NCCARF
National
Climate Change Adaptation
Research Facility

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

Protecting and restoring habitat to help Australia's threatened species adapt to climate change

Final Report

Ramona Maggini, Heini Kujala, Martin Taylor,
Jasmine Lee, Hugh Possingham,
Brendan Wintle and Richard Fuller

PROTECTING AND RESTORING HABITAT TO HELP AUSTRALIA'S THREATENED SPECIES ADAPT TO CLIMATE CHANGE

Ramona Maggini (University of Queensland)

Heini Kujala (University of Melbourne)

Martin. Taylor (WWF-Australia)

Jasmine Lee (University of Queensland)

Hugh Possingham (University of Queensland)

Brendan Wintle (University of Melbourne)

Richard Fuller (University of Queensland)

NCCARF
National
Climate Change Adaptation
Research Facility

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

THE UNIVERSITY OF
MELBOURNE

WWF®

Published by the National Climate Change Adaptation Research Facility

ISBN: 978-1-925039-29-0
NCCARF Publication 58/13

Please cite this report as:
Maggini, R, Kujala, H, Taylor, MFJ, Lee, JR, Possingham, HP, Wintle, BA, Fuller, RA 2013 *Protecting and restoring habitat to help Australia's threatened species adapt to climate change*, National Climate Change Adaptation Research Facility, Gold Coast, pp. 59.

Acknowledgements

This work was carried out with financial support from the Australian Government (Department of Climate Change and Energy Efficiency) and the National Climate Change Adaptation Research Facility.

The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision-makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

We thank Federico Montesino Pouzols and Atte Moilanen for help with design and implementation of optimisation algorithms and software trouble-shooting. For the supply and interpretation of data we are grateful to Jeremy VanDerWal, Kristen Williams, Tania Laity and Karl Newport. We also gratefully acknowledge Jeremy VanDerWal and April Reside for making available the R scripts that were adapted for this project and Lauren Hodgson and David Green for their support with the high performance computing facilities at James Cook University (Townsville) and University of Queensland. Peter Vesk and Libby Rumpff are thanked for their help and guidance on defining vegetation response curves to different conservation actions, and Tracey Regan, Jane Elith and Antoine Guisan provided helpful discussion. We also thank Megan Evans for her assistance in the preparation of the environment data.

Disclaimer

Cover image

Black-footed Rock-wallaby *Petrogale lateralis* © Klein & Hubert / WWF-Australia.

TABLE OF CONTENTS

ABSTRACT **1**

SUMMARY FOR POLICY MAKERS **2**

1. INTRODUCTION **4**

1.1 Purpose and need **4**

1.2 Objectives and aims **4**

2. METHODS **6**

2.1 Overview of methodological framework **6**

2.2 Phase 1: Distributional responses of threatened species to climate change **11**

2.2.1 Biological data 11
2.2.2 Climatic variables 11
2.2.3 Substrate variables 14
2.2.4 Modelling current and future species distributions 15

2.3 Phase 2: Optimal climate adaptation actions for threatened species **16**

2.3.1 Optimizing conservation actions using RobOff 16
2.3.2 Defining environments 17
2.3.3 Defining actions and their respective costs for optimisation 19
2.3.4 Estimating land acquisition costs 21
2.3.5 Estimating the impact of actions upon habitat condition 24
2.3.6 Analysis settings 24

2.4 Phase 3: Spatial prioritisation for habitat protection and restoration **26**

2.4.1 Combining species distributions and optimal actions in a spatial framework 26
2.4.2 Spatial prioritisation of actions 28
2.4.3 Analysis structure 28
2.4.4 Budget and spatial visualisation of actions 30

3. RESULTS **31**

3.1 Phase 1: Climate-driven changes in threatened species' distributions **31**

3.1.1 Assessing model performance 31
3.1.2 Relative contributions of each predictor variable 31
3.1.3 Climate-driven changes in geographic distributions 32
3.1.4 Current and future patterns of threatened species richness 35
3.1.5 Opportunities for protection and restoration 37

3.2 Phase 2: Optimal protection and restoration actions **39**

3.3 Phase 3: Spatial priorities for habitat protection and restoration **41**

4. DISCUSSION **47**

4.1 Improvements and Future Directions **48**

4.2 Closing remarks **49**

REFERENCES **50**

LIST OF FIGURES

Figure 1: Diagrammatic representation of Phase 1 of the project 7
Figure 2: Diagrammatic representation of the first part of Phase 2 of the project 8
Figure 3: Diagrammatic representation of the second part of Phase 2 of the project 9
Figure 4: Diagrammatic representation of Phase 3 of the project 10
Figure 5: The generalised process of modelling the response of species' distributions to climate change based on projecting forward the spatial distribution of the environmental niche currently occupied by the species 15
Figure 6: The four different factors used to define environments with their respective classifications 19
Figure 7: Map of environments 20
Figure 8: Distribution of estimated acquisition, (management, and transaction costs across Australia 23
Figure 9: Example of response curves showing the estimated change in condition as a result of each action for unprotected environments comprising rainforest vegetation 24
Figure 10: Illustration of time discounting 25
Figure 11: Illustration of how the optimal conservation actions from the RobOff analysis are transformed into a spatial format using modelled species' distributions under climate change 26
Figure 12: Example of how species' probabilities of occurrence are modelled as changing through time as a consequence of both a changing climate and habitat condition as influenced by conservation actions taken in 2015. 27
Figure 13: The changing distribution of one threatened mammal species under the business-as-usual climate change scenario (RCP8.5) 33
Figure 14: Maps showing total richness of modelled, currently threatened species per 0.01º (~1 km) grid cell across Australia for the present day and in 2085 under three scenarios of climate change arranged in order of increasing severity 36
Figure 15: Current and future patterns of richness of the modelled species within the different taxonomic groups 37
Figure 16: Spatial distribution of the environments where conservation actions listed in Table 12 could be deployed with a $3 billion budget in the optimal solution. 39
Figure 17: Distribution and priority of areas for conservation and restoration action for a $3 billion budget. 43
Figure 18: Example showing the distribution of areas targeted for conservation actions under two different climate change scenarios in the Adelaide region of South Australia 44
Figure 19: Best 17% of Australia's land area in terms of conservation value for the 504 currently threatened species 45

LIST OF TABLES

Table 1: Overview of the number of species per taxonomic group for which the modelling was undertaken 11
Table 2: Bioclimatic variables used for the modelling of the distribution of terrestrial Species of National Environmental Significance 12
Table 3: List of General Circulation Models used to project species distributions into the future 13
Table 4: Substrate-related variables used for modelling the distributions of terrestrial Species of National Environmental Significance 14
Table 5: Estimated costs of actively restoring one hectare of cleared area in each broad vegetation class 21
Table 6: Estimates of the cost of protecting State Forests through compensating forestry for capitalised annual operating surpluses 22
Table 7: Mean, minimum, maximum and cross-validated AUC values obtained for the Maxent models within each taxonomic group. 31
Table 8: Mean percent contribution of the predictor variables to the final Maxent Model 32
Table 9: Mean size of current and future (2085) geographic ranges and relative overlap for the five taxonomic groups and three scenarios of climate change 34
Table 10: Number of species with different magnitudes of geographic range change by 2085 under three different climate change scenarios 35
Table 11: Mean percentage of the geographic range of species in the present, future, and the overlap between the two, in which vegetation is intact, degraded, cleared or permanently lost (for definitions see text) and land is protected (P) or not protected (NP) 38
Table 12: Optimal set of conservation actions identified by RobOff for a total budget of $3 billion 40
Table 13: Optimal solution from the Zonation analyses for a total budget of $3 billion 42
Table 14: Concordance between existing priority schemes for the Biodiversity Fund Round 2 (http://www.environment.gov.au) 46

ABSTRACT

To help Australia's threatened species adapt to climate change, this project predicted the impacts of climate change on the distribution of 504 threatened species listed on the EPBC Act and found the best options for climate adaptation via protecting and restoring their habitat. It found that:

- Fifty-nine of the 355 threatened plant species and 11 of the 149 threatened animals considered could completely lose their climatically suitable range by 2085 under the most pessimistic (business as usual) climate change scenario, while four plant species face almost certain extinction due to complete loss of suitable range even under the most optimistic mitigation scenario tested.
- Climate is predicted to become unsuitable across more than half of their geographic distribution for 310 (61%) of the modelled species under the business-as-usual scenario and for 80 (16%) species under the early mitigation scenario.
- For an available budget of $3 billion, protecting an additional 877,415 km^2 of intact habitat, and restoring 1,190 km^2 of degraded habitat immediately was identified by the analysis as the optimal set of actions to help the 504 threatened species adapt to climate change assuming early mitigation. Under a more pessimistic business-as-usual climate change scenario, 837,914 km^2 of protection is required, along with 77 km^2 of restoration. In all cases, appropriate threat management within the protected areas is required.

SUMMARY FOR POLICY MAKERS

Australia's biodiversity is threatened by climate change, but we currently know little about the scale of the threat or how to deploy on ground conservation actions to protect biodiversity against the changes expected. In this project we predict the impacts of climate change for threatened species and delineate the best options for climate adaptation for all these species collectively via protecting and restoring their habitat.

For 504 of Australia's currently threatened species we predict their distributional responses to climate change, under three climate change scenarios of increasing severity: early mitigation, delayed mitigation and business-as-usual. We then simulate the optimal placement of new protected areas and where necessary, restoration of critical habitat for those species most affected by a changing climate, taking into account variation in the costs and benefits of acting in different places.

We measured the benefits of protecting and restoring habitat by considering the long-term availability and quality of habitat for threatened species as climate changes. We undertook a state-of-the-art multi-action optimisation that accounts for spatial and temporal habitat connectivity under climate change. The scale of the prioritisation analysis implemented here is unprecedented in the conservation literature, and is only possible because of recent advances in software sophistication and parallel computer processing power.

We discovered that:

- Fifty-nine of the 355 threatened plant species and 11 of the 149 threatened animals considered could completely lose their climatically suitable range by 2085 under the most pessimistic (business as usual) climate change scenario, while four plant species face almost certain extinction due to complete loss of suitable range even under the most optimistic mitigation scenario tested.
- Climate is predicted to become unsuitable across more than half of their geographic distribution for 310 (61%) of the modelled species under the business-as-usual scenario and for 80 (16%) species under the early mitigation scenario.
- For an available budget of $3 billion, protecting an additional 877,415 km^2 of intact habitat, and restoring 1,190 km^2 of degraded habitat immediately was identified by our analysis as the optimal set of actions to help the 504 threatened species adapt to climate change assuming early mitigation. Under a more pessimistic business-as-usual climate change scenario, 837,914 km^2 of protection is required, along with 77 km^2 of restoration. In all cases, appropriate threat management within the protected areas is required.
- Within the $3 billion budget, optimal allocation of protection focuses on forests and woodland areas of eastern Australia, Northern Territory, the Great Western Woodlands of Western Australia, and southern South Australia. Restoration effort is required mostly in south-eastern Australia.
- We tested a range of conservation budgets from $500 million to $8 billion, and found that the spatial pattern of priority does not change dramatically, and that conservation gains do not level off within that range, i.e. that each dollar invested up to at least $8 billion generates additional benefits for threatened species under climate change.

Our analysis deals only with threatened species, i.e. those currently most vulnerable to threats including climate change, and while this does not represent all Australian native animals and plants and how they may all be best provided for, these species have great immediate significance for national biodiversity policy.

In summary, the 504 threatened species considered in this study require an increase of between 838,077 km^2 and 878,590 km^2 in areas protected against loss or degradation either through legislation to protect habitat, designation of protected areas, or negotiations of long-lasting voluntary conservation covenants.

1. INTRODUCTION

1.1 Purpose and need

Anthropogenic climate change poses an emerging and accelerating threat to the world's species and ecosystems (Brereton *et al*. 1995; Hughes 2000; Foden *et al*. 2008). Rising temperatures and changes in the precipitation regime will cause rapid habitat and ecosystem changes, species distributional shifts and extinctions, particularly if species are unable to respond quickly (Pease *et al*. 1989; Thomas *et al*. 2004, Lawing & Polly 2011). Rapid human-induced climate change is particularly challenging, because evolutionary responses require heritable variation and time to unfold (Hoffmann & Sgro' 2011). Climate change has already been identified as an important cause of declines and distributional shifts of many species (Parmesan & Yohe 2003; Hughes 2000).

Australia's species are already shifting their distributions in response to climate change, and globally a climate-induced extinction crisis is underway (Hughes 2000; Walther *et al*. 2002; Thomas *et al*. 2004). Distributions and compositions of entire Australian ecosystems are expected to shift dramatically over the coming century and beyond (Steffen *et al*. 2009; Ferrier *et al*. 2012; Dunlop *et al*. 2012). Although we are beginning to learn more about where species and ecosystems might move as a result of climate change, we know very little about how best to respond to these changes at minimum cost, to maximise the long term persistence of Australia's biodiversity. We urgently need to move from science that predicts the impacts of climate change to decision science that supports difficult choices between climate adaptation options under uncertainty, and social and economic constraints (Heller & Zavaleta 2009; Wintle *et al*. 2011). Our overarching project goal is to move beyond predicting the impacts of climate change to delineate the best options for climate adaptation via optimal protection and restoration of habitat.

There currently exists very little tangible, scientific advice about how to best conserve biodiversity in a changing climate under realistic social and economic constraints (Wintle *et al*. 2011), beyond generalities about the urgent need to incorporate climate change into conservation planning (Mace & Purvis 2008; Dawson *et al*. 2011; Crossman *et al*. 2012; Gillson *et al*. 2013). Protected area establishment and where necessary, habitat restoration projects, must be sited in places that match distributional shifts likely to occur under future climate regimes, but we do not yet have the tools to do this taking into account costs and benefits.

Selecting species and ecosystems on which to focus is a daunting task. Wholesale ecosystem disassembly and reassembly is a very real prospect (Ferrier *et al*. 2007; Hobbs *et al*. 2009), yet much of Australia's environment legislation is focused around Species of National Environmental Significance. Moreover, the main goal of global conservation is arguably to prevent extinctions (Soulé 1986, Wilson 1992), and we therefore focus here on species that are currently threatened in Australia.

1.2 Objectives and aims

Our overarching project goal is to move beyond predicting the impacts of climate change to delineate the best options for climate adaptation via protection and restoration of habitat.

Specifically, our objectives are to:

- predict the future distributions of habitats that are critical for long term persistence and effective adaptation to climate change of threatened terrestrial Species of National Environmental Significance;
- model optimal protected area placement and where necessary, habitat restoration for species most affected by a changing climate, taking into account variation in costs and benefits;
- deliver a comprehensive plan for protected area expansion and habitat restoration across Australia by providing spatially explicit maps of where conservation actions are needed to minimise extinctions from climate change.

2. METHODS

2.1 Overview of methodological framework

The project is divided into 3 phases. Firstly, we model how the distributions of Australia's threatened species might shift with a changing climate (Phase 1), we then determine the combination of protection and restoration that could be undertaken for each combination of environmental conditions across the country to maximise habitat suitability for threatened species under climate change (Phase 2), and finally we build a spatial prioritisation of the protection and restoration actions (Phase 3).

Phase 1 entails modelling the current distribution of 504 nationally threatened species and projecting their distribution into the future under different climate change scenarios and for different time horizons (Figure 1). Applying 18 General Circulation Models, three climate change scenarios and eight time steps, to these distribution models, we estimate how distributions of Australia's threatened species might be affected by climate change.

Phase 2 entails synthesis of existing information about costs, benefits and likelihood of success of a suite of possible restoration and protection options (Figure 2). Using the newly available optimisation software RobOff, we identify an optimal set of actions to protect threatened species under a changing climate in the full range of environments across Australia (Figure 3).

Phase 3 entails combining the results of the first two stages to build spatial priorities for habitat protection and restoration (Figure 4). This represents a comprehensive plan for optimal protected area creation and habitat restoration across Australia in the form of spatially explicit maps of where habitat protection/restoration is needed to minimise extinctions from climate change for a given time horizon and available budget.

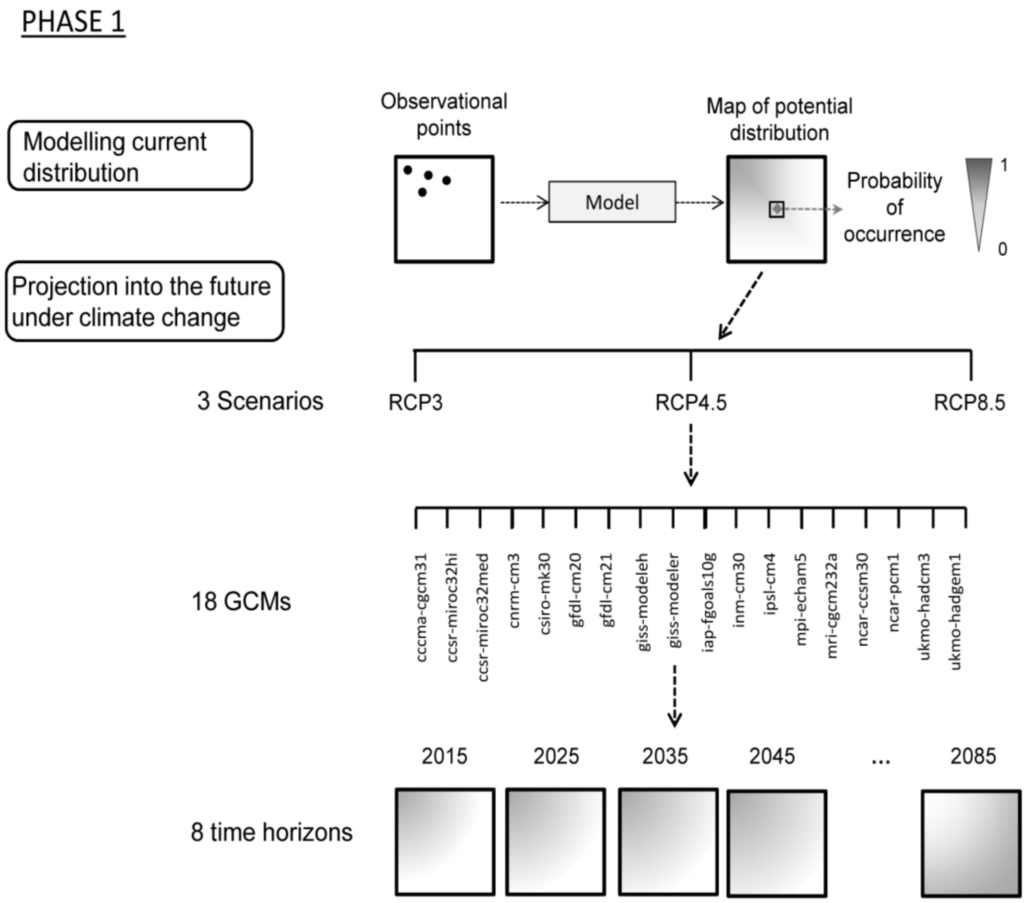


Figure 1: Diagrammatic representation of Phase 1 of the project

The current distributions of 504 terrestrial Species of National Environmental Significance are modelled and then projected into the future for three different climate change scenarios, 18 General Circulation Models and eight time horizons ranging from 2015 to 2085, separated by 10-year intervals.

