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Climate change adaptation strategies for Australian birds

Final Report

Stephen Garnett, Donald Franklin, Glenn Ehmke,
Jeremy VanDerWal, Lauren Hodgson, Chris Pavey,
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CLIMATE CHANGE ADAPTATION STRATEGIES FOR AUSTRALIAN BIRDS

Adaptation strategies for Australian birds

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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.

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ACKNOWLEDGEMENTS

The project would not have been possible without the decades of contribution by the birdwatchers of Australia to the distributional databases on which this report is based. Without their outstanding effort we would not be able to prepare for climate change or understand the processes that underlie bird distributions.

We have benefited from the combined knowledge of a great many people during the preparation of this book. We have been guided in this project by the BirdLife Australia Threatened Species Committee, particularly Hugh Ford who assiduously read and commented on the book that accompanies this research. We also received valuable comments from Leo Joseph of CSIRO, Lynda Chambers of the Australian Bureau of Meteorology, Nicholas Carlile and David Priddel of the New South Wales National Parks and Wildlife Service, Mike Weston of Deakin University, Richard Fuller of the University of Queensland and Wendy Foden of the World Conservation Monitoring Centre. Judit Szabo and Alistair Stewart played an essential role in helping assemble the bird life history data which underpinned the sensitivity analyses.

Organisationally, this book is a product of the National Climate Change Adaptation Research Facility at Griffith University. The project was formulated by Stephen Garnett, Stephen Williams, Jeremy Vanderwal, Alex Kutt and Stuart Butchart as a partnership between Charles Darwin University, James Cook University, CSIRO, BirdLife Australia and BirdLife International. The project was capably administered by Frank Sattler at NCCARF, Yvette Williams at James Cook University, James O'Connor at BirdLife Australia and Roanne Ramsey at Charles Darwin University's Research Institute for the Environment and Livelihoods.

ABSTRACT

In the first continental analysis of the effects of climate change on a faunal group, we identified that the climate space of 101 Australian terrestrial and inland water bird taxa is likely to be entirely gone by 2085, 16 marine taxa have breeding sites that are predicted to be at least 10% less productive than today, and 55 terrestrial taxa are likely to be exposed to more frequent or intense fires.

Birds confined to Cape York Peninsula, the Wet Tropics, the Top End of the Northern Territory (particularly the Tiwi Islands), the arid zone, King Island and southern South Australia (particularly Kangaroo Island) are most likely to lose climate space. There was some variation in the predictions of the 18 climate models deployed, but all predicted that the rainforest avifauna of Cape York Peninsula is likely to face the strongest challenge from climate change, particularly taxa currently confined to the Iron and McIlwraith Ranges. For marine birds, those nesting on Lord Howe and Norfolk Islands, the Great Barrier Reef and the Houtman Abrolhos are likely to face the greatest declines in local marine productivity. Changes in local marine productivity may also affect the endemic terrestrial birds of these islands, for which no climate modelling was possible. A small group of beach-nesting and saltmarsh birds may be affected by sea level rise.

Many taxa, and particularly seabirds, are potentially highly sensitive to climate change based on a set of ecological and morphological metrics. Small island taxa were most likely to be both exposed and sensitive to climate change, followed by marine and shoreline taxa. While threatened birds were more likely than non-threatened taxa to be exposed or sensitive to climate change, or both, a substantial proportion was neither.

A key action that needs to be undertaken immediately is fine scale modelling of regions identified as having numerous highly exposed bird taxa, in order to identify climatic refugia within the landscape. Such refugia can then be secured and managed appropriately for the future. The most urgent ongoing action is monitoring, with support for the Atlas of Australian Birds seen as a particularly cost-effective investment. In the future, the most expensive actions will be management of refugia, and captive breeding should all other approaches to conservation in the wild fail. However, most of those for which captive breeding is recommended as a last resort are subspecies of species that are widespread, either in Australia or in New Guinea.

For *in situ* management, the most important actions will be those that are already important – fire management, weed and feral animal control and, for marine taxa, controls on fishing. A small number of species-specific actions are suggested, and there appears to be no urgent requirement for corridors for the maintenance of taxa likely to be threatened with extinction – those few taxa not already living in areas where there are likely to be refugia will require assistance to colonise new climate space.

The cost of management over the next 50 years for persistence in the face of climate change of the 396 bird taxa that are very highly exposed, sensitive or both is

estimated at $18.8 million per year – $47,700 per year for each taxon. The biggest ongoing costs are monitoring and direct species management but refugia management and captive breeding may eventually be needed, and will be much more expensive.

