Australia, western Tasmania, the Queensland wet tropics, parts of the Northern Territory top end and the Kimberley region (Figure 20 and Figure 21). Appendix G lists the summary statistics for each bioregion and scenario.

The concepts of novel and disappearing ecological environments are important for interpreting the results. A novel ecological environment is one in which the assemblage of species that may form under climate change is unlike anything that exists at present. By contrast, a disappearing ecological environment is a present-day assemblage of species which may not be found in the future.

Figure 22: Patterns of Composite ecological change for vascular plants under the high emissions’ mild MIROC5 climate scenario.
This image combines three datasets: The potential degree of ecological change and the degree to which ecological environments are becoming novel or tending to disappear. The images on the right hand side of the figure guide interpretation, but continuous data (rather than the four categories) were used to produce the composite image. Note that the ecological similarity scaling for the novel and disappearing measures has been inverted. Source: Williams et al. (2014). See Appendix F for a summary explanation. Projection: geographic.

Williams et al. (2014) undertook a composite analysis of the present-day ecological environments for vascular plants projected to disappear or become novel, using one of the same emission
scenarios (RCP 8.5 in 2050) and both climate models (MIROC5 and CanESM2). These results, reproduced in Figure 22 and Figure 23, show where many unique ecological environments may be much reduced in the future. The brighter greens indicate where present-day and future ecological environments at the same location are most like each other. By contrast, the green areas shown on Figure 20 and Figure 21 indicate where the NRS continues to adequately represent some present-day ecological environments, even if they no longer occur in the future where they were originally found. These contrasts help explain why we find very low levels of present-day ecological environments represented by future occurrences in the NRS.

*Figure 23 Patterns of Composite ecological change for vascular plants under the high emissions’ hot CanESM2 climate scenario.*

This image combines three datasets: The potential degree of ecological change and the degree to which ecological environments are becoming novel or tending to disappear. The images on the right hand side of the figure guide interpretation, but continuous data (rather than the four categories) were used to produce the composite image. Note that the ecological similarity scaling for the novel and disappearing measures has been inverted. Source: Williams et al. (2014). See Appendix F for a summary explanation. Projection: geographic.

In the future some present day ecological environments will no longer exist. Of those that are retained, some may be greatly diminished in extent, while others may have expanded their range. Figure 20 and Figure 21 show the extent to which the remaining present-day ecological environments are captured in the NRS. The environments with at least 17% of their future extent located somewhere in reserves are shown in shades of green.

Ferrier et al. (2012) found that while contemporary ecological environments are likely to be very poorly represented in the NRS under climate change, the level of representation of the continent’s future environments in the NRS shows a remarkably similar pattern to the current representation.
of today’s environments. This suggests that the NRS will continue to include about the same amount of diversity of the continent’s habitats of the day in the future as it does presently.

As noted above, these analyses consider only a subset of the various processes of change influencing the future ecological character of Australian vegetation and the role of the NRS in retaining biodiversity. Actual change in biological composition resulting from climate change will be shaped by many factors, and associated sources of uncertainty, beyond those considered in this modelling.

In the previous work, Ferrier et al. (2012) highlighted where potential ecological change may be mitigated to some moderate extent in areas with significant environmental heterogeneity such as altitudinal variation. They suggested some expansion of the NRS may be needed to help manage the transition to represent a new suite of vegetation assemblages. Addressing the question of “where should these additional reserves be located?”, however, requires a different analysis. The analytical framework developed in the current study offers a foundation for now undertaking such an analysis. For example, this would enable consideration of the ecological environment expected to occur at a given location in the future, and to ‘look back’ at where similar ecological environments were distributed 50 years previously, and what proportion of that original distribution is likely to be protected in the future.

Discussion of these and other possible extensions to the analytical framework to more precisely inform current and future investment priorities to protect and restore habitat across entire landscapes is provided in Section 3 (from page 41).
Further work to inform future conservation actions and policy decisions

There is considerable potential to extend the analytical framework employed in this project to inform prioritisation and evaluation of investment in protection and restoration of habitat across entire landscapes (i.e., beyond the formal reserve system). The work that has been undertaken here offers a solid foundation on which to build this extended whole-landscape approach. To better appreciate what this extension would involve it is worth first reflecting on what the existing approach already considers and, most importantly, does not consider.

All of the analyses undertaken and reported here have focused on the representativeness of the NRS—that is, how well do existing protected areas represent the diversity of biologically-scaled ecological environments occurring across the Australian continent, and how might this level of representation change as a result of climate change? These analyses can therefore help in identifying, and mapping, ecological environments that are poorly represented in the NRS. If the fundamental objective driving investment in protection of habitat (either through formal reservation or through other mechanisms) is to fulfil the Comprehensive, Adequate, Representative criteria underpinning the NRS, then these poorly-represented environments might sensibly be viewed as high-priority candidates for protection. Any such prioritisation would need to integrate mapping of poorly-represented environments with mapping of the extent, and ideally condition, of native habitat—for example, by overlaying and/or masking the mapping of representativeness generated by this study with the Department’s “natural areas” layer (Department of the Environment, 2014c). Information on the cost and feasibility of protecting areas identified as potential priorities from this mapping would also clearly need to be factored into decision-making.

The measure of achievement, or success, driving the above approach is based purely on what is included within the NRS—that is, the level of representation of ecological environments achieved within the boundaries of protected areas. This approach is therefore blind to the condition of those portions of ecological environments falling outside of the NRS (other than ensuring that particular areas of land being considered for addition to the reserve system are in reasonable condition). In other words if 20% of an ecological environment is included within the NRS and the remaining 80% is in poor condition (e.g., cleared for cropping) then this would be considered an equally successful outcome as having 20% of that environment within the NRS but with the remainder covered largely by good-condition habitat.

Extending this approach to work in a truly whole-landscape context requires a fundamental shift in the measure of achievement underpinning conservation prioritisation and evaluation across the landscape. Achievement would now need to be assessed as a function of the condition of habitat across the entire (whole-landscape) distribution of ecological environments, not just the proportion of each environment included within the NRS. From this perspective inclusion of areas within the NRS is viewed as one mechanism for achieving a broader fundamental objective of whole-landscape conservation, rather than as the objective itself. Inclusion of a given area within the NRS can contribute to achieving this broader objective either by preventing any future decline.
in the present condition of habitat within that area that might have resulted from land-use change, or by improving this present condition through active removal of current pressures, or both.

In practical terms, how might the analytical foundation established by this project be extended to adopt this broader whole-landscape perspective? One relatively straightforward strategy would be to simply extend the analysis of representativeness presented here to consider not only representation of ecological environments within protected areas but also within areas of relatively natural (good condition) habitat, regardless of their protection status. Appendix H outlines an example of how this might be done. While this strategy offers a reasonably effective means of incorporating whole-landscape habitat extent and condition into the assessment of protected-area representativeness, it falls short of providing a comprehensive solution to the broader challenge of prioritising and evaluating investment in multiple types of actions across whole landscapes.