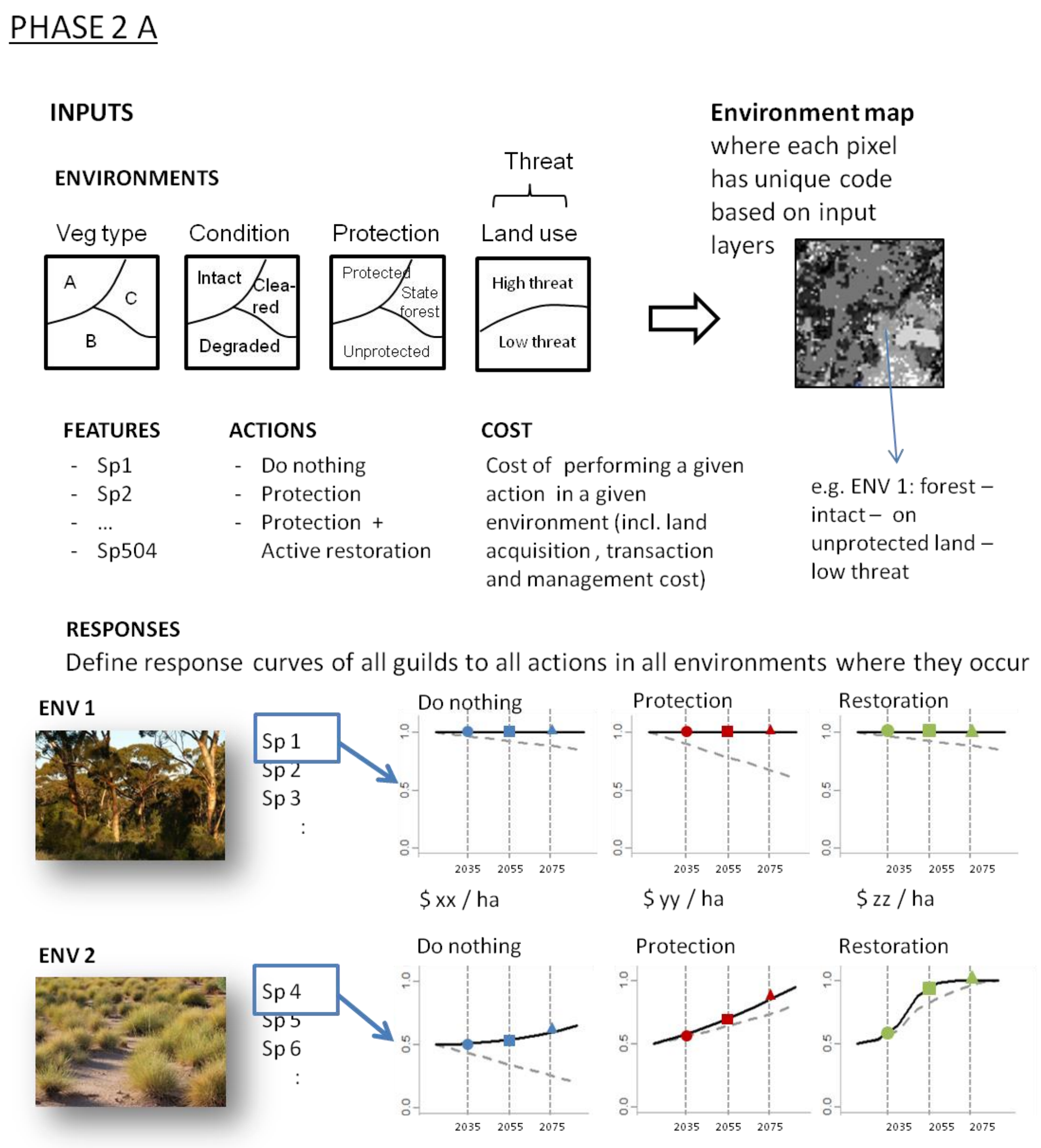


Figure 2: Diagrammatic representation of the first part of Phase 2 of the project

Species are assigned to environments defined by their major characteristics (main vegetation type, condition, level of protection and threat). For each environment we then define a set of available actions and their respective costs, and the expected response of species to those actions.

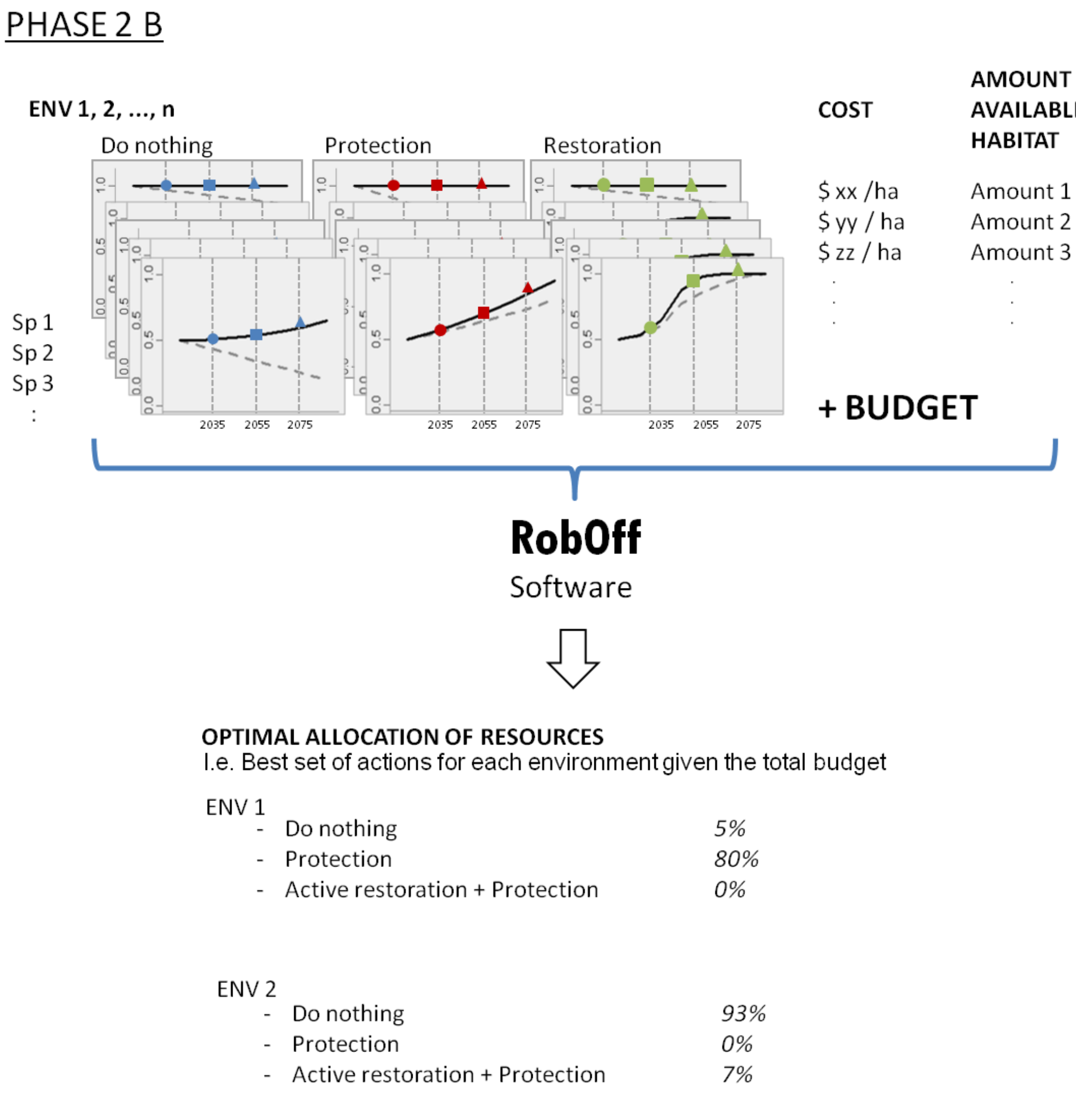


Figure 3: Diagrammatic representation of the second part of Phase 2 of the project

Information about environments, their area, action costs and expected responses is fed into RobOff software, which calculates the optimal set of actions that will maximise the conservation gains for all species given the defined total budget.

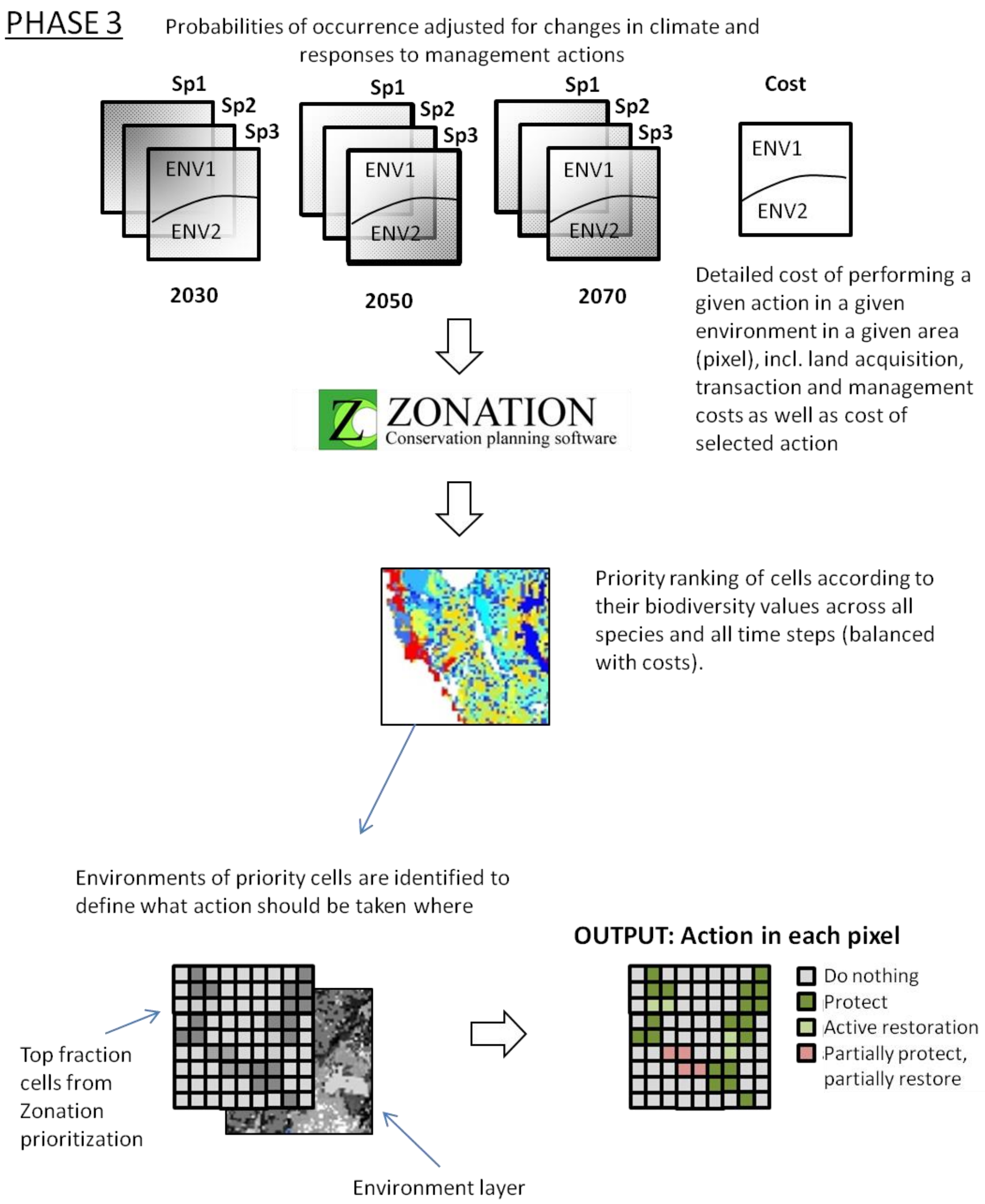


Figure 4: Diagrammatic representation of Phase 3 of the project

In this final phase, species' modelled distributions produced in Phase 1 are modified with the responses to the optimal set of actions defined in Phase 2. The adjusted distribution maps are then used to produce a spatial prioritisation of areas for actions, taking into account climate change driven shifts in species distributions, expected changes in habitat suitability due the actions taken as well as detailed spatial information of the cost of taking an action in each pixel. Priority sites for actions are then compared to the original environments to produce a map that shows what action(s) should be taken in each pixel.

2.2 Phase 1: Distributional responses of threatened species to climate change

2.2.1 Biological data

This project focuses on the Species of National Environmental Significance (SNES) listed in Australia's Environment Protection and Biodiversity Conservation Act (1999) and in particular on terrestrial species. Geolocated records of these species were obtained from the Australian Natural Heritage Assessment Tool (ANHAT) database (Department of Sustainability, Environment, Water, Population and Communities, Commonwealth of Australia). This dataset is the most comprehensive spatially referenced catalogue of threatened species occurrences in Australia, and has undergone extensive error checking with the Department. Data have been collated from a large number of agencies around Australia and include species location records from Australian museums, Australian herbaria, BirdLife Australia, CSIRO, state and territory governments and many other sources. Records of threatened/rare species are sensitive data, data were thus supplied by ANHAT in a denatured form. Location records were delivered as occurrences within a 0.01° (~1 km) grid-cell.

Threatened species tend to be narrowly distributed and as a consequence of this, an adequate amount of data could be gathered only for a limited number of species and taxonomic groups. Reflecting this, we restricted our analysis to terrestrial vascular plants and tetrapods (amphibians, reptiles, birds, mammals). We retained records with dates after 1950 and with a spatial precision of 1 km or lower. Duplicate observations within a grid cell were removed, and the lower limit for the number of occupied grid cells required for analysis was set at 20. This resulted in a total of 504 species available for analysis (Table 1).

Table 1: Overview of the number of species per taxonomic group for which the modelling was undertaken

Taxonomic group	Number of species
Vascular plants	355
Amphibians	22
Reptiles	30
Birds	48
Mammals	49
Total	504

2.2.2 Climatic variables

Climatic variables used for modelling the present and future distributions of the study species were provided by Dr Jeremy VanDerWal (Centre for Tropical Biodiversity & Climate Change, School of Marine and Tropical Biology, James Cook University) within a collaborative framework common to several NCCARF projects.

Current Bioclim climate surfaces were derived using ANUCLIM (based on 1976 to 2005 historic data). Future climate projections were sourced from the Tyndall Centre, University of East Anglia, UK (http://climascope.wwfus.org), and the downscaling and creation of 19 standard bioclimatic variables (http://www.worldclim.org/bioclim) for Australia were performed using the R package "climates" (VanDerWal *et al*. 2011a; http://www.rforge.net/climates/). All climatic layers were provided at the continental scale and at a 0.01° (~1 km) resolution, matching the grain of our species distribution data.

We used future projections for three emissions scenarios, 18 Global Circulation Models (GCMs), eight time horizons and a set of 19 bioclimatic predictor variables. A subset of the original 19 bioclimatic predictors was selected for the present study according to the expected impact on the target species. One of a pair of variables was discarded where the correlation coefficient between them exceeded 0.8 to prevent collinearity problems in model fitting. The biologically relevant bioclimatic variables retained for the analysis are listed in Table 2 and include mean annual temperature, seasonality, and precipitations of the wettest and driest quarters. In a changing climate, seasonality is predicted to increase. It is therefore important to incorporate seasonality when modelling the potential distribution of species (see, e.g. Thomas *et al*. 2004) because species niches are determined not just by average environments but also by the characteristic ranges of environmental variability.

Climatic extremes (e.g. warmest, coldest, wettest, driest) are often better predictors of species' distributions than annual mean values, because physiological tolerances of organisms have evolved within a certain range of environmental variation. Duration of extremes is also very important. It is usually more difficult for a species to survive to a prolonged period of unusually high temperatures or low precipitation than an isolated heat wave or short dry period. For all these reasons, we preferred precipitation of the wettest / driest quarter to annual precipitation. The same choice was not possible for temperature since mean temperature of the coldest quarter (Bioclim_11) was highly correlated with other selected bioclimatic predictors. Instead we used annual mean temperature (Bioclim_01).

Table 2: Bioclimatic variables used for the modelling of the distribution of terrestrial Species of National Environmental Significance

Variable	Description
Bioclim_01	Annual Mean Temperature
Bioclim_04	Temperature Seasonality (standard deviation *100)
Bioclim_15	Precipitation Seasonality (coefficient of variation)
Bioclim_16	Precipitation of Wettest Quarter
Bioclim_17	Precipitation of Driest Quarter

Representative Concentration Pathways (RCPs) have recently been adopted by the IPCC to replace the greenhouse gas emissions scenarios described in the Special Report on Emissions Scenarios (IPCC SRES 2000) and used in the IPCC 3d (TAR 2001) and 4th assessment report (AR4 2007). RCPs are the new scenarios that will be used for the next IPCC report AR5 planned for 2014 (Moss *et al.* 2010; Van Vuuren *et al*. 2011a). For this project we choose to project species distributions according to three scenarios representing different magnitudes of emissions. RCP 8.5 is a high-emission business as usual scenario characterised by a rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO2 equivalent) by 2100 (Riahi *et al*. 2011). RCP4.5 is a stabilisation scenario without an overshoot pathway but leading to 4.5 W/m^2 (~650 ppm CO2 equivalent) at stabilisation after 2100 (Thomson *et al.*, 2011). Finally, RCP 2.6 is a mitigation scenario with a peak in radiative forcing at ~ 3 W/m^2 (~490 ppm CO2 eq) before 2100 and then a decline to 2.6 W/m^2 by 2100 (Van Vuuren *et al.* 2011b). This scenario is also referred to as RCP3PD, referring to the radiative forcing trajectory (peak at 3 W/m^2, followed by a decline).

For ease of use, we refer to the three RCPs as early mitigation (RCP3PD), late mitigation (RCP4.5), and business-as-usual (RCP8.5).
For each of the climate change scenarios considered, climate projections were available for the 18 Global Circulation Models (GCMs) listed in Table 3 and for eight time points into the future spanning from 2015 to 2085, separated by 10-year intervals.

Table 3: List of General Circulation Models used to project species distributions into the future

Abbreviation	Global Climate Model	URL for description
cccma-cgcm31	Coupled Global Climate Model (CGCM3)	http://www.ipcc-data.org/ar4/model-CCCMA-CGCM3_1-T47-change.html
ccsr-miroc32hi	MIROC3.2 (hires)	http://www-pcmdi.llnl.gov/ipcc/model_documentation/MIROC3.2_hires.pdf
ccsr-miroc32med	MIROC3.2 (medres)	http://www-pcmdi.llnl.gov/ipcc/model_documentation/MIROC3.2_hires.pdf
cnrm-cm3	CNRM-CM3	http://www.ipcc-data.org/ar4/model-CNRM-CM3-change.html
csiro-mk30	CSIRO Mark 3.0	http://www.ipcc-data.org/ar4/model-CSIRO-MK3-change.html
gfdl-cm20	CM2.0 - AOGCM	http://www.ipcc-data.org/ar4/model-GFDL-CM2-change.html
gfdl-cm21	CM2.1 - AOGCM	http://www.ipcc-data.org/ar4/model-GFDL-CM2_1-change.html
giss-modeleh	GISS ModelE-H	http://www.ipcc-data.org/ar4/model-NASA-GISS-EH-change.html
giss-modeler	GISS ModelE-R	http://www.ipcc-data.org/ar4/model-NASA-GISS-ER-change.html
iap-fgoals10g	FGOALS1.0_g	http://www.ipcc-data.org/ar4/model-LASG-FGOALS-G1_0-change.html
inm-cm30	INMCM3.0	http://www.ipcc-data.org/ar4/model-INM-CM3-change.html
ipsl-cm4	IPSL-CM4	http://www.ipcc-data.org/ar4/model-IPSL-CM4-change.html
mpi-echam5	ECHAM5/MPI-OM	http://www.ipcc-data.org/ar4/model-MPIM-ECHAM5-change.html
mri-cgcm232a	MRI-CGCM2.3.2	http://www.ipcc-data.org/ar4/model-MRI-CGCM2_3_2-change.html
ncar-ccsm30	Community Climate System Model - version 3.0 (CCSM3)	http://www.ipcc-data.org/ar4/model-NCAR-CCSM3-change.html
ncar-pcm1	Parallel Climate Model (PCM)	http://www.ipcc-data.org/ar4/model-NCAR-PCM-change.html
ukmo-hadcm3	HadCM3	http://www.ipcc-data.org/ar4/model-UKMO-HADCM3-change.html
ukmo-hadgem1	Hadley Centre Global Environmental Model - version 1 (HadGEM1)	http://www.ipcc-data.org/ar4/model-UKMO-HADGEM1-change.html

2.2.3 Substrate variables

Substrate-related variables were provided by Kristen Williams (CSIRO Ecosystem Sciences), who compiled a comprehensive set of environmental variables providing nationally consistent information about soil, geology and terrain (Williams *et al*. 2010). An initial set of potentially relevant predictors was selected according to the ecological and physiological requirements of the target taxonomic groups. Some preliminary tests were then performed within Maxent (Phillips *et al*. 2006) to determine which of the pre-selected predictors were contributing the most in explaining the distribution of the target species. The predictors that were finally chosen were those with the highest gain when used in isolation in a model (jack-knife test within Maxent), and that showed inter-variable correlations lower than 0.8.

The final set of substrate predictors are listed and briefly described in Table 4 (for a comprehensive description of these variables see Williams *et al*. 2010, 2012). Corresponding maps have a continental extent and were provided in raster format at a 0.01° (~1 km) resolution.