EXECUTIVE SUMMARY

All Australian bird taxa were assessed for their vulnerability to climate change employing the risk model that vulnerability arises from a combination of sensitivity and exposure. We concentrate on identifying those taxa for whom climate change poses a risk of extinction.

Sensitivity to climate change was assessed using seven metrics representing specialisation (food types, feeding habitats, foraging substrates, climate specialisation and relative brain size), reproductive capacity (maximum annual rate of reproduction) and genetic variability (population size). Collectively, these directly or indirectly represent intrinsic traits that are related to the capacity to adapt to climate change. Marine birds were most likely to be sensitive to climate change, followed by those from small islands. Those from mangroves and inland waters had the lowest scores against the sensitivity metrics used.

Over 16.5 million bird location records of 1232 ultrataxa were analysed to assess the probable exposure of Australian bird taxa to climate change. For taxa of terrestrial environments and inland waters, 18 climate models were used to identify the median area of climate space suitable for each taxon in 2085 based on the assumption that current rates of greenhouse gas emissions will continue unabated. For marine taxa, the proxy for exposure used was the projected change in primary productivity in seas within 200 NM of their breeding colonies (i.e. the limits of the Australian Fishing Zone). In the absence of climate models, it was assumed that islands in waters where marine productivity declines may also suffer from an altered climate. The exposure of coastal and mangrove taxa was assessed subjectively based on projections for sea level rise.

Among terrestrial and inland waters bird taxa, exposure is likely to be greatest for taxa confined to Cape York Peninsula, the Wet Tropics, the Top End of the Northern Territory (particularly the Tiwi Islands), the central and southern arid zone, southern South Australia (particularly Kangaroo Island) and King Island. In addition, 61 terrestrial taxa were assessed as being exposed to the effects of projected increases in the intensity and frequency of fires. For marine taxa, projected productivity declines are greatest off eastern Australia, including around Norfolk and Lord Howe Islands, and around the Houtman Abrolhos in south-western Australia. A small number of beach-nesting and saltmarsh taxa are likely to be exposed to sea-level rise. While threatened birds were more likely to be exposed, sensitive or both, many were not and many non-threatened taxa had high scores for exposure and sensitivity metrics.

Modelling of refugia and a continuation of species management are the principal actions recommended for immediate implementation. In the future, refugia management and captive breeding are likely to dominate budgets for climate change adaptation. By far the most important actions are to continue to manage the current stressors to birds including fire, feral herbivores and predators, weeds and fishing, as these are likely to interact synergistically with climate change. Land clearance or fragmentation did not feature among the threats to Australian birds under climate

change in the near future. Similarly corridors, land purchase or habitat restoration had low priority for the most exposed or sensitive taxa.

The total cost over a 50-year period, without imposing a future discount rate or calculating net present value, is estimated to be $945 million – $2.4 million for each of the 396 bird taxa that are very highly exposed (177), sensitive (151) or both (68). This amounts to $19.8 million per year – $47,700 per taxon.

1. OBJECTIVES OF THE RESEARCH

This project aims to identify adaptation strategies for Australian birds based on modelling, building on a current review of the status of Australian birds.

No continent has yet devised a climate adaptation plan for an entire fauna group. Here we aim to combine sophisticated modelling with an understanding of the biology of each bird species to identify how birds will be affected by climate change, highlighting the species and species groups most likely to be affected. Data from the recent review of threatened Australian birds (Garnett *et al.* 2011) also allows assessment of the cost of management actions. The adaptation plan then applies strategies developed by the NCCARF Terrestrial Biodiversity Network (Shoo *et al*. in press) and others to create a model template on which other adaptation plans can build. Collaboration with BirdLife International has ensured that international adaptation innovations are also included.

Apart from this report the project has also drafted a “Climate change adaptation action plan for Australian birds” that identifies and prioritises birds that require adaptation strategies and where and when to implement these to maximize positive outcomes. This plan will allow government, land managers and conservation organisations to target investment effectively and protect Australian birds now and into the future. It also includes greater discussion about the issues involved in assessing vulnerability to climate change.

The project has objectives in each of the following areas:

Adaptation of existing conservation goals: the project has assessed the conservation goals identified in the 2010 review of threatened Australian birds (Garnett *et al.* 2011) as well as identifying goals for those that may be threatened by climate change. Spatial analysis has been used to help identify geographical synergies in adaptation strategies that can be adopted as well as enable prioritization between goals in terms of urgency.