An alternative approach for addressing this challenge would be to adopt the general modelling framework, described by Ferrier and Drielsma (2010), for integrating multiple pattern and process-related factors into whole-landscape conservation assessment. This approach involves modelling, and thereby projecting, the future condition of habitat in each grid-cell across the landscape of interest (in this case the whole Australian continent) as a function of the present state (condition) of that cell, present and future pressures acting on this state, and any proposed or implemented management interventions addressing these pressures. This spatial layer of future (projected) habitat condition is then combined with data on spatial patterns in the distribution of biodiversity (in this case biologically-scaled ecological environments), adjusted where necessary to reflect expected habitat redistributions in response to climate change, to thereby model the expected retention (persistence) of biodiversity within the landscape as a whole. As detailed by Ferrier and Drielsma (2010) this general approach to whole-landscape modelling can serve as a common, yet highly flexible, foundation on which to build a range of whole-landscape assessment activities, including:

- Mapping relative priority for investment in a given type of action across the landscape, by assessing the marginal change in biodiversity retention that would be achieved by applying this action to each and every grid-cell in turn (expressed relative to cost and feasibility if needed). This facilitates the generation of multiple priority grids across the region of interest, each addressing a different type of action (e.g., reservation, revegetation).

- Assessing the potential change in biodiversity retention achievable through applying spatially-explicit sets of actions—for example, a set of polygons delineating a proposed configuration of reserve additions. This enables interactive comparison of the benefit to be derived from alternative spatial-explicit options (again relative to cost and feasibility if needed).

- Estimating the total cumulative change in biodiversity retention expected as a result of actions actually implemented. This provides a means of progressively predicting biodiversity outcomes likely to be achieved through investments already made in habitat protection or restoration, thereby providing valuable information for monitoring, evaluation and reporting of progress.
Major components that would be involved in building such a modelling framework on top of the analytical approach already developed in this project are outlined in Figure 24. The GDM-based modelling of present ecological environments and their redistribution under climate change (in the blue-shaded section of the figure) is already well developed across the entire Australian landscape, and therefore also fit for this purpose (although there could be value in incorporating other biological groups and climate scenarios).

![Figure 24](image)

**Figure 24** A broad methodological framework for undertaking whole-landscape prioritisation and evaluation of conservation investment, building on the community-level modelling approach employed in this project. The yellow and blue colour-shaded sections of the diagram depict key components of the integrated modelling system that would underpin this capability. Components within the blue-shaded section have already been employed in the current project, while components within the yellow-shaded section would need to be added to the existing approach. The three coloured arrows, and associated text (in red, green and blue), represent major potential applications of this integrated modelling system.

Various options could be pursued for modelling and projecting habitat condition within each cell, depending on the level of rigour required, and the availability of time and resources. At the simplest end of the spectrum, future condition could be modelled using simple rules estimating the expected future condition of areas currently covered by native versus transformed vegetation (from the “natural areas” mapping: Department of the Environment, 2014c) under different classes of land tenure, use or management (as per Drielsma and Ferrier, 2006). Higher levels of sophistication and rigour could potentially be achieved through incorporation of habitat condition mapping currently being operationalised by CSIRO (Donohue et al., 2014; Harwood et al., 2016).
along with dynamic scenarios of future land-use change such as those developed for the Australian National Outlook initiative (Bryan et al., 2014; Hatfield-Dodds et al., 2015a; Hatfield-Dodds et al., 2015b).

Analytical techniques for projecting future retention of biodiversity as a function of projected GDM-based ecological environments and projected habitat condition are already well established within CSIRO, based on approaches originally described by Ferrier et al. (2004), Allnutt et al. (2008), and Mokany et al. (2012). These techniques have already been applied in a number of continent-wide projects including, most recently, the Australian National Outlook (Hatfield-Dodds et al., 2015a).

While these additional components of a whole-landscape approach to conservation investment (outlined in Figure 24) will require extra effort, they are feasible given the advanced development stage of an integrated modelling system. The amount of effort then required for any particular application will depend on the level of rigour and sophistication to apply in the first instance.
Appendix A Methods for assessing the representativeness of the current NRS

This Appendix provides additional technical detail related to the analysis of relative and effective level of protection for biodiversity within the terrestrial National Reserve System (NRS), consistent with the intent of the CAR (Comprehensive, Representative and Adequate) scientific framework.

Generalised dissimilarity modelling of biological diversity

Generalised dissimilarity modelling (GDM) is a statistical technique for modelling biological dissimilarity between pairs of geographical locations, as a function of environmental differences between these locations (Ferrier et al., 2007). Here we use the composition of vascular plant species observed to be present at each location to calculate dissimilarity, \( d_{ij} \), between successive pairs of locations, \( i \) and \( j \), using the Sørenson index (related to the Bray-Curtis index):

\[
d_{ij} = 1 - s_{ij} = 1 - \frac{2A}{2A + B + C}
\]

Equation 1

Here, \( A \) is the number of species common to both locations \( i \) and \( j \); \( B \) is the number of species present only at location \( i \), and \( C \) is the number of species present only at location \( j \). Consequently the compositional dissimilarity between two locations is the proportion of species found at one location that do not occur at the other location, averaged across both locations. The index ranges from 0 if the two locations have identical species through to 1 with no species in common.

Protected area boundaries (the NRS)

A protected area is defined as an area of land and/or sea especially dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed through legal or other effective means (IUCN, 1994).

The terrestrial protected area estate under consideration included the boundaries of properties meeting the NRS criteria as supplied in CAPAD14 (Department of the Environment, 2014a) combined with Indigenous Protected Areas subsequently declared up to and including October 2015 (Department of the Environment, 2015) (Figure 6). Four types of property boundaries are identified in CAPAD14 (Table 1). The two categories that do not meet the Commonwealth’s criteria for a property in the NRS account for 0.36% of the CAPAD14 dataset (501,854 ha: categories ND and D in Table 1). Seventy-two Indigenous Protected Area properties are included in the analysis, making up nearly 45% of the current areal extent of properties used in this analysis (i.e., CAPAD14 where NRS = I or Y, and additional IPA boundaries totalling 151,745,580 ha: from Table 1).
Table 1 Extent of boundaries defining protected areas in this analysis of NRS representativeness.

<table>
<thead>
<tr>
<th>NRS PROTECTED AREA IN CAPAD14</th>
<th>IPA/CAPAD14 BOUNDARY (HA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y (A protected area located</td>
<td>129,877,690</td>
</tr>
<tr>
<td>within the State and</td>
<td></td>
</tr>
<tr>
<td>Territory jurisdiction)</td>
<td></td>
</tr>
<tr>
<td>I (An interim protected</td>
<td>9,171,965</td>
</tr>
<tr>
<td>area - in the process of</td>
<td></td>
</tr>
<tr>
<td>gazetted/established)</td>
<td></td>
</tr>
<tr>
<td>ND (A protected area that</td>
<td>328,032</td>
</tr>
<tr>
<td>does not meet NRS criteria,</td>
<td></td>
</tr>
<tr>
<td>but compliments the NRS</td>
<td></td>
</tr>
<tr>
<td>with sympathetic</td>
<td></td>
</tr>
<tr>
<td>management)</td>
<td></td>
</tr>
<tr>
<td>N (A protected area that</td>
<td>173,822</td>
</tr>
<tr>
<td>does not meet the NRS</td>
<td></td>
</tr>
<tr>
<td>criteria)</td>
<td></td>
</tr>
<tr>
<td>Total CAPAD14</td>
<td>139,505,650</td>
</tr>
<tr>
<td>Indigenous Protected Areas</td>
<td>6,799,674</td>
</tr>
<tr>
<td>as at 31 October 2015</td>
<td></td>
</tr>
<tr>
<td>Indigenous Protected Areas</td>
<td>55,254,959</td>
</tr>
<tr>
<td>in CAPAD14</td>
<td></td>
</tr>
<tr>
<td>Total NRS (excludes 'ND'</td>
<td>151,745,580</td>
</tr>
<tr>
<td>and 'N')</td>
<td></td>
</tr>
</tbody>
</table>

1. Terrestrial properties in Antarctica, Scott Reef, Christmas Island and Lord Howe Island were excluded (see Appendix B).