Table 4: Substrate-related variables used for modelling the distributions of terrestrial Species of National Environmental Significance

Variable	Description
clay	Solum average clay content (%)
ksat	Solum average of median horizon saturated hydraulic conductivity (mm/h)
hpedality	Hydrological scoring of pedality (score)
geolmage	Mean geological age (log10 M years)

Clay content affects hydrology, nutrient content and fertility of the soil (Williams *et al*. 2012). In particular, the pedal structure and the limited drainage capacity of the soil directly affect root growth and thus the vegetation communities found in clay soils. The solum average saturated hydraulic conductivity (ksat) reflects the speed with which water moves through the soil and the pattern of deeper drainage (Western & McKenzie 2004). Ksat thus represents the soil water balance and may be relevant to plants that explore deeper soil horizons (Williams *et al*. 2010). Soil pedality represents the extent to which the soil is organised into structured aggregates, which influences water flow, nutrient transport and susceptibility to erosion. Although defined in a slightly different way, ksat and hpedality potentially deliver similar information, yet these two predictors were only weakly correlated (r = -0.3). Moreover, according to our preliminary tests of the species distribution modelling, these two predictors are both among the most useful predictors in explaining the distributions of the target species, and this held not only when they are each used in isolation but also when included together in the same model. Finally, the mean geological age (geolmage) estimates the rock age and indirectly represents the degree of weathering, soil formation and nutrient status (Williams *et al*. 2012) which in turn determines the vegetation assemblages that can occur in a place.

The predictors listed in Table 4 are variables that are typically used to model vegetation, since parent material and soil characteristics directly determine the type of plants and vegetation assemblages that can grow on them. However, here we use a common set of predictor variables to model all taxonomic groups under the rationale that even though substrate variables may not directly influence the distribution of fauna, they act indirectly by determining the type of vegetation growing in a locality, a key element of the biological structure of animal habitat.

2.2.4 *Modelling current and future species distributions*

The distributions of the selected threatened species were modelled using the software Maxent (Phillips *et al*. 2006). This is a machine learning method that models species distributions based on the principle of maximum entropy and is especially suitable for presence-only data. When using Maxent it is necessary to define a background sample of the environments in the study region against which presence records can be compared (Phillips *et al*. 2009). For this study we selected our background points within the IBRA bioregions (Interim Biogeographic Regionalisation of Australia, version 7, http://www.environment.gov.au/parks/nrs/science/bioregion-framework/ibra) in which each species occurred. A background sample of 10,000 grid cells was randomly chosen within the IBRA regions currently occupied by each species.

Once modelled, species' distributions were projected into the future for three RCPs, 18 GCMs and eight regularly spaced time points: 2015, 2025, 2035, 2045, 2055, 2065, 2075 and 2085 (according to the general framework in Figure 5). The modelling and projections were performed using R scripts made available by Jeremy VanDerWal and adapted to the needs of this project with the support of Jeremy VanDerWal and April Reside (James Cook University). Supplementary scripts were used to calculate summary characteristics of species projected distributions, such as the total area, number of patches and other metrics of fragmentation using the "ClassStat" function of the SDMTools package (VanDerWal *et al*. 2011b; http://rforge.net/SDMTools/). A final R script was used to summarise the projections based on different GCMs into one single map per scenario and time horizon showing the areas that are consistently predicted as favourable across the different GCMs, and to filter the potential distribution to obtain the realised distribution of the species used in the following phases of this project. The realised distribution is obtained by filtering out from the potential distribution the areas that are not within a currently occupied or directly neighbouring IBRA region.

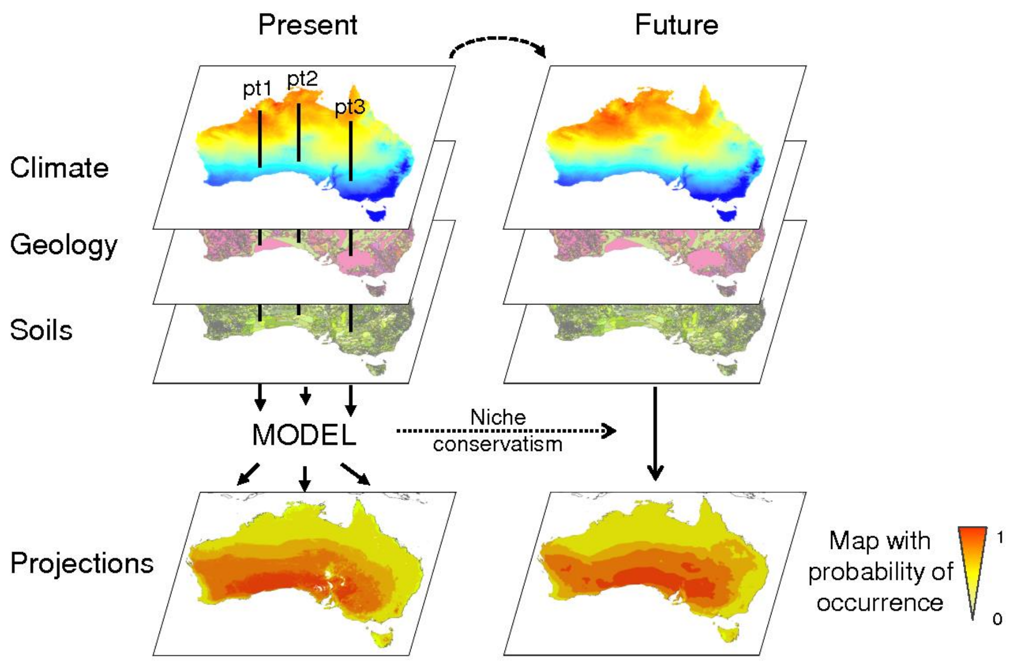


Figure 5: The generalised process of modelling the response of species' distributions to climate change based on projecting forward the spatial distribution of the environmental niche currently occupied by the species

2.3 Phase 2: Optimal climate adaptation actions for threatened species

Phase 2 comprises a non-spatial optimisation of multiple actions, taking into account the individual responses of the species to each of the proposed actions in each distinct environment across the continent. This involves choosing among a suite of different actions over seven million possible investment locations (1 km grid cells across Australia), and is hence a sizeable analysis. Phase 3 then spatially prioritises where in Australia the optimal set of actions should be undertaken, taking into account individual species' needs for long-term spatial and temporal habitat connectivity as climate changes.

2.3.1 Optimizing conservation actions using RobOff

We used the newly developed software RobOff 1.0 (Robust Offsetting, http://consplan.it.helsinki.fi/software/projects/roboff, Pouzols & Moilanen in press) to optimise the allocation of resources among different conservation actions for Australia's threatened species. RobOff is a software package that identifies a set of actions producing an optimal conservation outcome across multiple species and multiple environments for a given budget. It can manage multiple alternative conservation actions and their uncertain effects on species in different environments through time, and is therefore ideal for the question of prioritising protection and restoration in a changing climate.

The basic logic behind RobOff is as follows. Species occur in one or more environments, which are defined by characteristics such as vegetation type and condition. For each environment a set of actions is available and these actions may differ between environments. For example, a partly degraded grassland could be protected or restored, but an intact pristine rainforest can only be protected. In any environment we could also decide not to carry out any additional conservation actions. Whatever action we choose to do in a particular environment, it will have an effect on the species that occupy that environment. How species respond to a given action, whether it is protection, restoration or just not doing anything, varies, and species might have a different response to the same action if it is implemented in a different environment.

Using information about the environments where species occur, their respective area, available actions and the costs of those actions, RobOff calculates the set of actions within a given budget that maximises the conservation gains across all species and all environments. It achieves this by comparing different combinations of actions and calculating how well they perform in comparison to the option of not doing anything. The number of alternative action combinations increases rapidly when considering a large number of species and environments, and finding the best possible set of actions for a large analysis can quickly become computationally impossible. In such cases RobOff uses heuristic algorithms, which search smartly rather than exhaustively for solutions. Heuristic methods do not guarantee to find the single best solution, but in all cases they provide good, feasible solutions that are usually close to the optimum (Moilanen & Ball 2009).

Optimisation of actions across many species and many environments requires that we define (i) the environments in which our species of interest occur, (ii) the actions we could take in each environment, (iii) the estimated responses of species to each action in each environment, and (iv) the cost of performing each action in each environment.

2.3.2 *Defining environments*

The aim of this step is to find those main factors that determine which actions are available for each environment and which define the main differences in responses to the same actions in different environments. Capturing the complexity of environments across the Australian continent is not a trivial task, and is often limited by the availability and quality of data. Also, due to computational limitations the number of combinations of environments, actions and responses had to be kept reasonable. We identified four different major factors that we believed to be most important for defining the environments in which protection and restoration actions can be taken, (i) vegetation type, (ii) vegetation condition, (iii) level of current protection, and (iv) level of anthropogenic threat (Figure 6).

For vegetation type we used data from the National Vegetation Information System version 3.0 (NVIS, http://www.environment.gov.au/erin/nvis/index.html), which describes the main vegetation type in each 100 x 100 m pixel across Australia. We reclassified the 30 main vegetation categories into 8 classes and upscaled the resolution to 1 x 1 km (Figure 6a). Our eight classes were rainforest; forests and woodlands; shrublands; grasslands; wetlands; Chenopod, Samphire shrublands and Forblands; mangroves; other (aquatic environments, unknown and unclassified vegetation and bare ground). The latter class was discarded from the analysis. We used the pre-settlement version of NVIS (pre-1750) to reflect the full restoration potential of already degraded and cleared areas.

Condition of current vegetation cover was based on the Vegetation Assets States and Transitions version 2 (VAST 1995-2004, Thackway & Lesslie 2005) which gives the degree of anthropogenic modification of original vegetation in each pixel. Where possible, VAST was updated with more recent information about clearance obtained from the Forest Extent and Change (FEC, version 7 Jan 2011) spatial data at 25 m resolution for 1972, 1980, 1989, 2000 and 2010 (2006 for low clearing areas in the outback). For some locations we also used information from extant NVIS (National Vegetation Information System) and ABARES Land Use of Australia version 4 (2005-06). The purpose of updating the national VAST data was two-fold: first, to develop a more up-to-date layer of current vegetation cover, and second, to capture the history of vegetation cover changes wherever this information is available (as FEC does not have national coverage). Knowing the history of vegetation changes is important as the time point and intensity of anthropogenic modifications can define whether the natural vegetation of a site can recover through passive regrowth or if the site might require active restoration and replanting to recover. For example, former woodland areas that have been cleared for pasture more than several decades ago or have gone through intensive land uses such as cropping recover poorly after active land use has ceased and the areas have been set aside.

We applied the following procedure to map five categories of vegetation condition and hence revegetation potential across Australia (Figure 6b). First we aggregated the 25 m FEC to 1 ha grid scale and derived the maximum and minimum tree cover for the five time points. For all 1 ha grid cells categorised as ‘cleared’ or ‘regrowth’ in the extant NVIS data, each was classified as cleared if either (i) four or fewer of the sixteen 25 m * 25 m pixels comprising each 1 ha grid cell were classified as tree cover at a given time point, or (ii) if the number of pixels with the cell classified as non-forest dropped by six or more from the maximum observed across all time periods. We then overlaid the FEC maps for each time point onto the VAST classification and assigned pixels to different categories as follows:

Intact: If the pixel was categorised as 0-1 (‘residual’) in VAST and did not have any information from FEC or the FEC maps indicated no changes in vegetation cover.

Degraded: If the pixel was i) categorised as 2-3 (‘modified’ or ‘transformed’) in VAST and had no information from FEC, or ii) FEC maps indicated that it had been cleared in the past and had since regrown (that is, it was mapped as non-cleared in 2010/06, but mapped as cleared previously).

Cleared, regrowth possible: If the pixel was i) categorised as 4-5 (‘replaced’) in VAST and had no information from FEC, or ii) according to FEC cleared in 2010/06 but had been mapped as non-cleared in any of 1972, 1980, 1989 or 2000 time points, or iii) if the pixel was mapped as cleared at every time point including 1972, but the difference between maximum and minimum tree cover observed across the five time points was more than three 25 m * 25 m pixels out of the 16 present in the 1 ha grid cell, which indicated non-trivial changes in woody cover, and hence spontaneous regrowth was at least possible.

Cleared, replanting necessary: If the pixel was i) according to FEC maps cleared in each time point including 1972 and the difference between maximum and minimum tree cover observed across the five time points was less than three 25 m * 25 m pixels out of the 16 present in the 1 ha grid cell, or ii) cleared in 2010/06 and based on ABARES 2005/6 land use data the pixel was categorised as ‘croplands’, in which case the intensive land modifications were assumed to restrict any natural regrowth.

***Not included*:** If the pixel was categorised in the ABARES 2005/6 as ‘plantation’ or ‘intensive use’, we excluded it as infeasible for regeneration of native vegetation, regardless of the above rules.

All grid calculations were performed at the 1 ha grid scale and then aggregated to 1 km grid scale using a majority rule. We note that despite our best efforts to produce an estimate of habitat condition, the presented classification is more to describe the status of vegetation cover instead of explicitly capturing the level of *in situ* habitat degradation.

For each pixel we also assigned one of four protection states (Figure 6c): 1) currently protected using a combination of the published Collaborative Australian Protected Areas Database (CAPAD) 2010 release and National Reserve System additions not yet gazetted up to Oct 2012 generously provided by Parks Australia (note only CAPAD 2010 is displayed due to licence restrictions on more recent data); 2) Forest reserves from the spatial layer Tenure of Australia’s Forests 2008 from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) 3) Unprotected and 4) Not included- land under intensive uses or plantations according to the ABARES Land Use of Australia version 4 (2005-06). These land uses were excluded due to the low likelihood of them becoming available for any conservation actions. Cropping land was included because it is amenable to replanting in the near to medium term.

Finally, we included a crude estimate of anthropogenic threat based on the predominant land use type in each pixel. For this purpose we used the ABARES Land Use of Australia version 4 (2005-2006) to classify grid cells into areas with low threat or high threat as a result of human land uses (Figure 6d).The major land use types ‘Conservation and natural environments’ and ‘Water’ as well as the ‘Livestock grazing’ under ‘Production from relatively natural environments’ were considered as low threat, while all the other land use categories were considered as high threat (Production from

Dryland Agriculture and Plantations; Production from irrigated Agriculture and Plantations; Intensive uses; Production forestry in relatively natural environments).

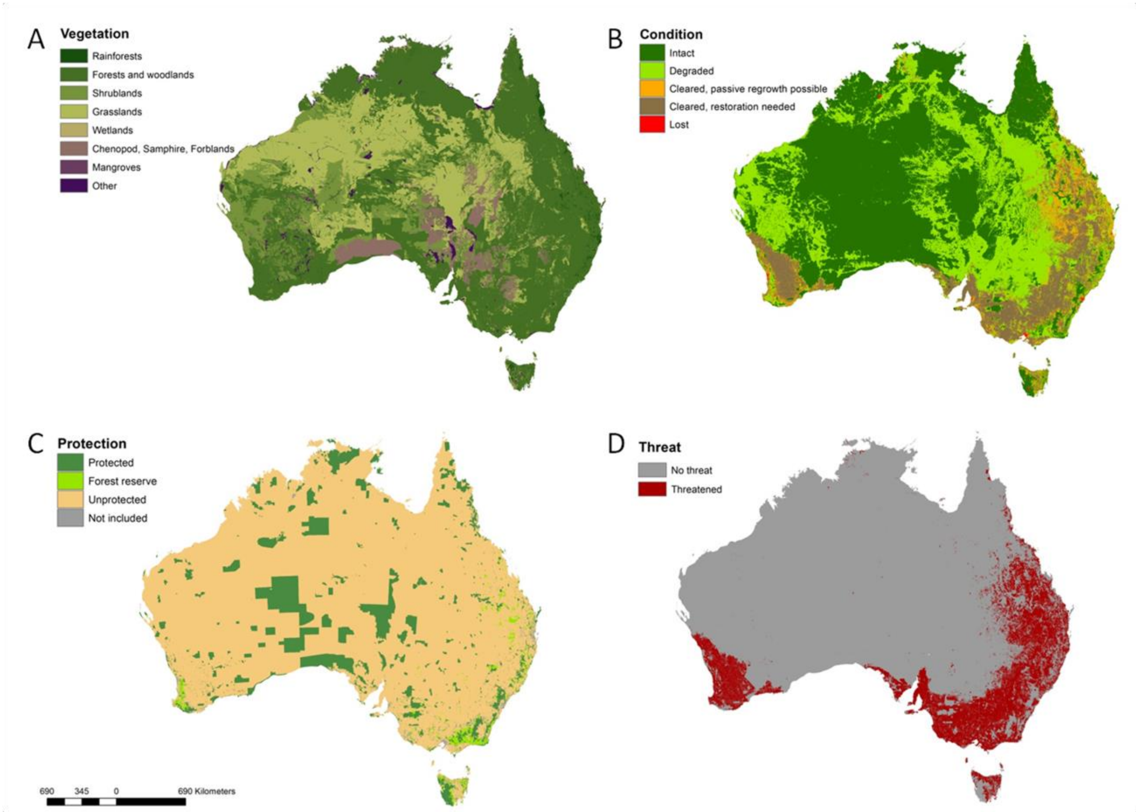


Figure 6: The four different factors used to define environments with their respective classifications

A) Vegetation type (pre-1750 NVIS), b) vegetation condition, c) protection status (only CAPAD 2010 is shown due to licence restrictions on displaying more recent data), and d) level of threat.

Categorizing each pixel according to combinations of these four main factors yielded 292 discrete environments out of the potential 320 combinations (8 vegetation classes * 5 conditions * 4 protection classes * 2 threat categories; Figure 7). Some of these environments occurred in areas excluded from the analysis (see above), resulting in 168 environments where actions could be taken (i.e. 7 vegetation classes * 4 condition * 3 protection classes * 2 threat categories).

2.3.3 Defining actions and their respective costs for optimisation

We considered three possible actions at the scale of each 1 km grid cell across Australia, (i) do nothing, (ii) protect the area, allowing passive regrowth, (iv) protect the area and undertake active restoration of natural vegetation. Protection guarantees legal status to a given area and includes the basic management actions needed to maintain the natural state of a site and foster passive vegetation regrowth in degraded areas. Active restoration implies more direct management actions such as modification of soil or water structures, removal of non-native species, or replanting of native vegetation, with the aim of restoring vegetation to its natural state. In practice, restoration implies different types of actions in different environments, depending on the vegetation type, threats and local conditions. More precisely defined actions could be implemented in a RobOff analyses if such detailed information were available for the whole of Australia.

Figure 7: Map of environments

Each shade of grey represents one of the 292 discrete environments with a unique combination of vegetation type, vegetation condition, protection status, and level of threat. The complexity of prioritising actions is apparent, especially in the south-eastern and south-western coastal regions.

Within RobOff, all three actions were by default made available for all environments, but there are some exceptions based on simple logic and information from the restoration literature: i) protected areas cannot be protected again, ii) restoration actions are not needed where vegetation is intact, except in some grasslands where pristine and semi-pristine areas need to be actively managed to maintain natural disturbance dynamics (e.g. Lunt & Morgan 2002), iii) areas where natural vegetation has been absent more than 40 years or which have been converted to croplands at any time point during the past 40 years cannot be restored by simple protection and passive regrowth but require active restoration, iv) mangroves can only be effectively recovered with active restoration (Lewis 2005).

The cost of each action was based on two components, the cost of protecting land and the cost of active restoration. In this analysis we excluded any potential costs of maintaining already existing protected areas. Hence we made the assumption that the available budget would be used to target entirely new areas for conservation actions and potential management and maintenance costs of existing reserve network will be funded from other sources. An approximate cost of restoration was based on estimates of actively restoring 1 ha area from a cleared to intact condition (Table 5). Restoration actions in degraded areas were estimated to cost half of that of cleared areas. Active management of intact grasslands was estimated to cost one quarter of the costs of actively restoring a cleared area. Any action taken on unprotected land or state forest also included the cost of protecting the land, which was further divided into three sources of cost: 1) land acquisition costs, 2) transaction cost, and 3) management costs intended to cover the basic maintenance of a protected area.