Landscape design, refugia and multi-use landscapes: the project has assessed the nature of the landscapes required by each threatened or potentially threatened bird species, highlighting those for which climate-induced landscape deficiencies may become a threat. Modelling as well as knowledge of the habitat needs and dispersal characteristics of each bird species is used to help identify which landscapes are in greatest need of active management for climate change.

Interaction with other key stressors: the project has assessed ways in which threats identified by a review of threatened Australian birds could be affected by climate change, and identified potential management strategies. This has been done spatially across multiple species allowing identification of threat overlaps and adaptation synergies that will lead to improved efficiencies in delivery of adaptation strategies as well as prioritisation.

The overall aim has been to provide a product, in the Adaptation Plan, that will be used by conservation practitioners to assist with management of climate change on the ground. The dataset itself should be an important tool for policy-makers needing an overview of the total investment needed for adaptation and the savings that can be made through integration across taxa and within landscapes.

2. RESEARCH ACTIVITIES AND METHODS

2.1 Selection of taxa needing adaptation strategies

2.1.1 Scope

This plan aims to understand the vulnerability of all Australian species and subspecies of birds that are resident in Australia or visit on migration to climate change and develop tailored adaptation strategies for those most at risk.

2.1.2 Geographic range

This plan covers all of Australia and associated islands on the continental shelf as far north as Boigu and Saibai Islands in Torres Strait, the offshore Commonwealth territories of Christmas Island, Cocos (Keeling) Islands, Heard Island and Norfolk Island, as well as Macquarie Island, which is administered by Tasmania, and Lord Howe island, administered by New South Wales. It also includes all seas out to the edge of the Australian Fishing Zone, which is 200 nautical miles except along the border with Papua New Guinea and Indonesia.

2.1.3 Taxonomy

The taxa considered in this adaptation plan include all species and subspecies breeding in Australia or for which >100 individuals are likely to visit Australian territory, including oceanic territories, in a year. This includes 708 species, 926 subspecies, and a total of 1,237 ultrataxa (subspecies plus species which have only one subspecies). Use of ultrataxa means that any record classified using this list can readily be converted to any other taxonomy.

Families and genera, and the order in which they are listed, follow Christidis and Boles (2008). Species follow BirdLife International (BirdLife International 2012) so that assessments in the Adaptation Plan are comparable with international assessments. This affects the albatrosses in particular, but also a small number of other taxa, as noted in the text. At the subspecies level the standard used is the Handbook of Australian, New Zealand and Antarctic Birds (Marchant and Higgins 1990, 1993; Higgins and Davies 1996; Higgins 1999; Higgins *et al*. 2001; Higgins and Peter 2002; Higgins *et al*. 2006a, 2006b, based on Schodde and Mason 1997, 1999) unless otherwise specified. In recent years a number of studies have failed to detect genetic variation between subspecies. We adopt the conservative precautionary view that, while genetic studies can detect differences between populations, some of which may not readily be apparent in the phenotype, a failure to detect variation may reflect incomplete sampling of the genome. The subspecies are presented in alphabetical order.

2.1.4 Habitat groups

Because the effects of climate change are going to vary geographically and the nature of models needed to predict change differs between the marine and terrestrial biospheres, it was necessary to divide taxa into one of six categories. For birds that crossed categories, the habitat used most, or likely to be critical in the face of climate change, was selected. The habitat groups and how they are considered in the adaptation plan are listed below (Table 1).

2.1.4.1 Terrestrial and Inland waters

Most birds occur primarily on either the mainland of Australia or on the larger offshore islands (Tasmania, Tiwi Islands, Kangaroo Island). For these areas regionalisation of GCMs was possible (see below), allowing projections of the extent to which the current climate experienced by a taxon is still likely to be present in the future, where those climatically suitable areas are likely to occur in the wider landscape and the breadth of the current climates experienced by the taxon compared to those that are potentially available across the entire country. For most birds the breeding and non-breeding ranges largely or entirely overlap. Some, however, migrate. Where the non-breeding range differs from the breeding range, the two ranges are considered separately, although adaptation recommendations are developed for the taxon as a whole. Where either the breeding or non-breeding range is outside Australia, however, only the Australian component of the range is considered here.