**Raster dataset (NRS2015)**

The grid resolution for the representativeness analysis is 9 second (approximately 250m by 250m, varying by latitude). The October 2015 IPA dataset was combined with those components of the CAPAD 2014 dataset meeting NRS criteria (i.e., ‘Y’ and ‘I’ in Table 1). Using ArcGIS™ 10.2, the resulting shapefile was converted to a binary raster at 0.00025° resolution in GDA94 (3 second, approximately 25m cells), using the Cell Centre option in the Polygon to Raster function. Using the Aggregate function, the areal coverage in each 0.0025° (9 arc second) analysis grid cell was calculated as a proportion 0 to 1 (hereafter referred to as NRS2015).

This choice of method to represent the high resolution vector dataset by a raster was influenced by the prevalence of smaller often linear properties and properties with highly convoluted boundaries (Figure 25 and Figure 26). Figure 27 shows how these protected areas, indicative of a fragmented landscape, were represented at 9” by their cell area proportions. This method allows reserves with relatively small overlap in a 9” grid cell to be included in the analysis.

The procedure was also tested in equal area Albers projection, but resampling to geographic projection generated errors >0.0025° (9”) on close examination of the smaller reserves compared with the original shapefile. All subsequent proportional area calculations were therefore carried out in geographic projection. An area bias correction was applied for reporting of results in equivalent areal measures.
Figure 25 Frequency histogram of property sizes converted to raster for the analysis of representativeness. Approximately 50 NRS properties are less than 0.25 ha in size, totalling about 5 ha.

Figure 26 Frequency histogram of property fragmentation converted to raster for the analysis of representativeness. Approximately 100 NRS properties exhibit extreme fragmentation (index > 100,000, totalling approximately 358,000 ha.)
Figure 27 Example showing how the frequent small and linear NRS properties were represented by 9 second grids. INSET: national extent of NRS data and location shown as a red circle.

GDM model of vascular plant compositional turnover

Biological data for this analysis were derived in April 2013 from the Australian Natural Heritage Assessment Tool (ANHAT) Database, courtesy of the Australian Department of the Environment. Taxonomic checking occurs before species are included in ANHAT. The vascular plants in this dataset comprise over 13,250 species, represented by 258 families in six taxonomic classes (Cycadopsida – 2 families, Liliopsida – 71, Lycopodiopsida – 3, Magnoliopsida – 177, Pinopsida – 4, Psilotopsida – 1). All taxa were grouped at the species level of taxonomic determination and unknown/unmatched taxa excluded. Introduced and cultivated plant specimen locations were excluded. Locations with a geoaccuracy greater than 2000 m were excluded; although locations that lacked a geoaccuracy estimate were included.

To minimise the effect of under-sampling due to non-systematic survey methodologies, only sites with more than 10 species, aggregated to a 9-second grid cell, were used. Furthermore, to minimise the effect of sampling bias toward populated, accessible regions, the site-pairs used in the analysis were randomly sampled equally within and between the 85 bioregions characterising environmental heterogeneity across the Australian continent. This sampling was applied using Biodiverse software (Laffan et al., 2010) coupled with custom site-pair sampler software (Rosauer et al., 2014). In addition, three under-sampling covariates were defined from the number of unique species, the number of original unique locations, and the number of unique observation...
records, per grid cell. These covariates, if included in the model, helped partial-out the effect of under-sampling of occurrence, as far as could be explained. Due to computation and processing time limitations when building the GDM model, the number of site-pairs used was approximately 1.5 million. These site-pairs encompassed 28,527 grid cells where vascular plants have been observed continent-wide (Figure 28). Gaps in biological surveys using these data and the same GDM model are currently being investigated in partnership with the Bush Blitz program to inform choice of new survey areas.

Figure 28 Location records for vascular plants where at least 10 distinct species are listed within a 9second grid cell. Data used in the GDM model: http://doi.org/10.4225/08/557F8520465F7.

The .NET GD Modeller software version 2.7 (Manion, 2012) was used to develop fitted models of species compositional turnover. The .NET software has been developed by the NSW Office of Environment and Heritage to support in-house applications and research collaborations. Many of the functions have now been incorporated into an R-package (Manion et al., 2016).

GDM model fitting followed the procedure outlined in Williams et al. (2012). Each variable group (baseline climate, substrate, and landform) was initially tested to identify which are likely to be used for predicting species composition in the model. The remaining variables were combined into a single model and tested for redundancy. The final subset of candidate variables was further screened for excessive correlation using a backward stepwise variable elimination procedure. Variables were retained in the model if they contributed at least 0.05% partial deviance explained when each was tested for removal. This procedure significantly reduces the number of predictors retained in the model.
The potential for a 4th spline to better define the shape of the retained predictors was tested selectively for those with the highest relative contribution, using the model fit criterion of at least 0.05% additional partial deviance explained. Following these tests the combined significance of the predictors was again tested using the backward elimination criterion. In this version of the GDM fitted model, coarser resolution substrate variables derived from national soil and geology mapping (used in previous CSIRO modelling), were excluded from the set of candidate environmental variables presented to the model.

The final GDM model comprised 17 environmental predictors (listed in Table 2) and can be downloaded from http://doi.org/10.4225/08/557FB520465F7 (Williams et al., 2013). The results can be visualised by classifying predicted compositional turnover Figure 7.

Table 2 The 11 topo-climate and six substrate predictors used in the model for vascular plants

<table>
<thead>
<tr>
<th>Topo-climate group:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>WDI: Atmospheric water deficit (precipitation minus potential evaporation) – monthly minimum (Williams et al., 2012) (topographically-scaled with evaporation)</td>
<td></td>
</tr>
<tr>
<td>TNX: Minimum temperature – monthly maximum</td>
<td></td>
</tr>
<tr>
<td>TXI: Maximum temperature – monthly minimum (topographically-scaled)</td>
<td></td>
</tr>
<tr>
<td>TXX: Maximum temperature – monthly maximum (topographically-scaled)</td>
<td></td>
</tr>
<tr>
<td>TRA: Annual temperature range (topographically-scaled by TXX)(TXX – Minimum temperature – monthly minimum)</td>
<td></td>
</tr>
<tr>
<td>PTI: Precipitation – monthly minimum</td>
<td></td>
</tr>
<tr>
<td>PTRX: Precipitation seasonality – maximum of differences between successive months (Williams et al., 2012)</td>
<td></td>
</tr>
<tr>
<td>PTS1: Precipitation – solstice seasonality composite factor ratio (Williams et al., 2012)</td>
<td></td>
</tr>
<tr>
<td>EPI: Potential (pan) evaporation – monthly minimum (topographically-scaled)</td>
<td></td>
</tr>
<tr>
<td>EAA: Annual total actual evaportranspiration terrain-scaled using MODIS</td>
<td></td>
</tr>
<tr>
<td>EAAS: Annual modelled total actual evapotranspiration modelled using topographically-scaled and CTI-adjusted water holding capacity</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substrate group:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>WII: Weathering intensity index (Wilford, 2012)</td>
<td></td>
</tr>
<tr>
<td>PC1_20: Spectra of surficial topsoils 0–20 cm – Principal Component 1 (Viscarra-Rossel and Chen, 2011)</td>
<td></td>
</tr>
<tr>
<td>PC2_80: Spectra of surficial topsoils 60–80 cm – Principal Component 2 (Viscarra-Rossel and Chen, 2011)</td>
<td></td>
</tr>
<tr>
<td>PC3_80: Spectra of surficial topsoils 60–80 cm – Principal Component 3 (Viscarra-Rossel and Chen, 2011)</td>
<td></td>
</tr>
<tr>
<td>SME80: Relative abundance of smectite clay minerals in surficial subsoil (60–80 cm) (Viscarra Rossel, 2011)</td>
<td></td>
</tr>
<tr>
<td>ELVFR1000: Elevation focal range within 1000 m (Gallant et al., 2011).</td>
<td></td>
</tr>
</tbody>
</table>

---

8 Reside et al. 2013
9 Variable is effectively equivalent to a bioclimatic predictor derived when using the BIOCLIM module of the ANUCLIM software (Xu & Hutchinson 2011).
Analysis of protected area representativeness

The GDM fitted model can be used to predict the ecological similarity \((s_{ij})\) between any pair of grid cells (e.g. grid locations \(i\) and \(j\)) as a function of its relationship with environment. If the ecological similarity between two grid cells equals 1, they are predicted to have the same biota. As similarity between grid cells decreases, the biota is predicted to be increasingly different.