Table 5: Estimated costs of actively restoring one hectare of cleared area in each broad vegetation class

Vegetation type	Cost ($1000/ha)
Rainforest	10
Forests and woodlands	5
Shrublands	3
Grasslands	2
Wetlands	10
Chenopods, Samphire shrubs and Forblands	3
Mangroves	5

2.3.4 Estimating land acquisition costs

To protect an area requires an enduring change in the land use to conservation from its existing use. The cost of acquiring or bringing land into protected areas is considered to be driven by tenure. Protecting public land would entail costs for settling the value of any existing uses. Private land requires purchase by a conservation agency or negotiation of a covenant on the land title with the existing landowner. Indigenous land requires an Indigenous Protected Area agreement. First, we constructed an updated tenure map for Australia using the most recent data from Geoscience Australia and ABARES, calling upon, in order of priority: Parks Australia: Collaborative Australian Protected Areas Database or CAPAD 2010 and the Nov 2012 update as already discussed (Figure 6c); ABARES: Aboriginal Land 1996; ABARES: Rangelands tenure 1999; ABARES: Forest tenure 2008 and Geoscience Australia: Land Tenure 1993. Gaps in a given layer were filled using the layer next in this list, until a complete tessellation of Australia was achieved.

Costs of acquisition were then estimated based on tenure as follows: for transfer of forest reserves to protected areas, we used the operating surplus for logging operations 2010-11 for state-owned native forestry corporations capitalised at 5% annual interest as detailed below; for Indigenous land regardless of tenure we used the average of $4.68 per hectare reported by Taylor *et al*. (2011) for Indigenous Protected Area agreements with the Australian Government; for other public land we used a nominal $0.10/ha; for leasehold land we used the improved land value calculated as full property value less unimproved land value as detailed below, and finally for freehold land we used full property value predicted from the unimproved land value of Carwardine *et al*. (2008) as detailed below.

Forestry reserves are typically state assets used by government-owned forestry corporations for commercial log sales. The operating cash surplus made by these corporations from native forest logging would need to be compensated, if portions of the forest were to be converted to protected areas. We obtained reported operating surpluses in each state with significant native forest logging (all except SA, NT, ACT) from 2010-11 annual reports and also the areas and gross log value for native forests in those states for 2010-11 from ABARES forestry statistics (Table 6). Since forestry corporations in NSW, Tasmania and WA also manage plantations, we discounted the operating surplus by the fraction of value of all logging represented by native forests in those states. Using these data, we estimated operating surplus per hectare of native forest in each state. Note that we did not include profit or loss due to changes in asset value, just the cash surplus. Hence these figures likely overestimate the real position. We estimated a capitalised in perpetuity present value for annual cash surplus dividing by 5%, the 10 year average monthly Reserve Bank of Australia cash rate. Essentially, this represents the endowment needed for annual interest of 5% to compensate for the operating surplus actually realised. In the case of Tasmania, which operated at a loss, we used a nominal $1 per hectare capitalised operating surplus (Table 6).

Table 6: Estimates of the cost of protecting State Forests through compensating forestry for capitalised annual operating surpluses

State	Operating surplus ($m)	Native forest log value ($m)[1]	All forest log value ($m)[1]	Native forest area (m ha)[1]	Native forest surplus ($/ha)	Capitalised at 5%
NSW [2]	$33.70	$91.50	$362.33	26.208	$0.32	$10.82
Vic [3]	$2.32	$138.04	same	7.838	$0.30	$9.88
Qld [4]	$5.50	$38.15	same	52.582	$0.10	$3.49
WA [5]	$5.01	$39.60	$339.87	17.664	$0.03	$1.10
Tas [6]	negative	$169.76	$322.82	3.116	negative	$1.00

The full value of a property (i.e. its market value) is the sum of Improved Land Value (ILV) and Unimproved Land Value (ULV). On freehold land we expect to have to pay the full value to achieve protection. On leasehold land, the government already owns the unimproved value of the land and thus only needs to compensate lessees for the Improved Value. Carwardine *et al*. (2008) compiled and mapped ULV data for Australia. We built a regression describing the relationship between ULV and full value based on data for 63 farming properties offered for sale on www.elders.com.au and www.realestate.com.au in February 2013. We sampled properties from every state and territory, at least 40 hectares in area, under low intensity grazing or cropping land use, for which address, area and asking price were all specified. We geocoded the addresses and mapped properties represented as point data to determine the ULV at each point. We then regressed asking price per 1000 hectare on ULV in dollars per 1000 hectare on a log-log scale, forcing the regression through the origin to provide a prediction of full value when only ULV is known (Figure 8a). The slope of the regression was 1.043 and ULV explained 32% of the variation in full value. There was some under-prediction of the full value of smaller properties and overprediction of the value of larger properties, perhaps reflecting the fact that ULV itself is an average over local government areas of values for properties of all sizes, including urban lots which have much higher market value per hectare than large farms.

Data on protected area management costs are very sparse. We conjectured that the chief driver of ongoing management cost is proximity to roads, towns and cities. Weeds in particular are primarily associated with roads (Forman & Alexander 1998). We attached some very coarse scaled information on protected area management from state parks agencies to the centroid of each national park in each state or territory (Commonwealth $28.71/ha, NSW $35.44/ha, NT $6.32/ha, Qld $10.22/ha, SA $2.45/ha, Tas $18.03/ha, Vic $46.88/ha, WA $2.71/ha taken from Taylor et al 2011). The only similar data available for private conservancies was the Australian Wildlife Conservancy with values taken from their Annual Report 2010 (in NSW $2.49/ha, in NT and Queensland $2.92/ha, in WA $3.79/ha).

[1] http://adl.brs.gov.au/data/warehouse/9aaf/afwpsd9abfe/afwpsd9abfe20121122/afwpsSummaries20121122_1.0.0.xlsx
[2] http://www.forests.nsw.gov.au/__data/assets/pdf_file/0003/438456/Forests-NSW-Annual-Report-2010-11.pdf
[3] http://www.vicforests.com.au/assets/vicforests%27%20annual%20report%202010-11.pdf
[4] http://www.nprsr.qld.gov.au/about/pdf/annual-report-derm-10-11.pdf
[5] http://www.fpc.wa.gov.au/content_migration/_assets/documents/about_us/annual_report/2011/annual_report_201011.pdf
[6] Operating loss so set nominal profit 1 c/ha
http://www.forestrytas.com.au/uploads/File/pdf/pdf2011/financial_statements_2011.pdf

We extracted the values of distance to cities, towns and major roads for the centroid of each of these protected areas and regressed the annual management cost on these three variables. The fitted regression was highly significant for each of the three candidate predictor variables (√ Management Cost= 6.868-0.193*√ Dcity -0.159√ Dtown +0.071*√ Dmajor_road). This regression was then applied to the spatial layers for the predictor variables to construct a management cost layer for Australia. Annual management costs were capitalised in perpetuity by dividing by the 5% interest rate as for forestry surpluses above (Figure 8b).

We set transaction costs to an arbitrary $20,000 per property (In Queensland for example, nature refuge gazettals cost roughly $25,000; Taylor *et al*. 2009). Clearly the transaction cost per hectare appropriate for use in our analyses then depends on the size of property subject to the transaction. We modelled property size using the same sample of 63 farming properties described above, using distance to the nearest town (Dtown) and city (Dcity) as predictor variables. We then applied this regression relationship [Log10(Area) = 0.9661*Log10(Dcity+1)+0.8436*Log10(Dtown+1)] to the Dcity and Dtown layers to produce a map of predicted property sizes for Australia, which we then divided into $20,000 to produce a per hectare transaction cost layer (Figure 8c).

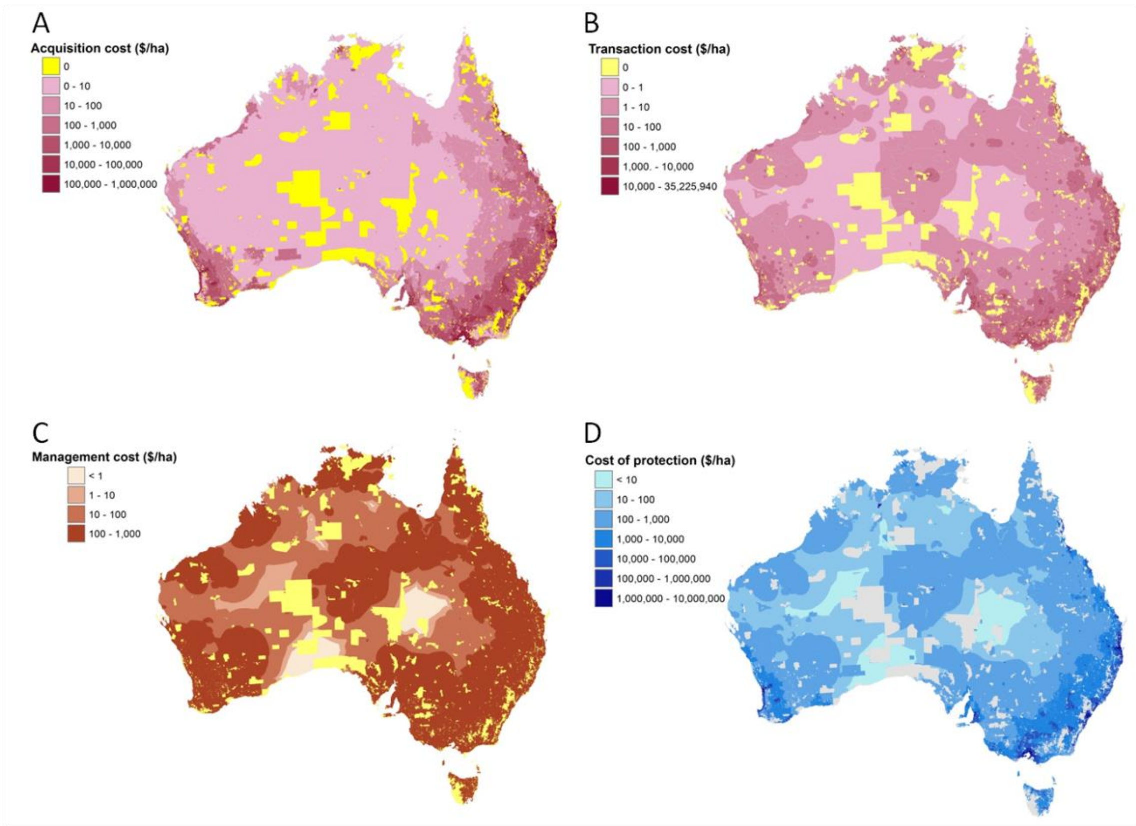


Figure 8: Distribution of estimated (a) acquisition, (b) management, and (c) transaction costs across Australia

These were summed to calculate (d) the net cost of protecting land in any given pixel outside current protected areas. Restoring land in a pixel is an additional cost that depends on the predominant vegetation type and the starting condition. The distribution of current protected areas is indicated with yellow or grey colours (only CAPAD 2010 data are displayed due to licence restrictions on showing more recent data).

2.3.5 Estimating the impact of actions upon habitat condition

An estimate of the effect of a given action in a given environment is calculated in RobOff via response curves. These curves show how the condition of the environment changes through time under each of the actions, including the action of "do nothing". Ideally these curves are species specific, showing how each action in each environment affects the suitability of those environments for the species. However, compiling such detailed ecological data for all of the considered species in a reasonable time frame is very difficult. Therefore, for simplicity and using available literature on vegetation cover and restoration in Australia, we created response curves for each environment, estimating how the general condition of that environment changes under each action (Figure 9). All species occupying a given environment were hence assumed to be similarly affected. A more sophisticated definition of these response curves, e.g. for species guilds sharing similar life history traits, could be used if the necessary information were available.

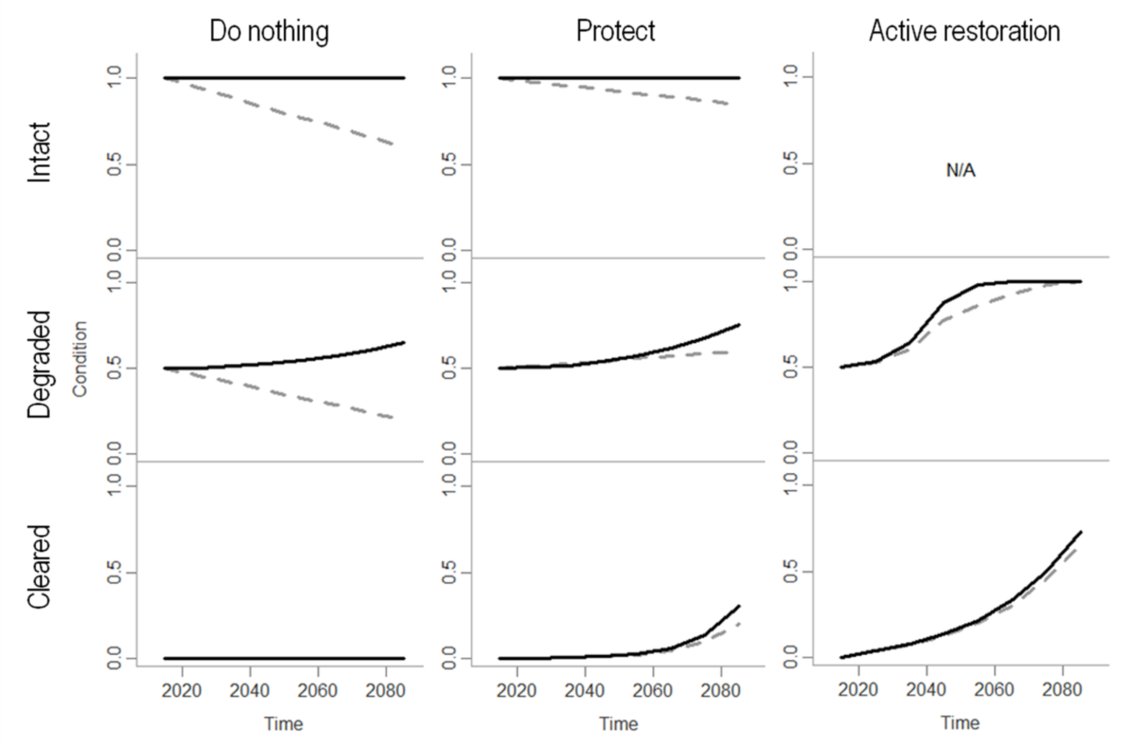


Figure 9: Example of response curves showing the estimated change in condition as a result of each action for unprotected environments comprising rainforest vegetation

Solid black lines show the response for environments that are currently not exposed to anthropogenic threats, dashed grey line shows environments considered to be threatened.

Response curves spanned the same time frame as that used to predict potential changes in species distributions under climate change, commencing in 2015 and running to 2085. Sensitivity of our findings to the substantial uncertainty about the responses to actions will be incorporated in journal publications arising from this report.

2.3.6 Analysis settings

We ran the RobOff analyses with budgets ranging from $0.5 billion to $8 billion to determine how the amount of available funds might drive the conservation outcomes. We selected a medium budget of $3 billion as the basis for the figures reported in this document. The $3 billion budget corresponds to conservation funding currently available under Caring for Our Country, round 2 ($2.2 billion over 5 years) and the Biodiversity Fund ($946 million over six years; http://www.environment.gov.au)

When calculating the optimal set of actions, RobOff can allow tradeoffs between species, such that the conservation outcome of one species can be sacrificed if this yields larger benefits to other species. This type of situation might arise if a habitat type is occupied by only one species and restoring or protecting that habitat is substantially more expensive than restoring and protecting other habitats with more species. In such occasions it can be worth "sacrificing" one species to achieve better outcomes for others (see Bottrill *et al*. 2009). However, for this analysis we did not allow such tradeoffs between species on the basis that they are all threatened. We also weighted all species and environments where those species occurred equally. However, different weighting or trade-off schemes could be considered for future analyses, given that among threatened species some are more imperiled than others.

To achieve the optimisation we used the Genetic Algorithm (Blum & Roli 2003) as our heuristic search method. The timeframe for any action to take effect was set to match the time frame of the projected distribution models under climate change, meaning that actions are taken at time point 2015 (the closest to current time) and the responses are measured until 2085 at 10 year intervals (see Figure 9). The algorithm then seeks a combination of actions that maximises the gains for all species at each time step. We used no time discounting for the conservation gains meaning that benefits that would be gained only in the longer term were considered to be equally valuable as the immediate benefits of an action (see Figure 10 for the rationale underpinning this).

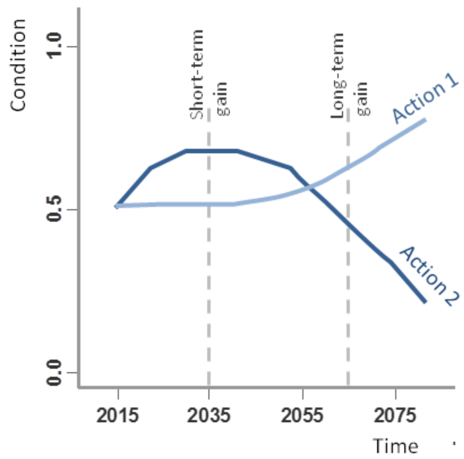


Figure 10: Illustration of time discounting

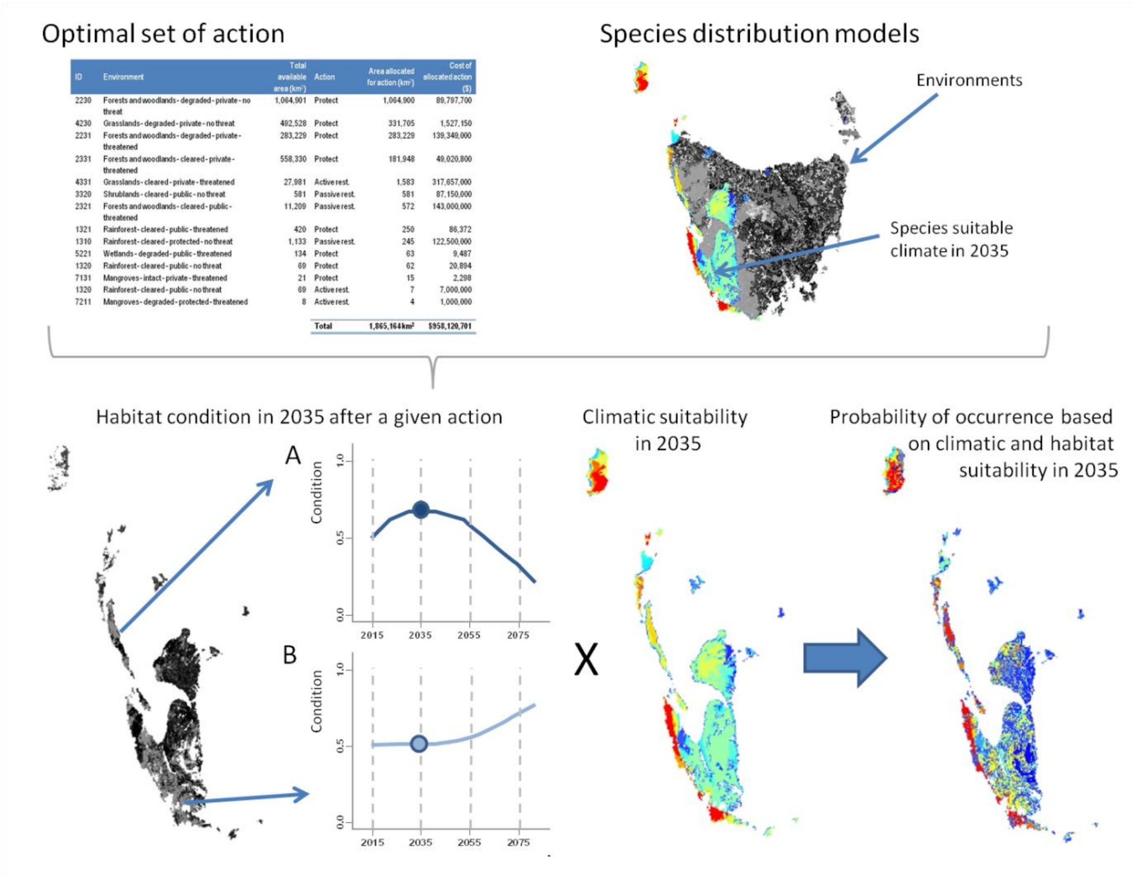
The figure shows the impact of two conservation actions on the condition of an environment (y-axis) through time (x-axis). The action is taken at time point 2015 and as a result of the action the condition of the environment changes during the following 70-year period. The immediate gains of doing action 2 are clearly higher than doing action 1. But as time passes the long term gains of action 1 outweigh those of action 2. Time discounting defines how the short-term and long-term gains are valued against each other. In some cases we might be interested in the immediate returns of an action and hence prefer action 2. This could be a plausible scenario when a species is highly threatened and has a high risk of going extinct without immediate improvement in its habitat. On the other hand, if the species is not at immediate risk of extinction we might be more interested in a sustainable solution, where the condition of the habitat at least stays the same or even improves in long-term, and therefore favour action 1. The time discounting option in RobOff can be used to set the balance between these two options.