Assuming pre-1750, intact ecological condition everywhere, we calculated the area of ecological environments \((A)\) similar to that of any given grid cell \((i)\) as the sum of pair-wise similarities between that grid cell and \(n\) other sampled grid cells \((j)\):

\[
A^\text{intact}_i = \sum_{j=1}^{jn} s^2_{ij}
\]

Equation 2

This calculation provides a baseline against which to measure protected area representativeness. Complete representation is achieved when the area of similar ecological environments within the protected area system for a given cell is equal to its intact area, i.e. \(A^\text{intact}_i = A^\text{protected}_i\).

We therefore calculate both the baseline area of similar ecological environments for an ecologically intact pre-1750 Australia, \(A^\text{intact}_i\) and the area under protection, as follows:

\[
A^\text{protected}_i = \sum_{j=1}^{jn} s^2_{ij} h_{ij}
\]

Equation 3

Here, \(h_{ij}\) is the reserved proportion of each grid cell. The representation \((R_i)\) of similar ecological environments to grid cell \(i\) is given by the proportion:

\[
R_i = \frac{A^\text{protected}_i}{A^\text{intact}_i}
\]

Equation 4

Calculation strategy to minimise area bias in cell by cell similarity comparison

The calculation of protected area representativeness was applied to classes of ecological similarity to account for the area relationship shown in Figure 29 when the similarity of a focal cell is compared with all other cells that vary in similarity.

![Figure 29](image)

Figure 29 A schematic spatial map showing the relationship between area (extent in contours) of similar ecological environments surrounding a grid cell of interest (black square) increasing as the threshold of similarity for comparison decreases (grey scale). Paler grey colours signify decreasing similarity. With distance from the focal cell, the number of cells (equated to extent, area) with a given similarity increases, such that there will be orders of magnitude more cells of low similarity (values approaching 0) compared with high similarity (values approaching 1).
Compared to the focal cell, since similarity relates to the number of species in common, it is reasonable to assume that the species found in low similarity areas are also found in areas of high similarity, but the inverse is not true. To account for this effect, and remove any associated bias, similarities are grouped into 0.05 bins (20 in total), and the area of similar ecological environments in both pre-1750 habitat and the reserve system are accumulated within bins. These binned similarities are cumulatively summed, and the calculation of representativeness weighted by the area of similar ecological environments in each case.

**Sampling strategy to capture small reserves**

In practice, it is not feasible to compute the comparison for all pairs of the 111 million grid cells at 9 second resolution for Australia. Therefore, each grid cell is compared with a representative sample of grid cells from the entire continent.

In previous continental scale analyses at 9 second resolution (e.g. Prober et al., 2015; Reside et al., 2013; Williams et al., 2014), sample sizes of ≈50,000 were used to compute ecological patterns. This sample size takes approximately 10 hours when run across 96 compute nodes, and is close to the maximum practical job size for such analyses undertaken using CSIROs high performance computing network. However, given the sometimes sparse and dispersed nature of protected areas, a higher sample density is required to adequately capture small reserves.

We devised a new sampling approach to iteratively increase sample density for more accurate representativeness analyses. Repeat runs of non-overlapping stratified samples of 50,000 grid cells were conducted as time allowed and compiled into a single calculation. In this instance, we undertook 40 such analyses, resulting in a total sample of 2 million grid cells (1.8% of grid cells).

For each of the repeat analyses ($q$), the area of similar ecological environments in pre-1750 (intact) condition ($A_{intact}$) and within the protected area system ($A_{protected}$) was recorded for each grid cell. The proportional protection of each grid cell, $R_q$, was then calculated by summing the numerator and denominator across the multiple non-overlapping analyses prior to division:

$$R_q = \frac{a^{NRS2015} + \sum_{q=0}^{q=40} q A_{protected}^q}{1 + \sum_{q=0}^{q=40} q A_{intact}^q}$$  \hspace{1cm} \text{Equation 5}

**Regional calculation of representativeness achievement**

The proportional protection of each grid cell ($R_q$, Equation 5) within a reporting region, was aggregated using an extension of the approach outlined in Ferrier et al. (2004), that excludes the weighting by richness and species-area scaling to provide a single metric of representativeness achievement as the geometric average, $P_d$, that is directly analogous to standard areal coverage reporting:

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\[
P_A = e^{\left( \frac{\sum_{m=1}^{n} \ln \left( \frac{R_m}{A_m^{\text{max}}} \right)}{\sum_{m=1}^{n} \ln \left( \frac{R_m}{A_m} \right)} \right)}
\]

*Equation 6*

\(P_A\) is the geometric mean of proportional representativeness achievement for a given reporting region varying in value between 0 and 1, and can be reported as a percentage by multiplying by 100. In this analysis, \(n=2,000,000\) (all sampled cells) and \(nA\) is the number of cells in the reporting area.

Additional statistics for the reporting region can also be derived, along with the geometric mean including the maximum and minimum cell values and the proportion of cells above or below a representativeness threshold (e.g. 17%). For comparison, the arithmetic mean is also provided.

**Geometric mean versus arithmetic mean**

There is increasing evidence in the literature that the geometric mean is a more appropriate measure for examining trends in biological diversity and for assessing whether targets have been met (Buckland et al., 2005; Buckland et al., 2011; Giljohann et al., 2015; McCarthy et al., 2014; van Strien et al., 2012). This is especially the case where trends in species abundances are being compared over time (Buckland et al., 2011). By combining values on a multiplicative scale (Equation 7), the geometric mean is less susceptible to extreme values and therefore more sensitive to the occurrence rate of all ecological units of interest.

The geometric mean (GM) of a set of data \([a_1, a_2, a_3, \ldots, a_n]\) can be derived from the formula:

\[
\left( \prod_{i=1}^{n} a_i \right)^{1/n} = \sqrt[n]{a_1 a_2 a_3 \ldots a_n}
\]

*Equation 7*

The arithmetic mean (AM), which is the sum of a series of numbers divided by the count of that series of numbers, applies when each score is an independent event. If the events are not independent, as for observing change in biodiversity relative to a baseline, the geometric average provides the accurate measure of the central tendency. The use of the geometric mean as a single metric for reporting on and comparing trends over time or between regions in overall NRS performance, from a model of continuous variation in biodiversity which uses sparse data on species occurrence to predict compositional trends spatially, is therefore appropriate here. This statistic appropriately accounts for differences in the relative spatial extent, or conversely uniqueness, of different ecological environments and is always slightly less than the arithmetic mean.