2.4 Phase 3: Spatial prioritisation for habitat protection and restoration

In Phase 1, we modelled the potential changes in species distributions under climate change, and in Phase 2 we developed a set of optimal actions to achieve maximum conservation gain for a given budget. To understand how the conservation actions should be distributed across Australia, the impacts of climate change in species' distributions need to be combined with the non-spatial RobOff results in a spatially explicit format.

2.4.1 Combining species distributions and optimal actions in a spatial framework

We estimated the impact of the recommended actions from the RobOff analysis on species occurrence in each 1 km grid cell across Australia at each time step by using the corresponding response curves to determine how the condition of the environment within each grid cell changes at each time step. We then estimated the likelihood that a species will occur in a given grid cell at a given time point by multiplying the original probability of occurrence (Phase 1) by the environment condition value from the response curves associated with the particular action and point in time (Phase 2; Figure 11).



ID	Environment	Total available area (km²)	Action	Area allocated for action (km²)	Cost of allocated action ($)
2230	Forests and woodlands - degraded - private - no threat	1,064,901	Protect	1,064,900	89,797,700
4230	Grasslands - degraded - private - no threat	492,528	Protect	331,705	1,527,150
2231	Forests and woodlands - degraded - private - threatened	283,229	Protect	283,229	139,349,000
2331	Forests and woodlands - cleared - private - threatened	558,330	Protect	181,948	49,020,800
4331	Grasslands - cleared - private - threatened	27,981	Active rest.	1,583	317,657,000
3320	Shrublands - cleared - public - no threat	581	Passive rest.	581	87,150,000
2321	Forests and woodlands - cleared - public - threatened	11,209	Passive rest.	572	143,000,000
1321	Rainforest - cleared - public - threatened	420	Protect	250	86,372
1310	Rainforest - cleared - protected - no threat	1,133	Passive rest.	245	122,500,000
5221	Wetlands - degraded - public - threatened	134	Protect	63	9,487
1320	Rainforest - cleared - public - no threat	69	Protect	62	20,894
7131	Mangroves - intact - private - threatened	21	Protect	15	2,298
1320	Rainforest - cleared - public - no threat	69	Active rest.	7	7,000,000
7211	Mangroves - degraded - protected - threatened	8	Active rest.	4	1,000,000
			Total	1,865,164 km²	$958,120,701

Figure 11: Illustration of how the optimal conservation actions from the RobOff analysis are transformed into a spatial format using modelled species' distributions under climate change

The ultimate goal is to predict the likelihood that a threatened species will occupy a particular grid cell at each time step given the climatic conditions and the conservation action that had been taken in the grid cell at the start of the time series.

We model all actions as having taken place in 2015, the time step closest to the present time. The habitat suitability for a species in a grid cell is then played out over time, based on a combination of the projections from the species distribution modelling and the environmental response curves (Figure 12). At the start of the time series in 2015, the probabilities from the species distribution modelling were transformed based on the initial vegetation condition in each environment (Figure 9). Climatic suitability values in each pixel were multiplied by the weighted sum of environmental condition values of all the actions suggested for the environment in question, in proportion to their area in each pixel. If the suggested actions did not cover all the available area within a grid cell, for the remaining part we assumed 'Do nothing' is taken and used the corresponding response curve. For example, if the optimisation suggested that 10% of the total area of environment A should be protected and actively restored, then all species values within pixels of this environment were multiplied with a condition value that was calculated from the response values of actions 'Protect + (active) restoration' and 'Do nothing' given their respective proportions of the area of targeted for action.

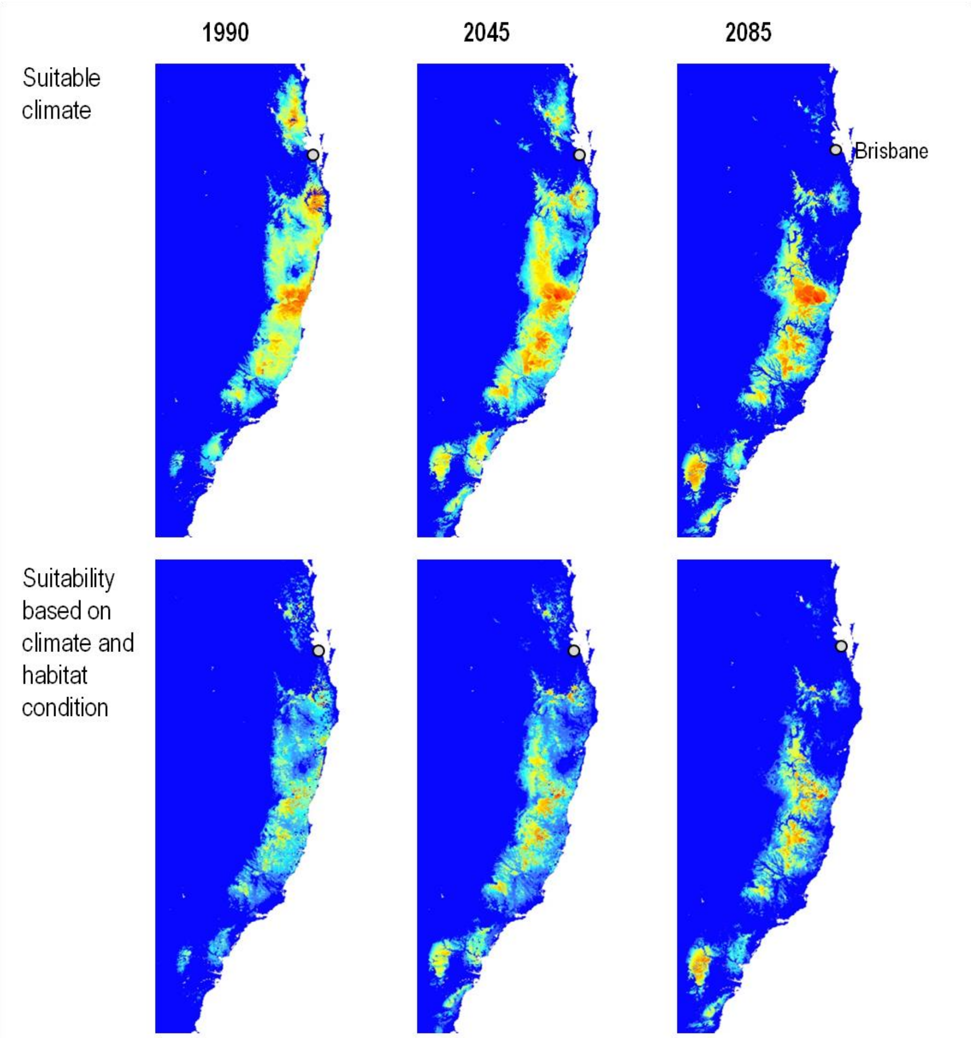


Figure 12: Example of how species' probabilities of occurrence are modelled as changing through time as a consequence of both a changing climate and habitat condition as influenced by conservation actions taken in 2015.

The figure illustrates a case of one threatened amphibian species, showing the expected change in suitable climate at three time steps on the upper panel and the combined change in climate and habitat suitability on the lower panel. Colours range from blue (low) to red (high) reflecting increasing suitability.

Thus, for this example the final condition value would be:

Condition(environment A) = 0.1 * Condition(Protect + restore) + 0.9 * Condition(Do nothing)

at any given time point. Similarly, for all pixels in environments for which no actions were suggested by the RobOff analysis, we assumed habitat suitability conditions to follow the 'Do nothing' response.

2.4.2 Spatial prioritisation of actions

In the final step of our analysis the RobOff transformed species distribution maps were used to create a spatial prioritisation for conservation and restoration actions across Australia. Taking into account the impacts of both future habitat suitability and future climate change required that for each time step a distribution map showing both climatic and habitat suitability was included for each species. We also wanted to take into account connectivity between each time step to guarantee that the resulting priority areas were not only of high importance for species current and future persistence, but that they would also facilitate species range shifts under changing climatic conditions. However, accounting for all these aspects for hundreds of species, multiple time steps and on a continental scale is technically non-trivial, and owing to computational difficulties we have not yet run the full analysis that takes spatial and temporal connectivity fully into account for all species. Therefore the results presented in this last part of the report have been produced using all 504 species under two climate change scenarios (RCP 4.5 and RCP 8.5), but excluding the aspect of connectivity. To explore the sensitivity of the results we also present solutions with and without connectivity for a subset of the original species pool including all currently threatened amphibians and birds of Australia (total of 70 species).

For the spatial prioritisation we used the Zonation software v 3.1 (Moilanen *et al*. 2005, Moilanen *et al*. 2012) which is freely available (www.helsinki.fi/bioscience/consplan/) and particularly well suited for the analysis of large GIS-based raster grid data sets that describe the distributions of many biodiversity features, such as species, habitats or ecosystem services (Kremen *et al*. 2008, Leathwick *et al*. 2008, Thomson *et al*. 2009). Zonation does not use *a priori* defined conservation targets. Rather, it produces a hierarchical priority ranking across all grid cells in the landscape based on occurrence levels and connectivities for species in cells, while balancing the solution simultaneously for all species used in the analysis (Moilanen *et al*. 2011). The ranking is defined by removing first that cell that has the smallest marginal value across all species, recalculating the relative values of remaining cells, and then repeating this procedure until no cells are left. Cells with high ranks are those with the highest conservation value across all species, and are retained last in the removal process. Priority areas for conservation can then be identified simply by taking any given amount of area with highest priority ranks, or by selecting the top fraction of ranked cells up to a given budget level.

2.4.3 Analysis structure

The main goal of this analysis was to spatially prioritise protection and restoration actions that would best facilitate species persistence under present and future conditions. Achieving this goal required that (i) for each species we should consider their respective distributions at all time steps, (ii) we should focus the prioritisation into those habitats for which RobOff analysis indicated conservation and restoration actions should be targeted, and (iii) the spatial prioritisation would be within the limits of a defined budget of $3 billion.

Areas for protection and restoration were prioritised using all 9 time-sliced distribution maps per species to ensure that the final selection would retain the most important areas as the climate changes within our timeframe (1990, 2015, 2025, 2035, 2045, 2055, 2065, 2075, 2085). Of course, climate change is likely to continue beyond 2085, and future climate change predictions can be used to update this analysis once such data are available. In the current analysis we have used 9 * 504 = 4536 input maps showing the likelihood of occurrence based on climate and habitat suitability (produced in Step 2) for priority calculations. To focus the prioritisation into those environments for which RobOff indicated that protection and restoration should be targeted, the ranking procedure in Zonation was constrained to cover only those areas selected for action by the RobOff analysis.

In addition, we explored how the inclusion of connectivity requirements could potentially alter the spatial distribution of areas for conservation actions, using currently threatened birds and amphibians (70 species) as an exemplar group. For this analysis we prepared 25 maps for each species following the framework of Kujala *et al*. (2013). These comprised:

- Nine distribution maps for each time step under the climate scenario RCP 8.5. We selected this scenario as shifts in the suitable climate of species are expected to be more pronounced under the more extreme climate scenario and hence, the connectivity needs more pressing.
- Sixteen connectivity maps, showing the connectivity value of each species occurrence from one time step to both the previous and following time step.

Prioritisation was then carried out as described above, but this time using all 25 distribution maps per species (total of 1750 input maps). We used two connectivity distributions between any two time steps, one for the connectivity from the first to the second time step and another for connectivity back from the second to the first time step. The former of these distributions represents source areas from where dispersal to future distribution areas is expected to take place. The latter represents stepping-stones, i.e. areas that species will occupy first when shifting their distribution, and which are expected to help species reach the core areas of the next future distributions. Connectivity calculations were implemented via the ecological interactions (type 1) technique of Zonation, which allows calculation of connectivity between two distributions (for details see Carroll *et al*. 2010, Rayfield *et al.* 2009). This technique weights the local values of a distribution at one time step depending on how well they are connected to a distribution at another time step, using a metapopulation-type decay function. Essentially, highest connectivity values are given to locations that are of high quality (i.e. high likelihood of occurrence) and are well connected to the high-quality sites of the following time step. The level of connection is naturally species-specific, as species dispersal capability and hence ability to reach new areas varies. In Zonation this is accounted for by scaling the connectivity values against species dispersal capabilities, given that such detailed ecological information is available. Based on information found from literature we estimated the dispersal speed of birds to be 10 km per decade (Chen *et al*. 2011) and that of amphibians to be 2 km per decade (Kujala *et al*. 2013). In the present analysis all time steps and connectivity layers were weighted equally but optional weighting schemes where e.g. higher weights are given to distributions closer to present time, could be implemented. Varying weights could also be assigned to different species.

2.4.4 Budget and spatial visualisation of actions

As in Phase 2, we simulated a budget of $3 billion for selecting priority areas for protection and restoration actions. After producing a priority ranking of the whole landscape, top priority areas were selected starting from the grid cell with the highest ranking and progressively incorporating lower-ranked cells until the budget was consumed. These top priority areas were then overlain onto the environments used in Phase 2 (Figure 7) to derive the amounts of each action required for each grid cell.

3. RESULTS

3.1 Phase 1: Climate-driven changes in threatened species' distributions

3.1.1 Assessing model performance

The current distributions of all vertebrate and plant species were modelled successfully. Models were evaluated according to the area under the curve (AUC) of a receiver operating characteristic plot (Fielding & Bell 1997) and by cross-validation (cross-AUC), and on average they proved to have very good discrimination ability across all taxonomic groups (Table 7).

Table 7: Mean, minimum, maximum and cross-validated AUC values obtained for the Maxent models within each taxonomic group.

According to the classification of Swets (1988), 0.5–0.7 indicates poor discrimination ability; 0.7–0.9 indicates reasonable discrimination; and 0.9–1 indicates very good discrimination.

	Amphibians	Reptiles	Mammals	Birds	Plants
Mean AUC	0.952	0.953	0.931	0.919	0.966
Min AUC	0.838	0.897	0.807	0.752	0.826
Max AUC	0.996	0.990	0.991	0.992	0.997
Mean cross-AUC	0.953	0.954	0.933	0.921	0.967

3.1.2 Relative contributions of each predictor variable

Climatic predictors made greater contributions to the final distribution models than substrate-related predictors (Table 8). The most powerful predictors were precipitation of the wettest quarter (bioclim_16), followed by precipitation of the driest quarter (bioclim_17), and then by temperature seasonality (bioclim_4) and annual mean temperature (bioclim_1). Precipitation seasonality (bioclim_15) had a lower contribution in comparison with the other climatic predictors, suggesting that the quantity of precipitation during critical periods was more important than its overall variability (Table 8).

The contribution of the substrate-related predictors was relatively low overall. This is perhaps due to the relatively coarse underlying data on which they are based (see Williams *et al*. 2012), especially when working at the continental scale. However, a contribution that is weaker than climate is to be expected, since climate determines the broad distribution of a species at a continental or regional scale, and then soil type acts as a filter at more local scales (Pearson & Dawson 2003).

Substrate-related predictors are generally used to model the distribution of plant species, but as described above we also used them to model the distributions of animals on the assumption that they indirectly provide information about vegetation communities that form habitat for animals. The substrate-related predictors performed very similarly (same magnitude) for animals and for plants (Table 8), suggesting that this assumption is reasonable.

Table 8: Mean percent contribution of the predictor variables to the final Maxent Model

Percent contributions were averaged over all species models within a given taxonomic group. Mean contribution gives the mean percent contribution of a given predictor across all the taxonomic groups.

Predictor	Amphibians	Reptiles	Mammals	Birds	Plants	Mean
Annual mean temperature	22	14	10	9	12	14
Temperature seasonality	9	16	14	19	12	14
Precipitation seasonality	5	10	8	12	13	9
Precipitation of Wettest Quarter	23	22	23	17	19	21
Precipitation of Driest Quarter	23	11	18	16	13	16
clay	2	6	5	7	5	5
geolmage	6	8	9	8	11	8
hpedality	6	6	7	6	10	7
Ksat	4	7	7	6	7	6

3.1.3 Climate-driven changes in geographic distributions

If climate and substrate conditions that currently limit species' distributions continue to do so in the future, our models predict that the geographic range sizes of threatened species will decline markedly as the climate changes, and that this decrease will be much more severe under the business-as-usual scenario than either of the mitigation scenarios (Table 9). These geographic range contractions are a consequence of a decline in the overall area in which suitable environmental conditions exist for these species. An example of a gradual decline as climate change progresses is shown in Figure 13. An overall decline in geographic range size is consistent across all taxonomic groups and all emissions scenarios; the only exception is represented by reptiles, which seem to enlarge their ranges at least under the early mitigation scenario (Table 9). Amphibians will be the most strongly affected with a loss in geographic range of 57% by 2085 under the most extreme scenario. This suggests a high vulnerability to climate change in this group, in agreement with an independent trait scoring analysis that identified amphibians as the most climate vulnerable taxon in Australia (Lee 2012).

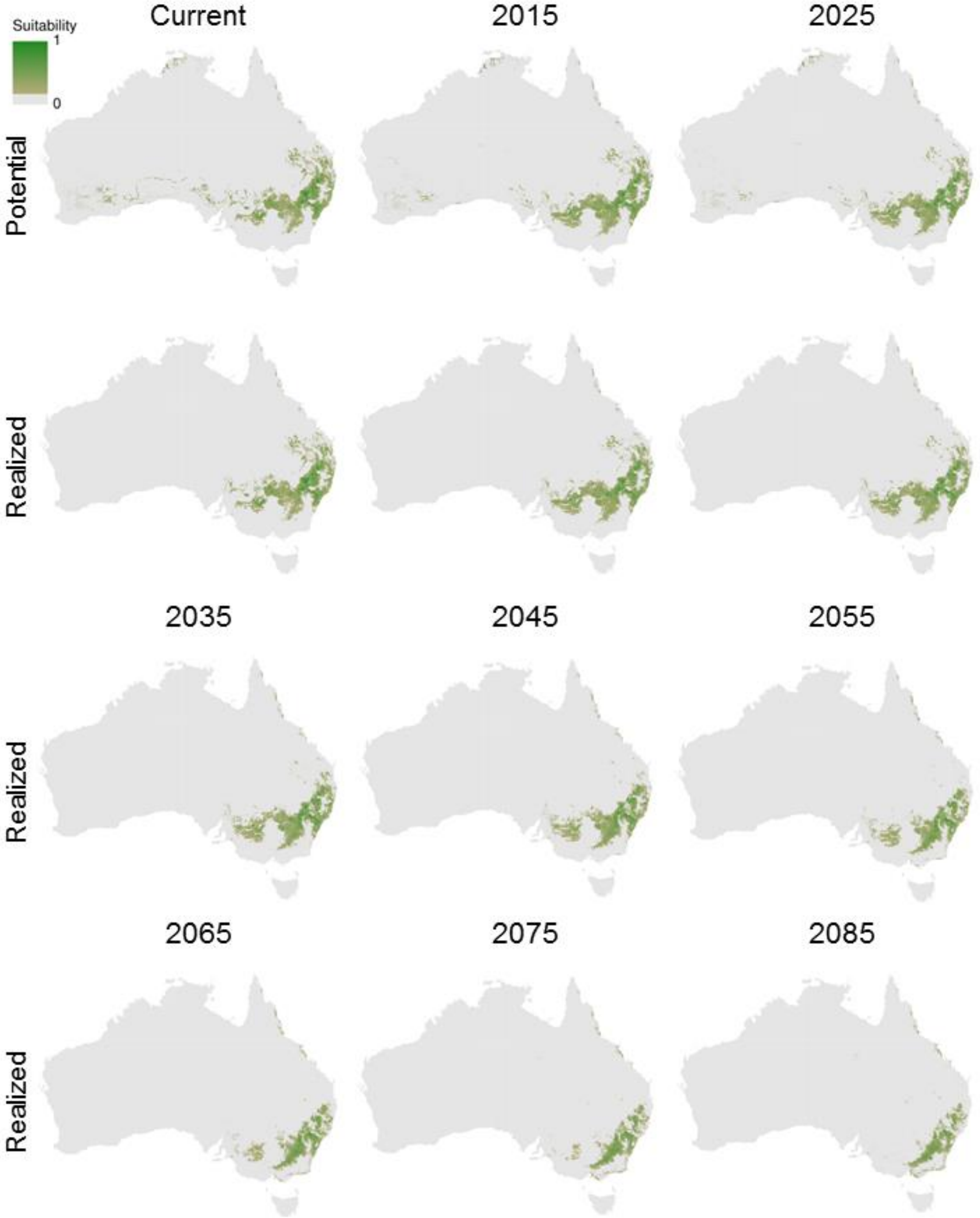


Figure 13: The changing distribution of one threatened mammal species under the business-as-usual climate change scenario (RCP8.5)

The first and second rows show the potential and realised distributions (current, 2015, 2025). Then the following rows only show the realised distributions for 2035-2085. Note that the realised distributions are obtained by filtering out from the potential distribution the areas that are not within a currently occupied or directly neighbouring IBRA region.

These geographic range contractions are predicted to result in the total loss of suitable environmental conditions for 4 (0.8%) of the 504 modelled threatened species by the year 2085 under the most optimistic early mitigation scenario and 70 (13.9%) under the most pessimistic business-as-usual scenario (Table 10). Plants are by far the most extinction-vulnerable groups with 59 species (16.6% of modelled plants) experiencing complete loss of suitable climatic conditions by 2085 under business-as-usual climate change. Many species will exhibit significant range contractions, with 310 (61.5%) species losing more than half of their geographic range by 2085 under the business-as-usual scenario (Table 10). More positively, 74 species (14.7%) could increase their geographic range size under the same business-as-usual scenario.

Table 9: Mean size of current and future (2085) geographic ranges and relative overlap for the five taxonomic groups and three scenarios of climate change

Taxonomic group	Scenario	Mean current range (km^2)	Mean future range (km^2)	Future range / current range	Mean overlap (km^2)	Overlap / current range
Amphibians (N = 22)	RCP3PD	64,835	57,256	0.88	48,189	0.74
	RCP4.5		46,891	0.72	38,510	0.59
	RCP8.5		27,560	0.43	21,403	0.33
Reptiles (N = 30)	RCP3PD	169,996	187,863	1.11	124,868	0.73
	RCP4.5		168,100	0.99	107,114	0.63
	RCP8.5		135,729	0.80	74,504	0.44
Mammals (N = 49)	RCP3PD	347,614	342,222	0.98	267,937	0.77
	RCP4.5		306,410	0.88	228,678	0.66
	RCP8.5		225,774	0.65	159,302	0.46
Birds (N = 48)	RCP3PD	465,802	438,825	0.94	382,144	0.82
	RCP4.5		407,812	0.88	343,992	0.74
	RCP8.5		336,364	0.72	268,579	0.58
Plants (N = 355)	RCP3PD	76,186	74,061	0.97	56,579	0.74
	RCP4.5		65,655	0.86	48,040	0.63
	RCP8.5		52,668	0.69	33,063	0.43

It must be borne in mind that our estimates of geographic range size are likely to be overestimates, given that we have modelled the potential natural distribution of the species, which will not always be fully occupied owing to human activities, ecological processes such as competition, geographic barriers, chance, and other threats such as fire that were not explicitly taken into account in our models. Moreover, although we have already restricted our predicted distributions to the areas inside currently occupied and neighbouring IBRA regions, further masking would be necessary on a case-by-case basis to remove unsuitable habitat types from the predictions (see Gaston & Fuller 2009 for an exploration of these issues in determining geographic range size). Despite this overestimation of absolute geographic range size, we can interpret confidently the relative changes in geographic range size over time and among the scenarios.

The ability of species to cope with shifting environmental suitability depends in part on the extent of overlap between the current and future distributions. Our models indicate that the overlap between current and future ranges varies markedly among taxa (Table 9), with just a third of the current ranges of amphibians remaining suitable by 2085 under RCP8.5, but just over half of the current ranges of birds remaining suitable. In part, this is no doubt a result of the much larger mean range sizes of threatened birds, but it is notable that the degree of overlap declines sharply across all taxa with increasingly severe emissions scenarios. On average across the taxonomic groups, in 2085, the proportion of the current range remaining climatically suitable will fall to 76%, 65%, 45% of the current ranges for early mitigation, late mitigation and business-as-usual climate scenarios respectively. This is concerning, since it is precisely in these overlap areas of persistent suitability on which conservation efforts could most profitably focus. Indeed, as a result of anthropogenic barriers or limited dispersal abilities, there is no guarantee that species will be able to reach areas that are climatically suitable in the future, but outside their current distribution.

Table 10: Number of species with different magnitudes of geographic range change by 2085 under three different climate change scenarios

		Increasing	Decreasing				
Taxonomic group	Scenario		<=10%	11-50%	51-90%	>90%<100%	100%
Amphibians (N = 22)	RCP3PD	8	6	7	1	0	0
	RCP4.5	4	1	13	3	0	1
	RCP8.5	2	1	6	10	1	2
Reptiles (N = 30)	RCP3PD	13	2	8	7	0	0
	RCP4.5	10	2	5	9	3	1
	RCP8.5	5	1	6	7	6	5
Mammals (N = 49)	RCP3PD	25	5	16	2	1	0
	RCP4.5	18	6	13	11	1	0
	RCP8.5	12	1	11	17	6	2
Birds (N = 48)	RCP3PD	13	11	20	4	0	0
	RCP4.5	8	6	26	5	3	0
	RCP8.5	4	2	26	9	5	2
Plants (N = 355)	RCP3PD	130	43	117	53	8	4
	RCP4.5	83	26	117	85	29	15
	RCP8.5	51	9	57	120	59	59
Total (N=504)	RCP3PD	189	67	168	67	9	4
	RCP4.5	123	41	174	113	36	17
	RCP8.5	74	14	106	163	77	70

3.1.4 Current and future patterns of threatened species richness

Changes in the distributions of individual species can be summarised spatially as differences in species richness across emissions scenarios and over time as climate continues to change. We built maps of the distributions of individual species first by transforming the relative likelihood of occurrence of the species into a presence or absence using the threshold that equates the entropy of thresholded and original distributions (Phillips *et al.*, 2006). We then overlaid the binary maps of each species' distribution to calculate the number of species predicted to occur in each grid cell. Threatened species are currently concentrated in the more mesic habitats of south-west Western Australia, the east and south-east of the country, and in the Top End (Figure 14). By 2085, although this general pattern will continue to hold, our models predict declines in the richness of modelled threatened species across the whole of Australia, and retraction toward the coastline, which increase in severity with increasingly pessimistic climate change scenarios (Figure 14). Some areas, mostly in arid interior will lose most or all of their threatened species, while others such as coastal Victoria and South Australia will retain much of their current threatened species richness.

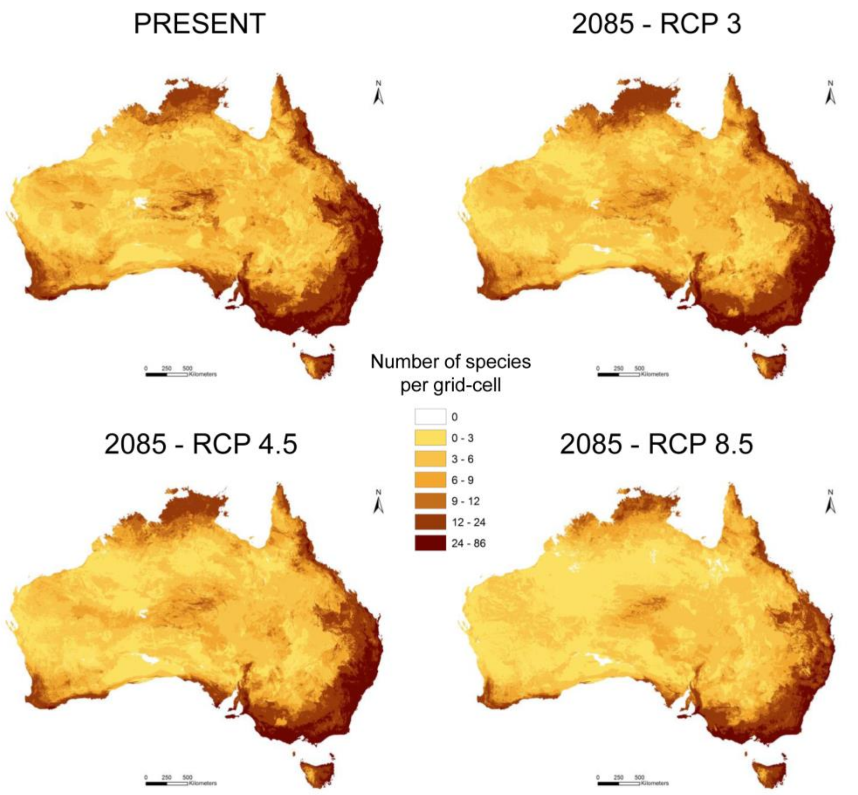


Figure 14: Maps showing total richness of modelled, currently threatened species per 0.01º (~1 km) grid cell across Australia for the present day and in 2085 under three scenarios of climate change arranged in order of increasing severity

The overall pattern of species richness masks considerable variation in the distributions of species in different taxonomic groups (Figure 15). Amphibians are mainly concentrated along the south-east coast, reptiles in the north, east and south coasts, while mammals, birds and plants are more widespread across the continent albeit with higher concentrations in some coastal regions. In general, species richness is predicted to decline more sharply away from the coasts in the future.

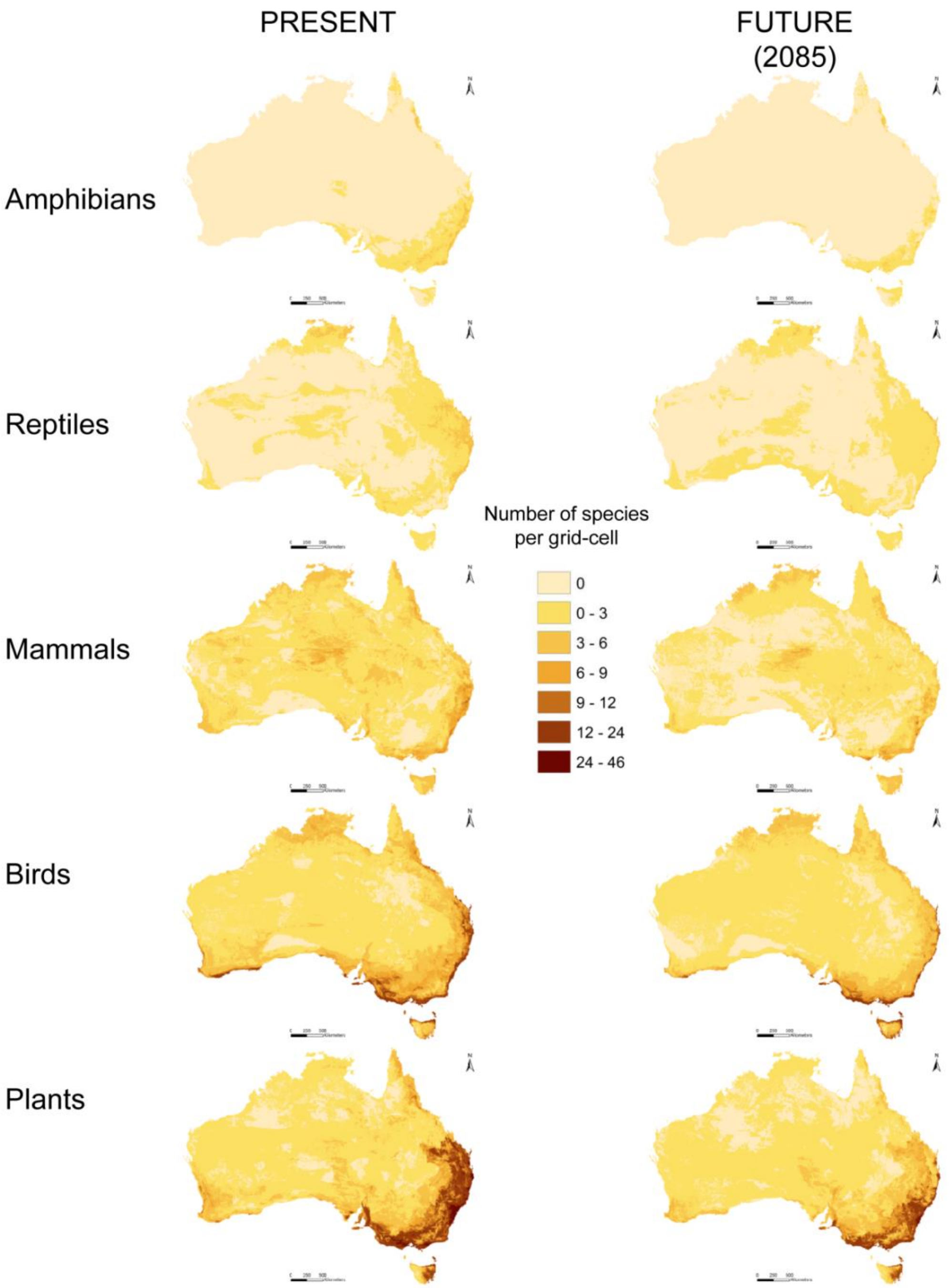


Figure 15: Current and future patterns of richness of the modelled species within the different taxonomic groups

Future maps are based on projections made under the business-as-usual climate change scenario (RCP8.5) and for the time horizon 2085.

3.1.5 Opportunities for protection and restoration

The central goal of this project is to determine the optimal habitat protection and restoration strategies for Australia to maximise the persistence of our threatened species in the future under climate change. For this purpose it is important to determine the status of the vegetation and the degree of protection of the land inside the projected ranges of the species.

To assess which proportion of the current, future and overlap ranges of the species are covered by intact, degraded, cleared or permanently lost vegetation and which proportion is protected, we overlaid them onto a reclassified map of the Vegetation Assets, States and Transitions (VAST v.2, http://daff.gov.au) combined with the most recently available map of the protected areas of Australia (CAPAD10 complemented by November 2012 update). The original classes 0 and 1 of VAST were considered as intact vegetation, classes 2 and 3 as degraded (modified), classes 4 and 5 as cleared (these are native vegetation replaced by non-native and cultivated species) and finally, class 6 (vegetation removed) as lost. VAST information about cleared areas was updated using the class "cleared" from the condition map (Figure 6b).

On average across all the threatened species considered, 27% of the vegetation inside the current geographic distributions is intact, 26% is degraded, 46% is cleared and 1% is lost (Table 11). The proportion of intact vegetation within environmentally suitable areas for threatened species will not decline in a changing climate (Table 11). Assuming the condition of the vegetation remains constant, intact land will on average represent a slightly larger fraction, 28%, of the overall geographic range than at present, though it must be remembered that range sizes will decline markedly as a result of climate change. These data indicate there are many opportunities for protection and restoration. Approximately half of the intact habitat currently occupied by the threatened species is not protected (Table 11), and this is much the same for projected future habitats and overlap zones relative to the footprint of the current reserve system. The only exception are amphibians, for which the protected portion of intact habitat is much larger than the unprotected portion (Table 11). Habitat across a substantial proportion of current and future ranges and the overlap zone are degraded, offering potential for restoration activity. Conservation actions could at least initially focus on the overlap zone between current and future ranges. In those zones, 28% of the vegetation is intact, 26% is degraded and 45% is cleared (Table 11). As a first priority, protection actions could usefully focus on the 13% of intact vegetation in overlap zones that is not yet protected and the restoration actions on the degraded vegetation of which only 5% is already protected.

Table 11: Mean percentage of the geographic range of species in the present, future, and the overlap between the two, in which vegetation is intact, degraded, cleared or permanently lost (for definitions see text) and land is protected (P) or not protected (NP)

		Present								Future (2085)								Overlap							
		Intact		Degr		Cleared.		Lost		Intact		Degr		Cleared.		Lost		Intact		Degr		Cleared.		Lost	
		P	NP	P	NP	P	NP	P	NP	P	NP	P	NP	P	NP	P	NP	P	NP	P	NP	P	NP	P	NP
Amphibians	RCP3PD									28	14	8	20	1	28	0	1	30	14	8	20	2	27	0	0
	RCP4.5	29	16	7	19	1	28	0	1	30	15	8	19	1	26	0	1	32	15	8	18	2	25	0	0
	RCP8.5									31	14	8	18	2	26	0	1	33	14	8	19	2	24	0	0
Reptiles	RCP3									13	19	5	21	1	41	0	1	13	18	5	20	1	42	0	1
	RCP4.5	14	18	4	21	1	42	0	0	13	20	5	19	1	41	0	0	13	20	5	17	1	43	0	0
	RCP8.5									16	15	7	22	1	39	0	1	17	14	5	18	1	44	0	1
Mammals	RCP3PD									19	25	5	24	1	25	0	0	20	25	5	24	1	25	0	0
	RCP4.5	19	26	5	24	1	25	0	0	21	24	5	24	1	25	0	0	22	24	5	24	1	24	0	0
	RCP8.5									25	21	5	23	1	25	0	0	25	23	5	23	1	23	0	0
Birds	RCP3PD									13	16	5	20	2	44	0	1	13	16	5	19	2	43	0	1
	RCP4.5	13	16	5	21	1	43	0	1	13	16	5	19	2	44	0	1	13	15	6	19	2	44	0	1
	RCP8.5									16	15	5	18	2	44	0	1	16	14	5	17	2	45	0	1
Plants	RCP3PD									11	11	5	22	1	49	0	1	11	11	5	21	1	49	0	1
	RCP4.5	12	11	5	21	1	49	0	1	12	11	5	22	1	48	0	1	12	10	5	21	2	49	0	1
	RCP8.5									15	10	6	21	2	45	0	1	15	10	6	20	2	47	0	1
Overall		13	13	5	22	1	45	0	1	15	13	5	21	1	43	0	1	15	13	5	21	1	44	0	1
		27		26		46		1		28		26		45		1		28		26		45		1	

These data show considerable opportunities for both protection and restoration in the future distributions of Australia’s threatened species.

3.2 Phase 2: Optimal protection and restoration actions

The actions identified by RobOff under a budget of $3 billion were focused overwhelmingly on protection, which was identified as the optimal action for more than 99% of the environments selected by RobOff for action (Table 12). This likely results from the high relative cost of any kind of restoration activity relative to protection alone, but this is good news in the sense that strategically targeted protected areas have great potential to conserve threatened species in a changing climate. The actions were strongly focused on forests and woodlands which support the largest number of the threatened species considered. Within the $3 billion budget almost all of the actions were on freehold or leasehold land, although a small area of state forest was also included in the solution (Table 12).

The environments in which actions should take place were spread across the continent, but with noticeable concentrations in the Lake Eyre Basin, central Queensland, Northern Territory, and western WA (Figure 16). This is not yet a priority map (because the cost of taking action in each pixel has not yet been incorporated), but it does show the locations of the environments in which it is optimal to act.

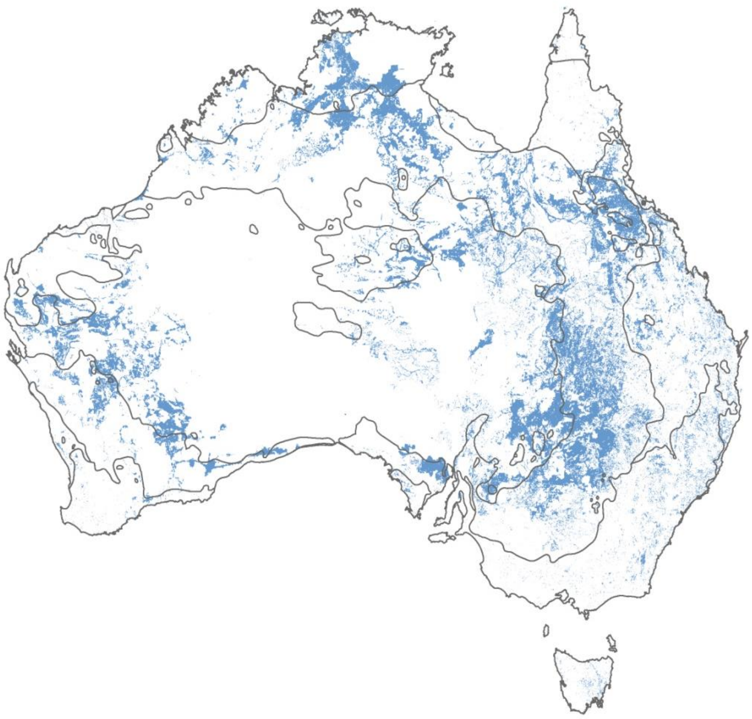


Figure 16: Spatial distribution of the environments where conservation actions listed in Table 12 could be deployed with a $3 billion budget in the optimal solution.