**Regional reporting comparing areal and GDM-scaled measures**

In addition to the GDM-scaled calculation of representativeness achievement, \(P_A\) (Equation 6), the standard areal representation was also calculated \((P_{Ai})\). The total area of reserves within a region, \(X_i\), was simply divided by the total area of the region:
Regional reporting used IBRA 7 (Department of the Environment, 2014b) bioregions and sub-regions. These regions were converted to 9 second rasters using Cell Center in ArcGIS™ Polygon to Raster function. Both measures (standard areal and $P_j$ index of representativeness) were calculated for each region using the rasterised “NRS 2015” data set to enable direct comparison. The proportional calculations in geographic projection can be converted to actual areal values by multiplying by the area, for example in hectares, if desired.

Statement of model and data limitations

Measures derived from predictions and projections of ecological similarity provide one of the few tools available for planners to envisage present-day patterns and potential futures for biological communities. When carefully used in combination with other sources of information, they can help to inform planning. Nevertheless, models are always subject to limitations, and predictions from these models will therefore be subject to various forms of uncertainty, some of which are difficult to estimate.

The broad limitations of the data and models employed in this project include:

- The environmental coverage of the biological survey data is incomplete, which affects the accuracy of the biodiversity model. Environmental coverage for vascular plants is shown in Figure 30.
- 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 Figure 31.
- 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.
- Land 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.

Information about the limitations of any model of biodiversity or the environment assists planners to decide how much emphasis to place on the outputs and their usefulness in the different phases of planning. Here we provide two measures that characterise different types of spatial limitations in the biodiversity modelling and their application to climate change. These are additional to the
uncertainty associated with climate change, which is expressed through the use of different climate models and emission scenarios (for example, see Technical Note 3 in Williams et al., 2014).

Figure 30 (upper) shows how well the biological survey data represent the different places where vascular plant species are found across Australia, as a basis for modelling ecological similarity (i.e.,

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mostly in the high coverage, blue and pale yellow colours on the legend). This is calculated as a function of the proportion of the density of survey effort within GDM-scaled environmental space. A threshold is defined, specific to the biological group, beyond which the environmental space is considered adequately sampled.

Extrapolation of statistical models to new environments outside the range of the data used to fit them is sometimes necessary. This is not ideal because potential novel relationships between species composition and the more extreme environments expected under climate change cannot be fully accounted for. Where extrapolation is high in some parts of the landscape, greater caution is needed in using the data to make critical decisions about those places.

Figure 30 (lower) shows that model extrapolation into other areas of the Australian landscape for present-day climate is nil or negligible across most of Australia. Extrapolation here is calculated as the sum of the absolute ecological distances for each of the GDM-scaled environmental variables, beyond the data range used to fit the model. The contribution to extrapolation by individual variables (not shown) indicates how sensitive the model is to each.

![Extrapolation of GDM model for vascular plants](image)

**Figure 31** The degree to which the GDM model for vascular plants has been extrapolated to new environments.

Extrapolation is also nil or low across most of Australia for the climate scenarios investigated here (Figure 31). As might be expected, the projection of ecological similarity using the more extreme high emissions’ *hot CanESM2* climate scenario results in more areas of extrapolation.
Appendix B  Extent by reserve type and IUCN management category

This Appendix presents a summary of the reserves used in the analysis of NRS representativeness derived from CAPAD14 (Table 3) and integrated with Indigenous Protected Areas (Table 4) data.

Table 3 Extent of the NRS from CAPAD 14 used in this analysis (excludes Antarctic reserves, Scott reef, Christmas Island, Lord Howe Island).

<table>
<thead>
<tr>
<th>TYPE</th>
<th>TYPE_ABBR</th>
<th>IUCN Management Category</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>IA</td>
<td>IB</td>
</tr>
<tr>
<td>5(1)(g) Reserve</td>
<td>S5G</td>
<td>139,346</td>
<td>63,059</td>
</tr>
<tr>
<td>5(1)(h) Reserve</td>
<td>SSH</td>
<td>138</td>
<td>8,403</td>
</tr>
<tr>
<td>Aboriginal Area</td>
<td>AA</td>
<td>1,053</td>
<td>1,053</td>
</tr>
<tr>
<td>Biodiversity Hotspot</td>
<td>HPOT</td>
<td>1,171,121</td>
<td>1,171,121</td>
</tr>
<tr>
<td>Botanic Gardens (Commonwealth)</td>
<td>BG (COM)</td>
<td>158</td>
<td>158</td>
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10 IUCN Management Categories classify protected areas according to their management objectives. The categories are recognised by international bodies such as the United Nations and by many national governments as the global standard for defining and recording protected areas and as such are increasingly being incorporated into government legislation. See, [http://www.iucn.org/theme/protected-areas/about/categories](http://www.iucn.org/theme/protected-areas/about/categories)

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Assessing the ecological representativeness of Australia’s terrestrial National Reserve System: A community-level modelling approach | 59
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Table 4 Extent of Indigenous Protected Areas as at 31 October 2015, included in this analysis and integrated with valid NRS properties in CAPAD14.

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<td>TOTAL</td>
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Appendix C Continuous measure of protected area representativeness by States and Territories

This Appendix shows proportional protection (%) of ecological environments (scaled by vascular-plant composition) within NRS2015 reserves within each state and territory. Greens indicate the minimum 17% threshold representation has been achieved. Class boundaries and colours match histogram bars in Figure 11.

Figure 32 Tasmania - proportional (%) protection of ecological environments (scaled by vascular-plant composition) within NRS2015 reserves.
The NRS properties used in this analysis are shown in Figure 6. Projection: Australian Albers
Figure 33 Victoria - proportional (%) protection of ecological environments (scaled by vascular-plant composition) within NRS2015 reserves. The NRS properties used in this analysis are shown in Figure 6. Projection: Australian Albers.
Figure 34 Australian Capital Territory - proportional (%) protection of ecological environments (scaled by vascular-plant composition) within NRS2015 reserves.

The NRS properties used in this analysis are shown in Figure 6. Projection: Australian Albers.
Figure 35 New South Wales - proportional (%) protection of ecological environments (scaled by vascular-plant composition) within NRS2015 reserves.
The NRS properties used in this analysis are shown in Figure 6. Projection: Australian Albers.
Figure 36 Queensland - proportional (%) protection of ecological environments (scaled by vascular-plant composition) within NRS2015 reserves.

The NRS properties used in this analysis are shown in Figure 6. Projection: Australian Albers.
Figure 37 Northern Territory - proportional (%) protection of ecological environments (scaled by vascular-plant composition) within NRS2015 reserves.

The NRS properties used in this analysis are shown in Figure 6. Projection: Australian Albers.
Figure 38 South Australia - proportional (%) protection of ecological environments (scaled by vascular-plant composition) within NRS2015 reserves.
The NRS properties used in this analysis are shown in Figure 6. Projection: Australian Albers.
Figure 39 Western Australia - proportional (%) protection of ecological environments (scaled by vascular-plant composition) within NRS2015 reserves.
The NRS properties used in this analysis are shown in Figure 6. Projection: Australian Albers.
Appendix D Standard areal measurements of regional representativeness

This Appendix shows the standard area measure of the extent of NRS properties within bioregions and subregions (Figure 40).

Figure 40 Standard areal extent of the NRS within IBRA bioregions and subregions. Greens indicate environments for which the minimum 17% threshold representation has been achieved. The NRS properties used in this analysis are shown in Figure 6.
Appendix E  Comparison of representativeness estimation methods

This appendix includes tabular (Table 5), graphical (Figure 41, Figure 42) data comparing the average GDM-scaled measure (geometric means) with the standard areal measure and related summary calculations.