The dark lines show the Australian climate zones based on the Köppen classification. Note that the RobOff analysis does not identify specific areas for action, rather it describes in which environments actions should be taken and how the total budget should be allocated between those environments. The optimal locations for actions are later identified in the spatial prioritisation done in Phase 3.

Table 12: Optimal set of conservation actions identified by RobOff for a total budget of $3 billion

All species and environments were weighted equally and tradeoffs in the conservation outcomes between species were not permitted. The table shows the type of environment, the proportion of the overall area selected by RobOff that comprises that environment, the action that should be taken, and the proportion of the environment for which the action is to be implemented. All other environments are assumed to continue with the 'no action' scenario.

Environment	**Fraction of total area selected by RobOff in which Environment occurs**	**Action**	**Fraction of Environment allocated for action**
Forests and woodlands (degraded, unprotected, low threat)	95.95%	Protect	16.45%
Wetlands (degraded, unprotected, low threat)	2.79%	Protect	26.51%
Wetlands (degraded, unprotected, high threat)	0.13%	Protect	86.32%
Chenopod, Samphire shrublands and Forblands (cleared with replanting needed, unprotected, high threat)	0.7%	Protect + restore	8.67%
Mangroves (intact, unprotected, low threat)	0.34%	Protect	16.85%
Shrublands (intact, state forest, high threat)	0.03%	Protect	100%
Wetlands (intact, state forest, high threat)	0.02%	Protect	99.14%
Mangroves (cleared with replanting needed, unprotected, low threat)	0.02%	Protect + restore	73.08%
Shrublands (cleared with regrowth possible, state forest, low threat)	<0.01%	Protect + restore	100%
Mangroves (cleared with replanting needed, unprotected, high threat)	<0.01%	Protect + restore	91.67%
Rainforest (cleared with regrowth possible, state forest, low threat)	<0.01%	Protect + restore	12%
Grasslands (degraded, state forest, high threat)	<0.01%	Protect	18.75%

Many of the actions are targeted to areas categorised as under high threat, highlighting the urgency with which some areas need to be protected and restored. This implies that the loss of these areas would cause substantial conservation losses, hence RobOff prioritises these actions. Overall, however, the selected environments represent a balanced solution between biological importance, ongoing threats posed by habitat loss and costs of taking conservation actions. We note that the area / cost ratio of each action varies substantially, although RobOff has identified cases where the benefit/cost ratio makes it worth investing in more expensive actions. We weighted all species equally in this analysis, enabling some relatively species poor environments such as mangroves (supporting 44 of all threatened species but being the main habitat to only one threatened mammal) to be prioritised in the resulting set of actions.

Varying the overall budget resulted in surprisingly small changes to the way funds were allocated to different actions and environments. Irrespective of budget, the clear focus of actions remained in protecting currently unprotected lands and targeting actions to forests and woodlands. On average, 97% (range 88-100%) of the total budget was always allocated to protecting land, and 94% (84-100%) of the budget was targeted to environments comprising forest or woodlands. Further preliminary exploration indicated that the overall level of conservation gain continues increasing with larger budgets, and does not level off within the range of budgets tested (i.e. up to $8 billion).

3.3 Phase 3: Spatial priorities for habitat protection and restoration

Within the environments identified as candidate targets for protection and restoration under the $3 billion budget, Zonation produced a hierarchical ranking of grid cells based on their conservation value and the cost of taking the required actions in each grid cell. Depending on climate change scenario, the analysis identifies that action should be taken across 878,605 km^2 (RCP4.5) or 837,991 km^2 (RCP8.5) of Australia's land surface (Table 13). This equates to about 12% of terrestrial Australia, and the vast majority of the implicated action is protection of intact habitat. However, there are important albeit small areas of restoration that form an integral part of this conservation plan (Table 13). Perhaps counterintuitively, the area of protection required under the business-as-usual scenario was smaller than that under the early mitigation scenario. This is most likely because under stronger climate change scenario species distributions move more rapidly towards coastal regions where land costs are notably higher. Hence, under constant budget regime smaller amount of area can be targeted for conservation actions.

The spatial locations of the highest priority sites within our example budget of $3 billion are shown in Figure 17a. As the ranking of cells reflects the relative conservation importance of areas, it could for example be used to suggest a temporal order of rolling out conservation actions on the ground, although careful consideration of feasibility, costs and threats should also be incorporated into such decisions. The top priority sites defined by the available budget under the two climate scenarios RCP 4.5 and RCP 8.5 cover approximately 13 and 12% of Australia, respectively. This is higher than the figure suggested in the RobOff results, most likely due to the high variability in land cost values and the fact that in the Zonation analysis we use detailed cost data specific to each grid cell rather than the median values across environment type used in RobOff. Hence, using more detailed spatial information of costs allows Zonation to find more cost-efficient solutions.

The table shows the amount of area occupied by each environment across Australia, along with that selected by the algorithm under two climate change scenarios. Because the budget is consumed with these priority actions, the analysis suggested a 'Do nothing' action for all of the remaining environments.

Table 13: Optimal solution from the Zonation analyses for a total budget of $3 billion

Environment	Total area occupied by the environment (km^2)	Action	Area selected in optimal solution (RCP4.5)	Area selected in optimal solution (RCP8.5)
Forests and woodlands (degraded, unprotected, low threat)	1,000,391	Protect	849,028	811,176
Wetlands (degraded, unprotected, low threat)	29,096	Protect	23,785	22,223
Wetlands (degraded, unprotected, high threat)	1,389	Protect	1,257	1,214
Chenopod, Samphire shrublands and Forblands (cleared with replanting needed, unprotected, high threat)	7,316	Protect + restore	1,156	67
Mangroves (intact, unprotected, low threat)	3,525	Protect	2,740	2,709
Shrublands (intact, state forest, high threat)	335	Protect	326	319
Wetlands (intact, state forest, high threat)	250	Protect	243	238
Mangroves (cleared with replanting needed, unprotected, low threat)	182	Protect + restore	22	8
Shrublands (cleared with regrowth possible, state forest, low threat)	15	Protect + restore	8	2
Mangroves (cleared with replanting needed, unprotected, high threat)	12	Protect + restore	2	0
Rainforest (cleared with regrowth possible, state forest, low threat)	50	Protect + restore	2	0
Grasslands (degraded, state forest, high threat)	37	Protect	36	35
		Total	**878,605**	**837,991**

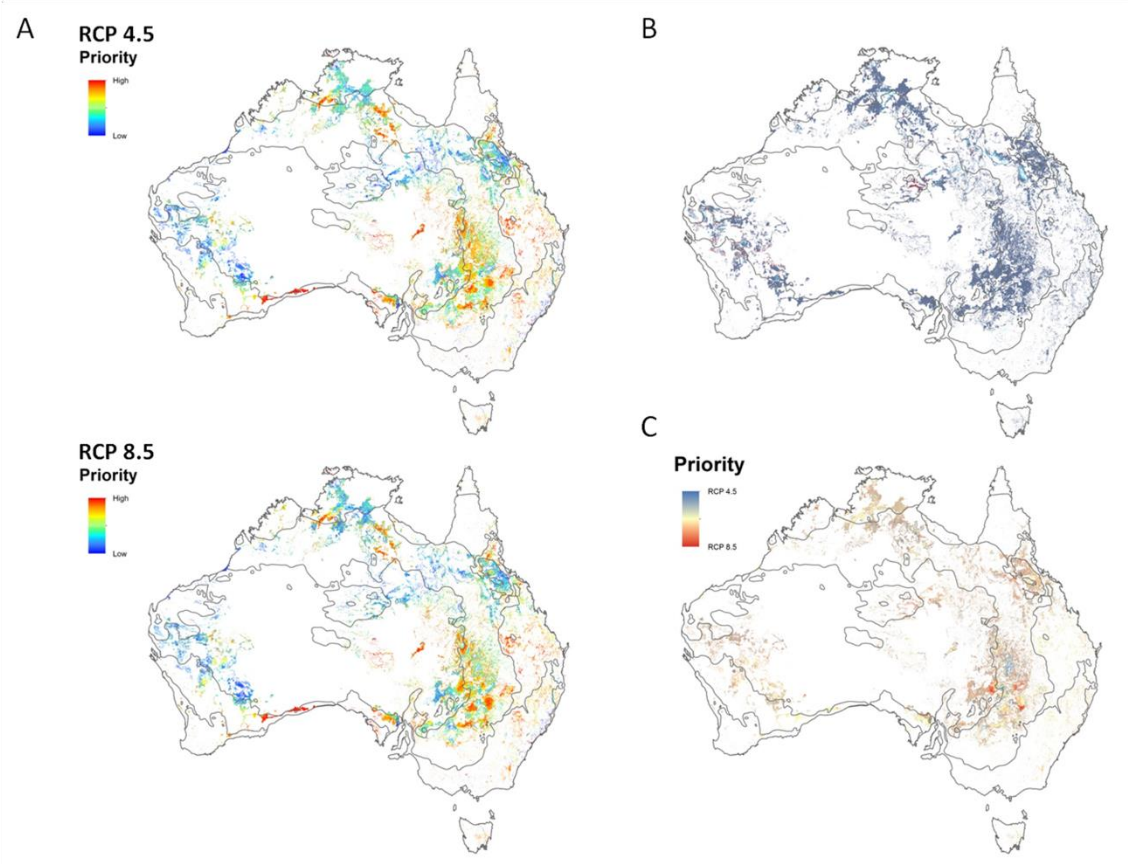


Figure 17: Distribution and priority of areas for conservation and restoration action for a $3 billion budget

Panel A shows areas targeted for actions under two different climate scenarios, RCP 4.5 and RCP 8.5. Colours ranging from blue to red reflect increasing importance of areas. Panel B shows the spatial difference between the two solutions, where dark grey areas are targeted for actions under both climate scenarios, light blue areas are targeted only under RCP 4.5 scenario and red areas under RCP 8.5 scenario. Panel C shows the relative difference in priority within the overlapping area (dark grey areas in panel B), increasing blue colour reflecting higher priority under RCP 4.5 scenario and increasing red under RCP 8.5 scenario.

The current vegetation map (Figure 6b) shows that especially in NSW, Queensland, Northern Territory and WA large proportions of the high priority areas are currently degraded, suggesting that these areas are under considerable pressure from human actions. Our two different scenarios about the severity of future climate change (RCP 4.5 and RCP 8.5) had only a minor effect on the overall configuration of priority sites, although there were small differences both in the distribution (Figure 17b) and relative priority (Figure 17c) of sites targeted for actions. On regional and local levels, however, different expectations about the severity of climate change can lead to rather large differences in which actions should be taken, as illustrated for a part of South Australia in Figure 18.

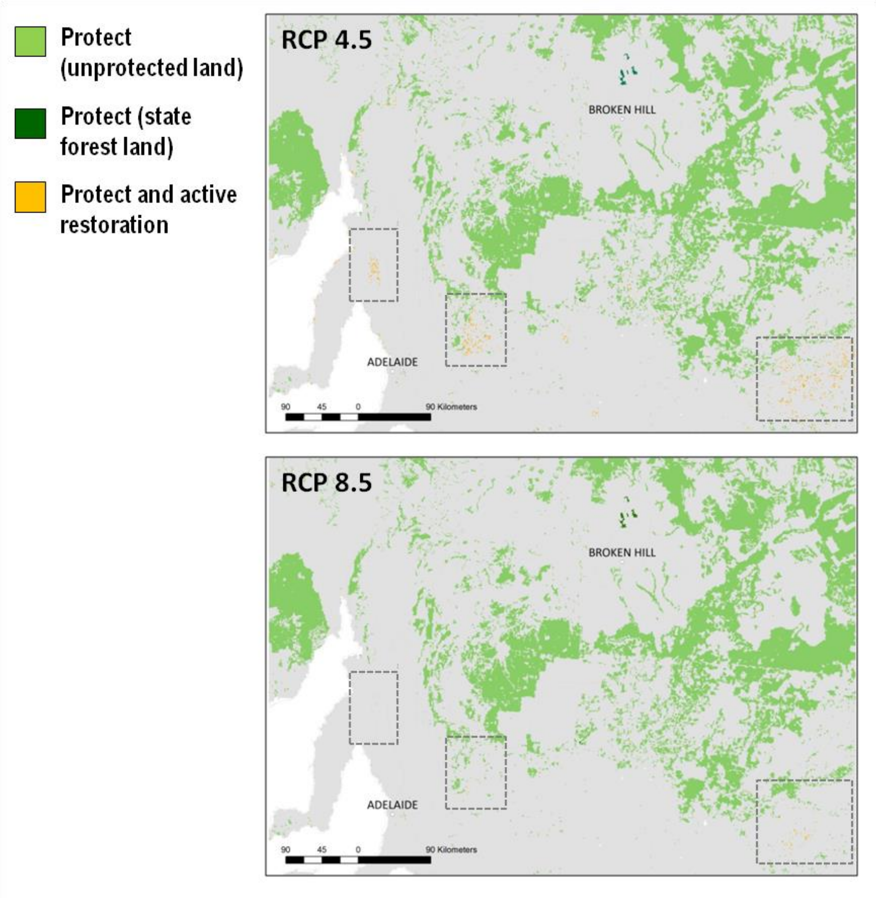


Figure 18: Example showing the distribution of areas targeted for conservation actions under two different climate change scenarios in the Adelaide region of South Australia

The upper panel shows areas most important for different actions under the scenario RCP 4.5 and lower panel the respective areas under scenario RCP 8.5. The boxes identify areas where different severities of climate change will alter the optimal set of actions. In this example, a more pronounced change in climate renders the restoration of these areas less important, and consequently the funds are allocated to actions taken elsewhere in Australia.

The priority areas for conservation actions in Figure 17a capture on average 15% of species current distributions and 13 and 11% of their 2085 distributions under climate scenarios RCP 4.5 and RCP 8.5, respectively. This is rather low and suggests there are many biologically valuable sites outside of this selection that are being assigned the ‘do nothing’ by our prioritisation. There are several possible reasons for this, including that these sites are not currently under any immediate threat or that with a budget of only $3 billion, comprehensive conservation gains are difficult to achieve on a continental scale. It is important to emphasize that the goal of this prioritisation was to identify most important areas for the actions, not the biologically most important areas *per se*.

However, to explore the latter we re-ran the species distribution data through additional prioritisation where the ranking process is relaxed, allowing Zonation to rank cells independent of the actions assigned to the cells from RobOff results (Figure 19). This revealed that from a purely biological perspective the most important areas that will maximise persistence through time under changing climate and habitat conditions for Australia’s currently threatened species lie on the southern and eastern coasts, south-west Western Australia, Tasmania and parts of the Top End. The areas shown in

Figure 19 correspond to 17% of Australia's land surface, and capture on average 78 and 79% of species current distributions and 74 and 71% of their 2085 distributions under the two climate scenarios RCP 4.5 and RCP 8.5, respectively. A considerable proportion of these top priority sites are already protected by the current protected area network: for both climate scenarios, of the best 5% of all areas across Australia, approximately 33% is within current protected areas. Of the best 10%, approximately 27% is already protected. This high level of protection probably contributes to the relatively low priority that many of these areas received in our Zonation analysis.

Comparisons between Figures 17a and 19 also reveal that there is roughly 500,000 km^2 and 740,000 km^2 of high priority areas under the two climate scenarios RCP 4.5 and RCP 8.5, respectively, that are currently not protected nor targeted for further conservation actions under the scheme suggested by the \$3 billion RobOff analysis. These areas are either under no immediate threat or too expensive to be included to the optimal action scheme. Given the distribution of the priority areas (Figure 19), estimated land costs (Figure 8d), and land use intensity (Figure 6), it is more likely that majority of these areas are not targeted for actions due to high costs rather than lack of threat.

It is important to understand the difference between the maps in Figures 17a and 19. Whereas figure 19 shows the most important areas for species under changing climate, figure 17a shows where conservation actions under the \$3 billion budget should be targeted in order to best facilitate species persistence, given that not all areas in Figure 19 can be protected.

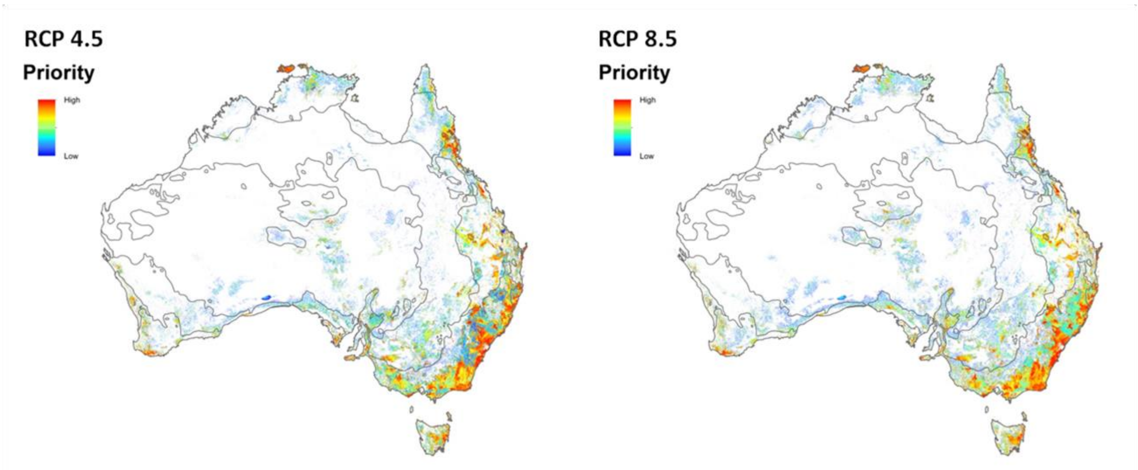


Figure 19: Best 17% of Australia's land area in terms of conservation value for the 504 currently threatened species

These areas retain sites with highest importance for species, taking into account the expected changes in climatic suitability under two scenarios (RCP 4.5 and RCP 8.5) and the expected changes in habitat suitability after optimal actions have been taken at time point 2015. Colours range from blue to red reflecting increasing priority within the best 17%. Note that here the ranking of areas is purely based on their biological values, ignoring other factors such as cost and threat.

Technical constraints currently preclude full consideration of spatial and temporal connectivity across all species. However, to explore the potential impacts of excluding connectivity from our results we re-ran the prioritisation using data for birds and amphibians, and compared the spatial configuration of selected areas with and without connectivity. The outcomes of the two prioritisations were extremely similar, both solutions identifying approximately 14% of Australia's land area where conservation actions should be targeted. Out of these priority areas 99.7% were selected with or without connectivity being included. The overwhelming similarity of the results implies that connectivity needs are already well captured in our analysis because we have included data on climate and habitat suitability at 10 year intervals throughout our time horizon.

Uncertainty about and weighting of present and future distributions is not currently included in the analysis. However, both RobOff and Zonation provide means of including such uncertainties. In the publication version of this work, we will explore methods for incorporating some key uncertainties in the analytical solution and/or a sensitivity analysis. Characterising and dealing with uncertainties for such a large optimisation problem is extremely technically challenging but should be pursued given the number of assumptions involved in the implementation of the study.

We measured the concordance between the areas for investment identified in our analyses with priority areas as published for the Australian Government's Biodiversity Fund round 2 (pending funding announcements at time of writing) as well as priority 1 and 2 areas for the National Reserve System of Taylor *et al.* 2011. There was poor overlap between our spatial prioritisation and the distribution of Biodiversity Fund round 2 target areas (Table 14). Only 20% of the optimal solutions for either the business-as-usual or the mitigation climate scenarios fell within this priority area, which is lower than the 28% of Australia that it covers. In contrast, our optimal solution aligned strongly with priorities identified for the National Reserve System (Table 14).

Table 14: Concordance between existing priority schemes for the Biodiversity Fund Round 2 (http://www.environment.gov.au)

Excludes urban waterway priority areas and NRS expansion targets based on application of simple conservation planning principles (Building Nature's Safety Net; Taylor et al. 2011). Figures are very similar for the late mitigation and business-as-usual climate scenarios, so the mean is presented here.

Priority Scheme	Percentage of Australia covered by Priority Scheme	Percentage of our solution that overlaps priority scheme
Biodiversity Fund round 2 target areas 1	28%	20%
Building Nature's Safety Net priority 1 bioregions	7%	28%
Building Nature's Safety Net priority 1 and 2 bioregions	20%	69%

Biodiversity Fund target areas do not appear at present to be oriented toward protecting the climate-shifted and connecting habitats of species listed as threatened under Commonwealth legislation. While the Biodiversity Fund exists to deal with much broader issues than just the representation of threatened species under climate change, it is worth noting that priorities for the National Reserve System based on simple representation rules for ecosystems and threatened species are well aligned with the solutions developed here.

4. DISCUSSION

Our analyses predicts that based on current best estimates of future climate change and without any changes to the conservation tenure or reduction in existing threats to biodiversity, conditions will become predominantly climatically unsuitable by 2085 for 310 (61%) of the 504 EPBC listed threatened species included in our analysis. The combination of protection and restoration that we have identified here represents the optimal strategy for keeping as many of these species extant given limited resources, based on the best available information about the way that species are likely to respond to climate change and the protection and restoration options considered. Clearly, there are significant uncertainties associated with our projections and our recommendations. However, the recommendations we provide represent the 'best bet' recommendations given current information and knowledge. We encourage users of this information to seek improvements and refinements to predictions and evaluations of adaptation investment benefits as new information becomes available, as modelling methods improve. When decisions about how to protect threatened species are undertaken at finer scales, consideration of factors which we could not consider in our continental-scale analysis may improve the reliability of predictions and the effectiveness of conservation investments. Our analysis is specifically aimed at achieving a coherent national-level investment prioritization which can then be refined at finer scales (e.g. bioregion or catchment), using the best available information at the relevant scale.

The spatially optimal allocation of \$3 billion that we provide in Figure 17 is our solution for the case in which the budget has this particular limitation. Results not presented here indicate that increasing the budget up to \$8 billion results in a linear increase in conservation benefit, with no flattening of the net benefit-cost curve. This indicates that \$3 billion is by no means an optimal budget or close to enough for securing the future of Australia's listed threatened species. Further analysis is required to understand (i) the precise relationship between conservation budget and the number of species that lose a significant proportion of their habitat, and (ii) the conservation budget allocation beyond which biodiversity returns start to diminish.

A budget constraint of \$3 billion leads to a particular optimal solution that does not conserve the most suitable habitat for many of the species included in the analysis. That is because the areas that are identified as having the highest biological value at 2085 are in the coastal regions, especially including the south-eastern coastal ranges. These areas are relatively expensive to protect, so tend not to be included in our cost-constrained solution. Figure 19 shows the most important conservation areas that would be conserved if cost was not a consideration. There is a significant amount of area identified in Figure 19 that does make it into the cost-constrained solution. Table 12 also highlights the percentage of environments warranting conservation action by Roboff that were not included in the final Zonation solution. The consequence of the cost constraints on our current solution manifests as a shift in investment to inland areas that are less costly to acquire or restore than the coastal range areas that would ideally be conserved. Mapping exactly how the allocation of investment varies spatially depending on budget constraints will be the subject of future research.

Across the variety of budget options tested in this study, habitat protection dominated the set of optimal actions for maximizing the availability of suitable and connected habitat for threatened species in the face of changing climate, although restoration played an important role for some species in some locations. Protection was the optimal action across c. 840,000 - 880,000 km^2 of Australia under a total conservation budget of \$3 billion depending on which future climate scenario is considered. The total area within which it was found to be optimal to actively restore habitat was 77 - 1,190 km^2. The lower bound on the restoration budget represents the optimal solution under the more extreme climate scenario. This somewhat counter intuitive result occurs because under the more extreme climate scenario, the allocation of investment is forced toward coastal areas which are more expensive (and therefore less cost-efficient) to restore, and for which the greatest gains are made through protection against the threat of clearing for urban or agricultural development rather than restoration *per se*. Optimal allocation of protection effort focused on forests and woodland areas of eastern Australia, Northern Territory, the Great Western Woodlands of Western Australia, and southern South Australia. Restoration effort is required mostly in south-eastern Australia.

4.1 Improvements and Future Directions

Our optimal solution is likely to be sensitive to (i) the accuracy of the climate change projections, (ii) how the environments are defined, (iii) how the species are predicted to respond to climate change and the response curves are drawn, (iv) estimates of costs, and (v) whether tradeoffs among species are allowed. It would be worthwhile conducting sensitivity analyses of these various parameters to establish which components are most important in driving the optimisation results. The results of any optimisation depend on how the various factors that feed it are balanced, and this is ultimately a process that must be guided by the objectives, together with information about constraints on where and how action can take place.

Unless greenhouse gas emissions are brought sharply under control, climate seems likely to continue to change beyond the time horizon of our study 2085. While the details of our optimisation do not change dramatically among the different climate change scenarios investigated here (Figure 17b,c) there is of course the potential that change beyond 2085 will eventually alter priorities. Uncertainty about climates so far in the future, and in the pattern of the human response to climate change means that we can do little to model the likely outcomes explicitly. One promising approach is to incorporate uncertainty systemically in the modelling (e.g. Iwamura *et al*. 2010; Wintle *et al*. 2011), and our analysis could be extended in that direction.

The analyses of the benefits derived from protection and restoration actions undertaken here explicitly include time lags associated with the accrual of benefits to biodiversity. For example, if restoration actions relevant to grassy woodlands such as replanting or ecological thinning take 40 years to bring benefits to woodland birds, then this is included in the analysis of whether this is a suitably cost-effective way to conserve woodland birds. Our analyses assume all conservation investments result in a permanent change of land use toward conservation, either through transfer of state land to the protected estate or purchase or covenanting of private lands. A different approach might also allow for temporary conservation or " stewardship " contracts which only last for 10-15 years. If we included such an option, it would be necessary to incorporate greater uncertainty in the long term benefits of conservation and it is likely that a much larger area would have to be subjected to such short term contracts to provide a buffer against the uncertainty about the long-term security of stewardship arrangements. Nonetheless, the potentially lower costs of stewardship schemes (compared with land purchase) may allow for actions to be carried out over a larger area than can be achieved with direct purchase. The trade-off between the security of tenure change versus the prospect of larger areas of conservation under stewardship payment represents an interesting future research priority. Including the threat of habitat loss after the cessation of a stewardship arrangement would be necessary for a coherent analysis of this option. The spatial variation in clearing threat (perhaps more acute in near-urban areas) would be important to capture.

4.2 Closing remarks

Our analysis suggests that the budget of approximately $3.2 billion from the Biodiversity Fund and Caring for Our Country can be allocated in a way that secures future habitats of threatened species under climate change. We recommend that the bulk of this money be spent protecting and managing c. 840,000 - 880,000 km^2 of intact vegetation covering 12-13% of Australia, and the restoration of 77 – 1,190 km^2 of degraded vegetation to recreate natural environments and connected habitats suitable for all species. We have estimated this outcome based on direct investment by government in land purchase and in replanting of native vegetation and natural regrowth. Some of this cost could be offset by targeted investment of carbon farming funds.

REFERENCES

Blum, C. & Roli, A. 2003. Metaheuristics in combinatorial optimization: overview and conceptual comparison. *ACM Computing Surveys*, 35, 268-308.

Bottrill, M.C., Joseph, L.N., Carwardine, J., Bode, M., Cook, C., Game, E.T., Grantham, H., Kark, S., Linke, S., McDonald-Madden, E., Pressey, R.L., Walker, S., Wilson, K.A. & Possingham, H.P. 2009. Is conservation triage just smart decision making? *Trends in Ecology & Evolution*, 23, 649–654.

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

Carroll, C., Dunk, J.R. & Moilanen, A. 2010. Optimizing resiliency of reserve networks to climate change: Multispecies conservation planning in the Pacific Northwest, USA. *Global Change Biology*, 16, 891-904.

Chen, I.-C., Hill, J.K., Ohlemüller, R., Roy, D.B. & Thomas, C.D. 2011. Rapid range shifts of species associated with high levels of climate warming. *Science*, 333, 1024-1026.

Crossman, N.D., Bryan, B.A. & Summers, D.M. 2012. Identifying priority areas for reducing species vulnerability to climate change. *Diversity and Distributions*, 18, 60-72.

Dawson, T.P., Jackson, S.T., House, J.I., Prentice, I.C. & Mace, G.M. 2011. Beyond predictions: Biodiversity conservation in a changing climate. *Science*, 332, 53-58.

Dunlop M., Hilbert D.W., Ferrier S., House A., Liedloff A., Prober S.M., Smyth A., Martin T.G., Harwood T., Williams K.J., Fletcher C. & Murphy, H. 2012. *The Implications of Climate Change for Biodiversity Conservation and the National Reserve System: Final Synthesis.* A report prepared for the Department of Sustainability, Environment, Water, Population and Communities, and the Department of Climate Change and Energy Efficiency. CSIRO Climate Adaptation Flagship, Canberra.

Ferrier, S., Manion, G., Elith, J. & Richardson, K. 2007. Using generalized dissimilarity modelling to analyse and predict patterns of beta diversity in regional biodiversity assessment. *Diversity and Distributions*, 13, 252-264.

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

Fielding, A.H. & Bell, J.F. 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation*, 24, 38–49.

Foden, W., Mace, G., Vié, J.-C., Angulo, A., Butchart, S., DeVantier, L., Dublin, H., Gutsche, A., Stuart, S. & Turak, E. 2008. Species susceptibility to climate change impacts. *In*: J.-C. Vié, C. Hilton-Taylor and S.N. Stuart (eds). *The 2008 Review of The IUCN Red List of Threatened Species*. IUCN Gland, Switzerland.

Forman R. & Alexander L. 1998. Roads and their major ecological effects. *Annual Review of Ecology, Evolution & Systematics,* 29, 207-231.

Gaston, K.J. & Fuller, R.A. 2009. The sizes of species' geographic ranges. *Journal of Applied Ecology*, 46, 1–9.

Gillson, L., Dawson, T.P., Jack, S. & McGeoch, M.A. 2013. Accommodating climate change contingencies in conservation strategy. *Trends in Ecology & Evolution*, 28, 135–142.

Heller, N.E. & Zavaleta, E.S. 2009. Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation*, 142, 14-32.
Hobbs, R.J., Higgs, E. & Harris, J.A. 2009. Novel ecosystems: Implications for conservation and restoration. *Trends in Ecology and Evolution*, 24, 599-605.
Hoffmann, A.A. & Sgro, C.M. 2011. Climate change and evolutionary adaptation. *Nature*, 470, 479-485.
Hughes, L. 2000. Biological consequences of global warming: Is the signal already apparent? *Trends in Ecology and Evolution*, 15, 56-61.
IPCC SRES. 2000. *Special Report on Emissions Scenarios: A special report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, UK.
Iwamura, T., Wilson, K.A., Venter, O. & Possingham, H.P. 2010. A climatic stability approach to prioritizing global conservation investments. *PLoS ONE*, 5, e15103.
Kremen, C., Cameron, A., Moilanen, A., Phillips, J., Thomas, C.D., Beentje, H., Dransfield, J., Fisher, B.L., Glaw, F., Good, T.C., Harper, G.J., Hijmans, R.J., Lees, D.C., Louis, E., Nussbaum, R.A., Raxworthy, C.J., Razafimpahanana, A., Schatz, G.E., Vences, M., Vieites, D.R., Wright, P.C. & Zjhra, M.L. 2008. Aligning conservation priorities across taxa in Madagascar with high-resolution planning tools. *Science*, 320, 222-226.
Kujala, H., Moilanen, A., Araújo, M.B. & Cabeza, M. 2013. Conservation planning with uncertain climate change projections. *PLoS One,* 8(2), e53315
Lawing, A.M. & Polly, P.D. 2011. Pleistocene climate, phylogeny, and climate envelope models: An integrative approach to better understand species' response to climate change. *PLoS ONE*, 6, e28554.
Leathwick, J., Moilanen, A., Francis, M., Elith, J., Taylor, P., Julian, K., Hastie, T. & Duffy, C. 2008. Novel methods for the design and evaluation of marine protected areas in offshore waters. *Conservation Letters*, 1, 91-102.
Lee, J. 2012. Understanding the climate vulnerability of Australia's threatened species. B. Sc. Honours Thesis, University of Queensland.
Lewis, R.R. 2005. Ecological engineering for successful management and restoration of mangrove forests. *Ecological Engineering*, 24, 403-418.
Lunt, I.D. & Morgan, J.W. 2002. *The role of fire regimes in temperate lowland grasslands of south-eastern Australia. Flammable Australia: The Fire Regimes and Biodiversity of a Continent* (eds R.Bradstock, J.Williams & A.M.Gill), pp. 177-196. Cambridge University Press, Cambridge, UK.
Mace, G.M. & Purvis, A. 2008. Evolutionary biology and practical conservation: Bridging a widening gap. *Molecular Ecology*, 17, 9-19.
McKenzie, N.J., Jacquier, D.W., Ashton, L.J. & Cresswell, H.P. 2000. *Estimation of soil properties using the Atlas of Australian Soils*. Technical report 11/00, CSIRO Land and Water, Canberra.
Moilanen, A. & Ball, I. 2009. Heuristic and approximate optimization methods for spatial conservation planning. *In*: Moilanen, A., Wilson, K.A. and Possingham, H.P. (eds.) *Spatial conservation prioritisation*. p. 58-69. Oxford University Press Inc., New York.
Moilanen, A., Franco, A.M.A., Early, R.I., Fox, R., Wintle, B. & Thomas, C.D. 2005. Prioritizing multiple-use landscapes for conservation: Methods for large multi-species planning problems. *Proceedings of the Royal Society B: Biological Sciences*, 272, 1885-1891.
Moilanen, A., Anderson, B.J., Eigenbrod, F., Heinemeyer, A., Roy, D.B., Gillings, S., Armsworth, P.R., Gaston, K.J. & Thomas, C.D. 2011. Balancing alternative land uses in conservation prioritisation. *Ecological Applications*, 21, 1419-1426.
Moilanen, A., Meller, L., Leppänen, J., Montesino Pouzols, F., Arponen, A. & Kujala, H. 2012. *Zonation spatial conservation planning framework and software v. 3.1*,

User manual, 287 pp. ISBN 978-952-10-7893-4 (paperback), ISBN 978-952-10-7894-1.

Moss, R. H., J. A. Edmonds, K. A. Hibbard, M. R. Manning, S. K. Rose, D. P. van Vuuren, T. R. Carter, S. Emori, M. Kainuma, T. Kram, G. A. Meehl, J. F. B. Mitchell, N. Nakicenovic, K. Riahi, S. J. Smith, R. J. Stouffer, A. M. Thomson, J. P. Weyant & T. J. Wilbanks. 2010. The next generation of scenarios for climate change research and assessment. *Nature*, 463,747-756.

Parmesan, C. & Yohe, G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 421, 37-42.

Pearson, R.G. & Dawson, T.P. 2003. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography*, 12, 361-371.

Pease, C.M., Lande, R. & Bull, J.J. 1989. A model of population growth, dispersal and evolution in a changing environment. *Ecology*, 70, 1657-1664.

Phillips, S. J., R. P. Anderson & Schapire, R.E. 2006. Maximum entropy modeling of species geographic distributions. Ecological Modelling 190, 231-259.

Phillips, S.J., Dudik, M., Elith, J., Graham, C.H., Lehmann, A., Leathwick, J. & Ferrier, S. 2009. Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data. *Ecological Applications*, 19, 181-197.

Pouzols, F.M. & Moilanen, A. In press. RobOff: software for analysis of alternative land-use options and conservation actions. *Methods in Ecology and Evolution*. http://dx.doi.org/10.1111/2041-210X.12040

Rayfield, B., Moilanen, A. & Fortin, M.J. 2009. Incorporating consumer-resource spatial interactions in reserve design. *Ecological Modelling*, 220, 725-733.

Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic & Rafaj, P. 2011. RCP 8.5-A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, 109, 33-57.

Soulé, M.E. 1986. *Conservation biology: The science of scarcity and diversity*. Sinauer Associates, Sunderland, MA.

Steffen, W., Burbidge, A., Hughes, L., Kitching, R., Lindenmayer, D., Musgrave, W., Stafford Smith, M. & Werner, P.A. 2009. *Australia's biodiversity and climate change*. CSIRO publishing, Melbourne.

Swets, J.A. 1988. Measuring the accuracy of diagnostic systems. *Science*, 240, 1285-1293.

Taylor, M. F. J., Adams, V. M., Segan, D. B. & Pressey R. L., 2009. *20 million hectares by 2020: Protected areas, green infrastructure and green jobs for Queensland*. WWF-Australia, Sydney.

Taylor, M. F. J., Sattler, P. S., Fitzsimons, J., Curnow, C., Beaver, D., Gibson, L. & Llewellyn, G. 2011. *Building Nature's Safety Net 2011: The state of protected areas for Australia's ecosystems and wildlife*. WWF-Australia, Sydney.

Thackway, R. & Lesslie, R. 2005. *Vegetation Assets, States and Transitions (VAST): accounting for vegetation condition in the Australian landscape*. BRS Technical Report, Bureau of Rural Sciences, Canberra.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., de Siqueira, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huerta, M.A., Peterson, A.T., Phillips, O.L. & Williams, S.E., 2004. Extinction risk from climate change. *Nature*, 427:145-148.

Thomson, A. M., K. V. Calvin, S. J. Smith, G. P. Kyle, A. Volke, P. Patel, S. Delgado-Arias, B. Bond-Lamberty, M. A. Wise, L. E. Clarke & Edmonds, J.A. 2011. RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change*, 109, 77-94.

Thomson, J.R., Moilanen, A.J., Vesk, P.A., Bennett, A.F. & Mac Nally, R. 2009. Where and when to revegetate: A quantitative method for scheduling landscape reconstruction. *Ecological Applications*, 19, 817-828.

VanDerWal J., Beaumont L., Zimmermann N. E. & Lorch, P. 2011a. Package 'climates': Methods for working with weather and climate. www.rforge.net/climates/.

VanDerWal, J., Falconi, L., Januchowski, S., Shoo, L. & Storlie, C. 2011b. *SDMTools - Species Distribution Modelling Tools: Tools for processing data associated with species distribution modelling exercises*. http:// http://rforge.net/SDMTools/

Van Vuuren, D.P., Edmonds, J.A., Kainuma, M., Riahi, K., Thomson, A.M., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J. & Rose, S. 2011. The representative concentration pathways: an overview. *Climatic Change*, 109, 5-31.

Van Vuuren, D. P., Stehfest, E., den Elzen, M.G.J, Kram, T., van Vliet, J., Deetman, S., Isaac, M., Goldewijk, K.K., Hof, A., Beltran, A.M., Oostenrijk, R. & van Ruijven, B. 2011. RCP2.6: exploring the possibility to keep global mean temperature increase below 2 degrees C. *Climatic Change*, 109, 95-116.

Walther, G-R, Post E *et al*. 2002. Ecological responses to recent climate change. *Nature*, 416, 389–395.

Western, A. & Mckenzie, N., 2004. *Soil hydrological properties of Australia version 1.0.1.* Melbourne: CRC for Catchment Hydrology.

Williams, K.J., et al., 2010. *Harnessing continent-wide biodiversity datasets for prioritising national conservation investment.* Canberra: CSIRO Ecosystem Sciences, A report prepared for the Department of Sustainability, Environment, Water, Population and Communities, Australian Government, Canberra.

Williams, K.J., Belbin, L., Austin, M.P., Stein, J.L. & Ferrier, S. 2012. Which environmental variables should I use in my biodiversity model? International Journal of Geographical Information, *Science*, 26, 2009-2047.

Wilson, E.O. 1992. *The Diversity of Life.* Harvard University Press, Cambridge, MA.

Wintle B.A., Bekessy S.A., Keith D.A., van Wilgen, B.W., Cabeza, M., Schröder, B., Carvalho, S., Falcucci, A., Maiorano, L., Regan, T.J., Rondinini, C., Boitani, L. & Possingham, H.P. 2011. Ecological-economic optimization of biodiversity conservation under climate change. *Nature Climate Change*, 1, 355-359.

WWF

THE UNIVERSITY OF MELBOURNE

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

NCCARF
National Climate Change Adaptation Research Facility