Based on data presented in Table 5 for bioregions, Figure 43 shows where protection levels are below 17% for each bioregion and subregion, and within these, the respective proportion of ecological environments represented in the NRS. These maps indicate where more work may be needed to improve the adequacy of biodiversity protection.
Table 5. Average (as geometric mean) bioregional and continental representation of vascular plants within the NRS (B) compared with areal coverage (A, C) and level of under representation of ecological environments (D).

The percentage of ecological environments that are <17% represented in the NRS was calculated from the histogram data in 2% classes. Four bioregions are excluded from this analysis: 18-COS-Coral Sea, 42-ITI-Indian Tropical Islands, 64-PSI-Pacific Subtropical Islands, 66-SAI-Subantarctic Islands.

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<th>IBRA7 bioregion Code</th>
<th>IBRA7 Bioregion label</th>
<th>IBRA7 Bioregion ID</th>
<th>Land area (ha)</th>
<th>A. Areal extent (%)</th>
<th>B. GDM-weighted extent (% GM)</th>
<th>C. Difference (A-B) in coverage</th>
<th>D. % ecological environments &lt;17% in NRS</th>
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Assessing the ecological representativeness of Australia’s terrestrial National Reserve System: A community-level modelling approach

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<tr>
<th>IBRA7 bioregion Code</th>
<th>IBRA7 Bioregion label</th>
<th>IBRA7 Bioregion ID</th>
<th>Land area (ha)</th>
<th>A. Areal extent (%)</th>
<th>B. GDM-weighted extent (% GM)</th>
<th>C. Difference (A-B) in coverage</th>
<th>D. % ecological environments &lt;17% in NRS</th>
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</table>

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Assessing the ecological representativeness of Australia’s terrestrial National Reserve System: A community-level modelling approach

Figure 41 Comparison of representation outcomes using standard areal and GDM-scaled geometric average applied to IBRA bioregions. The blue line shows the line of equality.

$y = 0.4364x + 0.0774$  
$R^2 = 0.8519$

Figure 42 Relationship between the geometric mean for regional proportional representation achievement and the proportion (%) of ecological environments below 17% threshold (data in Table 5)
Figure 43 Proportion (%) of ecological environments (scaled by vascular-plant composition) within each IBRA region (upper) and subregion (lower) below 17% protection in the NRS. The NRS properties used in this analysis are shown in Figure 6.
Appendix F  Methods for assessing representativeness of the NRS under different climate scenarios

This Appendix provides additional detail pertaining to the methods employed to evaluate representativeness of the National Reserve System (NRS) under different climate scenarios. The methods outlined here have been adapted from Ferrier et al. (2012).

Approach

The major steps in building the application to evaluate how well contemporary ecological environments are represented by the National Reserve System under different climate scenarios are depicted in Figure 44. A GDM model is fitted using biological and environmental data (grey box), incorporating climate variables along with other factors driving distribution patterns (e.g. landform and substrate). Global climate scenarios are downscaled by combining with the baseline climate (using ANUCLIM software), and used to project patterns of ecological similarity. The resulting baseline (predicted) and projected patterns of ecological similarity are then applied to various analyses of representativeness within the NRS. These outputs provide the foundation for a number of different ways to view the implications of climate change on the NRS. Here we focus on a particular analysis, being the proportional representation of present-day ecological environments under future climatic conditions where they occur in the National Reserve System (i.e., present – future). The modelling framework is illustrated in more detail in Figure 45.

Figure 44 Major steps in the workflow using GDM to model and project future representativeness of the National Reserve System under different climate scenarios
The model of vascular plant compositional dissimilarities developed using baseline climates is used to project compositional dissimilarities for a given future climate scenario as illustrated in Figure 45 (adapted from Ferrier et al., 2012). The model-fitting process automatically identifies non-linear transformations of the original environmental variables (attributes) such that the summed environmental difference (distance) between each pair of sites (say, \(a\) and \(b\)) correlates, as closely as possible, with the observed compositional dissimilarity between these sites.

The curved line in the top-left graph represents the so-called “link function” used in GDM to account for the well-known asymptotic relationship between increasing environmental difference and observed compositional dissimilarity (the latter cannot exceed 1 once sites share no species).

The “intercept” in this graph represents the observed compositional dissimilarity expected between two sites with identical environmental conditions. This baseline dissimilarity summarises the effects of ecological factors other than those modelled and the effects of sampling error. Under a changing climate, the intercept is assumed constant, and so only the component of compositional turnover driven by changing climate is applied in the change analyses.

On the right-hand side of Figure 45 the GDM model fitted to compositional dissimilarities observed between pairs of sites under baseline (present) environmental conditions is used to estimate (by projecting) the level of change in ecological environments expected under a given climate scenario. As future climates may depart from baseline conditions, the model extrapolates using the last 10% of the linear trend from each end of the fitted function. The baseline fitted and future projected models of compositional dissimilarity are then used to estimate change in ecological environments. Here, the non-linear transformations of environmental variables from the fitted model are used to calculate the difference associated with any particular site (say \(x\)) given the environmental attributes of this site under present and future climatic conditions.
Climate change scenarios

A total of four climate change scenarios were examined comprising two emission scenarios and two climate change models for the change period 1990-2050 (c.60 years). Two CMIP5 climate models—the Model for Interdisciplinary Research on Climate produced by the Japanese research community (MIROC5 - (Watanabe et al., 2010)) and the Canadian Earth System Model (CanESM2 - (Chylek et al., 2011))—were used to project ecological change by 2050 under two greenhouse gas emission scenarios (using representative concentration pathways 4.5 and 8.5 Wm⁻² radiative forcing which equate to approximately 1.4 and 2°C of global warming respectively by 2050) (van Vuuren et al., 2011). Across all representative concentration pathways (RCPs), global mean temperature is projected to rise by 0.3 to 4.8 °C by the late-21st century (Table 6).

In deciding which climate scenarios to use, we considered biodiversity planning decisions that would have implications over the next 30-50 years, for example, current actions influencing the retention of overall biodiversity in the landscape (Williams et al., 2014). RCP 8.5 represents a low mitigation response, business as usual scenario, while the RCP4.5 represents a moderate global mitigation response. The two climate models (MIROC5 and CanESM2) represent the spectrum of ‘Maximum Consensus’ plausible futures varying from a relatively mild, and a relatively hot climate scenario with moderate rainfall change, respectively (Whetton et al., 2012). These choices are appropriate to use for planning decisions given current global trends in greenhouse gas emissions, plausible options for mitigation, and the in-built momentum in the climate-earth system.

The climate scenario data were downscaled to match the ~250m grid resolution of the climate data used to model ecological similarity. Broad patterns were rescaled using 1990-centred (30 year average) monthly gridded climate data. The climate scenario data represented similar 30-year averages centred on 2050 (see details in (Harwood et al., 2012). The resulting future climate scenario data therefore captured some of the fine scale topographic patterns that are important drivers of biodiversity response (see details in (Reside et al., 2013).

<table>
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<tr>
<th>AR5 scenario</th>
<th>2046-2065 mean °C (and likely range)</th>
<th>2081-2100 mean °C (and likely range)</th>
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<td>1.0 (0.3 to 1.7)</td>
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<td>RCP 4.5</td>
<td>1.4 (0.9 to 2.0)</td>
<td>1.8 (1.1 to 2.6)</td>
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<td>RCP 6.0</td>
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<td>RCP 8.5</td>
<td>2.0 (1.4 to 2.6)</td>
<td>3.7 (2.6 to 4.8)</td>
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</table>

Table 6 Mid- and late-21st century (2046-2065 and 2081-2100 averages, respectively) projections of global warming and global mean sea level rise from the IPCC Fifth Assessment Report (IPCC AR5 WG1) are tabulated below. The projections are relative to temperatures and sea levels in the late-20th to early-21st centuries (1986-2005 average). Temperature projections can be converted to a reference period of 1850-1900 or 1980-99 by adding 0.61 or 0.11 °C, respectively. Reproduced from (IPCC, 2013)
Representativeness of the NRS under climate change

Representation of biodiversity in reserves under the present-day climate (here, a 30-year average centred on 1990) was calculated for each grid cell as the area of similar ecological environments found within the reserve system, as a proportion of the area of similar ecological environments which would be present in a pre-1750 landscape; where the latter represents the baseline against which we measure representation.

Under climate change, the calculation of representation is very similar to Equation 5 (Appendix A). The baseline remains the same, i.e. the area of similar ecological environments which would be present in a pre-1750 landscape (under present-day average climates, assumed before the onset of rapid climate change). However, for representativeness, we now calculate the proportion based on the area of similar ecological environments found within the reserve system under a future (projected) climate.

The representation ($R_i$) of similar ecological environments under future climate to grid cell $i$ is given by the proportion:

$$R_i = \frac{A_{\text{protected(future)}}}{A_{\text{minic(current)}}}$$

Equation 9

The specific nature of the ecological environments represented within the reserve system may change, but in this analysis, the baseline remains constant, i.e. the representation of present-day ecological environments within the NRS. Since in most cases, future climates will be different to baseline climates (novel), this difference will be directional (i.e. warmer, though variable rainfall) and the future area of similar ecological environments compared with their present day extent will generally be reduced. This reduced area of present-day (characteristic) ecological environments in the future means that the area reported as protected is also reduced. As a corollary to this analysis, new types of ecological environment may arise, in the future, in existing protected areas. This latter comparative analysis was demonstrated by Ferrier et al., (Ferrier et al., 2012), but is not repeated here.

Novel and disappearing ecological environments

Williams et al. (2014) demonstrated the complexity of trends in ecological change as a composite of three indices - the *Potential degree of ecological change* and the degree to which *ecological environments are becoming novel or disappearing*. This integrated measure shows where different combinations of change may occur and how extreme that change may be. The different types of change suggest different types of vulnerability and therefore different strategic goals may be required within a single region and for a particular biological group.

This map series (reproduced below) is useful to compare with the results depicting future representativeness of the National Reserve System, showing where change may be attributed to the phenomenon of novel and disappearing ecological environments. Where green colours dominate the image, the potential for change is relatively low and these areas are more likely to retain their characteristic ecological environments, and potentially represented in the reserve system if future occurrences also reside within those boundaries.
Wherever the *Potential degree of ecological change* is scored low, ecological environments can neither be novel nor disappearing and minimal change is expected. But when the *Potential degree of ecological change* is scored high, a variety of possible types of change can occur depending on whether scores for *Novel or Disappearing ecological environments* are also high. Our composite colour-based index highlights five general types of change with different possible consequences for biodiversity where different approaches to adaptation might be applicable.

1. Minimal change (green colours) - Local environments are neither becoming novel nor tending to disappear because ecological similarity remains relatively high. The bright green areas signify regions of less change where future ecological environments are expected to be within the current adaptive range of the flora at present.

2. Change but not novel or disappearing (olive and orange colours) - The potential for local change is high but future environments have current analogues and current environments will still be present somewhere on the continent in the future.

3. Disappearing but not becoming novel (red colours) – Future local environments have current analogues (and these could be anywhere across the Australian continent), but the species of current environments may have nowhere to go (their ecological environments are disappearing) and a subset of valued species may require intensive or *ex situ* management.

4. Becoming novel but not disappearing (blue colours) - Future local environments will be unprecedented in type (not previously represented anywhere across the Australian continent), but species of current environments will still have suitable environments available somewhere on the continent, but may require assistance to get there.

5. Both novel and disappearing (purple and pink colours) – Future local environments are unprecedented (not previously represented anywhere across the Australian continent), and the species of current environments have nowhere to go (their ecological environments are disappearing).

Various colour blends indicate departures from the contemporary ecological environment. Shades of blue-green (e.g. olive and teal colours) and red-green (orange and brown colours) are variously places where there will be moderate levels of change, but similar environments broadly exist elsewhere and species generally have somewhere to assemble.

The pink and purple colours signify regions that increasingly contain places where the future local ecological environments are unprecedented in nature (novel assemblages), and the present array of species have nowhere to go (disappearing assemblages).

Notably the patterns are different for the different biological groups with varying contrasts between the mild and hotter climate scenarios (Williams et al., 2014).
Appendix G Additional results summarising the analysis of future proportional protection

Summary statistics mapped for bioregions and subregions in Figure 46 to Figure 49 (for continuous measures see Figure 20 and Figure 21).

Figure 46 Geometric mean of % protection (in NRS) of ecological environments (scaled by vascular-plant composition) of the future (2050, MIROC5, RCP 4.5) occurring by region and subregion. Greens indicate environments for which the minimum 17% threshold representation has been achieved. The NRS properties used in this analysis are shown in Figure 6.
Figure 47 Geometric mean of % protection (in NRS) of ecological environments (scaled by vascular-plant composition) of the future (2050, MIROC5, RCP 8.5) occurring by region and subregion. Greens indicate environments for which the minimum 17% threshold representation has been achieved. The NRS properties used in this analysis are shown in Figure 6.
Figure 48 Geometric mean of % protection (in NRS) of ecological environments (scaled by vascular-plant composition) of the future (2050, CanESM2, RCP 4.5) occurring by region and subregion. Greens indicate environments for which the minimum 17% threshold representation has been achieved. The NRS properties used in this analysis are shown in Figure 6.
Figure 49 Geometric mean of % protection (in NRS) of ecological environments (scaled by vascular-plant composition) of the future (2050, CanESM2, RCP 8.5) occurring by region and subregion. Greens indicate environments for which the minimum 17% threshold representation has been achieved. The NRS properties used in this analysis are shown in Figure 6.
Appendix H Representation of ecological environments in the broader landscape context

The continuous measure of protected area representativeness indicates to what extent the natural distribution of ecological environments characteristic of a given location are represented in the National Reserve System, without considering the broader landscape context. In practice, a poorly protected location may be situated within a largely unmodified landscape, and the surrounding relatively intact ecosystems indirectly support retention of its biodiversity. Conversely, a well-protected location may be relatively isolated in a highly modified landscape, where its original biodiversity may continue to decline.

The retention of original biodiversity within the NRS requires consideration of the broader landscape context:

1. Reserves are effectively managed for conservation by reducing external pressures such as habitat fragmentation and alien species invasions attributed as causing native species extinctions or population declines, and so tend to confer a greater degree of long term protection for retained species than an intact landscape potentially subject to future modification. Extant original condition habitat outside reserves cannot be expected to afford the same level of protection, even where part of an extensive intact landscape. Mapping the spatial distribution of external pressures and threats that modify natural habitat, taking local legislative constraints and management into account, is critical to whole landscape considerations.

2. Climate change, as shown in this report, is an extensive additional pressure on ecological systems to respond, adapt and change, which cannot be “protected” against and which will apply equally to sites both inside and outside reserves.

3. In practice, habitat intactness, quality or condition is a continuous property of the landscape. As for point 1, above, this has implications both inside and outside reserves. Locations within reserves may already be degraded to some extent, so cannot offer the same degree of protection as intact reserved cells. Locations outside reserves will also vary in their condition state, and a whole-landscape approach will ideally consider spatially varying known or inferred ecosystem condition states where this information is available or can be derived.

Consideration of these three properties of the whole landscape: effectiveness in managing pressures and threats and levels of protection afforded by tenure; climatic change forcing of ecological responses; and habitat condition/ modification states, will result in a more nuanced account of a landscape’s capacity for biodiversity retention and so inform prioritisation and investment decisions. Schematic examples demonstrating how additional information can support a more nuanced approach to biodiversity assessment are presented in Figure 50 and Figure 51.
Figure 50 Different views of the landscape of representativeness: a) NRS 2015 representativeness; b) natural areas layer; and c) nominal condition layer (for illustration only).

The cluster of reserves to the top left is less well represented in the NRS than those in the bottom right. However, if we consider the broader landscape context, we see that clearing in the bottom right places additional pressure on the cluster in that area.

Figure 51 Example demonstrating ways of working towards a more nuanced approach to representation: a) NRS 2015 representativeness; b) Natural Areas layer; c) Landscape Representation (i.e., the proportion of intact ecological environments represented in the Natural Areas layer).

This provides an indication of the support given by intact ecosystems to each cell. It cannot be treated in the same way as representation within reserves due to differing levels of protection. d) A simple approach to the combination of a) and c), calculated as (2a+c)/3 such that representation in the broader landscape is given a weight half that of the NRS due to an increased threat level. Use of a more accurate condition layer and a threat layer would add value.
Appendix I  Accessing the data

9-second gridded continental Australia: present (1990) and future (2050) proportional protection of ecological environments in the National Reserve System 2015 (GDM: VAS_v5_r11)

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 resulting datasets depicting proportional protection of vascular plants are listed in Table 7 and are available for public download via the CSIRO Data Access Portal. 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.

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.

2. Use the search engine to locate datasets and maps you are after (see tables below for what is available). Recommended DAP search term: ‘proportional protection’.

3. Once you have selected and clicked the 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.

### Table 7 Datasets available on the CSIRO Data Access Portal (GDM: VAS_V5_R11).

<table>
<thead>
<tr>
<th>Report Section</th>
<th>Title of measure</th>
<th>Climate scenario</th>
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<tr>
<td>Assessing current representativeness, results from page 25</td>
<td>Present-day representation (proportional protection) of ecological environments (Vascular Plants) in the National Reserve System 2015</td>
<td>baseline Climate 1990 centred</td>
<td>ESRI float file (9sec grids), GDA94, geographic projection</td>
</tr>
<tr>
<td>Assessing future representativeness, results from page 35</td>
<td>Future representation (proportional protection) for present day ecological environments (Vascular Plants) in the National Reserve System 2015</td>
<td>MIROC5, 2050, RCP 4.5 MIROC5, 2050, RCP 8.5 CanESM2, 2050, RCP 4.5 CanESM2, 2050, RCP 8.5</td>
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<tr>
<td>Assessing current representativeness, results from page 25</td>
<td>Proportion of present-day ecological environments achieving 17% or more representation (proportional protection) of Vascular Plants in the National Reserve System 2015 by IBRA7 bioregion</td>
<td>baseline Climate 1990 centred</td>
<td>Excel spreadsheet of summary statistics and histogram data by bioregion derived from the 9sec gridded data</td>
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</tbody>
</table>
Adequacy (sensu CAR): A protected area network that is inclusive of sufficient amount and configuration of good quality habitat within a managed landscape to maintain the integrity of meta-populations, species and ecological communities through intrinsic ecosystem processes (e.g., regeneration regimes, population dynamics, food web interactions).

Aichi Target: In CBD decision X/2, the tenth meeting of the Conference of the Parties, held from 18 to 29 October 2010, in Nagoya, Aichi Prefecture, Japan, adopted a revised and updated Strategic Plan for Biodiversity, including the Aichi Biodiversity Targets, for the 2011-2020 period. The new plan consists of five strategic goals, including twenty Aichi Biodiversity Targets: https://www.cbd.int/sp/default.shtml.


Biodiversity surrogate: Proxy information for assessing biodiversity complementarity of places. A common hypothesis is that the pattern of species "turnover" over different geographic areas for one taxonomic group will indicate the pattern for all biodiversity.11


C-A-R (Comprehensive, Adequate, Representative): The NRS is underpinned by a scientific framework focussed on the dual principles of representation and persistence applied to Australia’s distinctive flora, fauna and supporting habitats. This framework focuses attention on three informative criteria from which indicators of performance, measuring expectations of intrinsic ecological function, can be developed, known as ‘comprehensiveness, adequacy and representativeness’ (C-A-R). C-A-R was first defined to address forest conservation objectives in Australia (Commonwealth of Australia, 1992) and has been extended and refined through subsequent processes, including marine protected area design in Australian Commonwealth waters. These principles can be extended to considerations of species, ecosystems and landscape management under global change (climate and land use) for broadened application to whole of landscape management.

Comprehensiveness (sensu CAR): A protected area network that is inclusive of examples of all the native biota and natural landscapes that are characteristic of a region in which they have evolved.

Community-level model: 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.

Compositional turnover: 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.

Convention on Biological Diversity: The United Nations Environment Programme (UNEP) convened the Ad Hoc Working Group of Experts on Biological Diversity in November 1988 to explore the need for an international convention on biological diversity. By February 1991, the Ad Hoc Working Group had become known as the Intergovernmental Negotiating Committee. Its work culminated on 22 May 1992 with the

11 See more at: http://australianmuseum.net.au/biodiversity-standford-encyclopedia-of-philosophy#sthash.chpnyLaG.dpuf

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They of MIROC5 and the quality trajectories applying RCP – Representative Concentration Pathway (RCP). 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.

**Geometric mean:** A type of mean or average, which indicates the central tendency or typical value of a set of numbers by using the product of their values (as opposed to the arithmetic mean which uses their sum). The geometric mean is defined as the \( n^{\text{th}} \) root of the product of \( n \) numbers.\(^{12}\)

**IBRA bioregion or subregion:** An ecological land classification of Australia into distinct bioregions or subregions based on common climate, geology, landform, native vegetation and species information, applying the Interim Biogeographic Regionalisation for Australia (IBRA) method.

**MIROC5:** The MIROC5 climate model is Version 5 of the atmosphere-ocean general circulation model cooperatively produced by 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).

**Proportional protection:** Is the proportion of the total distribution of a given ecological environment (i.e. the proportion of all cells with a similar environment to that of a particular location) included within formal reserves (for a specified analysis domain).

**RCP – Representative Concentration Pathway:** Four greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its Fifth Assessment Report (AR5) for climate modelling and research. They describe possible future climates, all of which are considered plausible depending on emission levels 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/m², respectively).

**Representativeness (sensu CAR):** Is the degree to which the original extent of species, ecosystems and ecological processes characteristic of a realm or a jurisdiction occur within protected areas in sufficient quality or quantity to persist *in situ* over the long term

**Vascular plants:** 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). The model of vascular plants used in this report included species of fern, gymnosperm and angiosperms.
References


Department of the Environment (2014b) Interim Biogeographic Regionalisation for Australia (IBRA), Version 7 (Subregions). Australian Government Department of the Environment, Canberra, Australia.

Department of the Environment (2014c) Natural areas of Australia - 100 metre (digital dataset). Australian Government Department of the Environment, Canberra.


http://www.nature.com/nature/journal/v527/n7576/abs/nature16065.html#supplementary-information.

IUCN (1994) Guidelines for Protected Areas Management Categories. IUCN (The World Conservation Union), Cambridge, UK and Gland, Switzerland.


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