2.1.4.2 Coastal (intertidal) and Mangroves

The Intertidal group includes all taxa that obtain most of their food in the intertidal zone while in Australia. Most are migratory shorebirds that use quite different habitats while breeding, principally freshwater wetlands or grasslands. Others are Australian species that feed intertidally then nest near the sea. A subset of these is the guild of taxa that live most of their lives within mangroves, nesting in the trees and feeding either in the trees or from the mud at low tide. Because maritime and terrestrial climates interact along the coast, models that predict climate impacts on terrestrial or maritime domains alone are unable to account for the interaction between land and sea on temperature and rainfall. Therefore the impact of climate change on these two groups is assessed separately to the other groups.

2.1.4.3 Small island

Small island species are terrestrial or inland waters taxa that have either colonised oceanic islands or were marooned on continental islands as sea levels rose over the 12,000 year period after 20,000 BP (Alley *et al* 2005). All subspecies on islands are part of widespread species but all the oceanic islands except Norfolk, Lord Howe and Christmas Island also have endemic species not found elsewhere. As with intertidal and mangrove taxa, no regional models have been developed that can predict the extent of climatic change at the scale of these islands. However, unlike with the coastal zone, a much stronger influence of the maritime climate can be expected and, because all are relatively high, sea level rise will have less impact. Therefore exposure to birds on these islands is assessed separately.

2.1.4.4 Marine

Marine taxa are those that obtain their food primarily from the sea. Most breed on small islands where they are protected from most terrestrial predators, though some will also breed on the mainland. A number of marine species currently visit Australian seas from distant breeding sites so that conservation management of these species for Australia is confined to the marine domain. For such species models of climate at the breeding sites are lacking, because they are either coastal or on small islands, but there are global models describing changes in the marine habitat that can be adapted to provide some measure of exposure (see below).

Table 1. The number of Australian bird taxa in each habitat class for which climate change adaptation was considered

Habitat class	Breeding status	Species	Subspecies	Ultrataxa
Terrestrial	Breeding and non-breeding	449	713	882
	Breeding only	3	6	6
	Non-breeding only	8	7	10
Inland waters	Breeding and non-breeding	71	41	81
	Non-breeding only	11	2	11
Coastal	Breeding and non-breeding	7	7	9
	Non-breeding only	21	11	24
Mangrove	Breeding and non-breeding	21	50	54
Small island	Breeding and non-breeding	12	28	34
Marine	Breeding and non-breeding	60	42	68
	Breeding only	9	5	12
	Non-breeding only	34	14	41
Total	Breeding and non-breeding	620	881	1,128
	Breeding only	12	11	18
	Non-breeding only	74	34	86
Grand total		706	926	1,232

2.2 Exposure and Sensitivity

To be vulnerable to climate change, a species must be both *exposed* to change and *sensitive* to that exposure (Foden *et al.* 2008; Williams *et al.* 2008; Dawson *et al.* 2011). Exposure “refers to the extent of climate change likely to be experienced by a species” (Dawson *et al.* 2011). Sensitivity may be understood as species-specific properties that modify the potential impact experienced from exposure (*sensu* Williams *et al.* 2008). Some treat adaptability separately to sensitivity (e.g. Chin *et al.* 2010; Summers *et al.* 2012) but here we include it as the opposite end of sensitivity continuum because the relevant traits are so often the same. To identify taxa most in need of adaptation planning we assessed exposure and sensitivity independently.

2.2.1 Exposure

2.2.1.1 Data sets

2.2.1.1.1 Assembly of data

Locational data was obtained by BirdLife Australia, component databases of the Atlas of Living Australia and many other sources. Records were consolidated into unique points at a grid size of 2 km x 2 km. For continental terrestrial and inland waters taxa these data were used to create climate space models based on a presence-only species distribution modelling method that assumes that information about where a species occurs provides useful information about the environmental limits of that species. For marine taxa they were used to define breeding ranges (in conjunction with other published data).

2.2.1.1.2 Vetting of data

As these data were largely collected opportunistically (data collected for other reasons than species distribution modelling) and brought together from disparate sources, it often included errors. The raw observations were therefore validated (cleaned and corrected), first for taxonomic accuracy and then for positional accuracy. Records were validated by creating polygons encompassing the breeding and non-breeding ranges of species and subspecies. Polygons were created using a three step process.

1. A minimum convex polygon was created that encompassed all records.
2. Polygons were then matched against existing distribution maps to identify known major gaps in distribution which were then excluded from the polygons.
3. Outliers were queried and assessed as to whether they were
    a. wrong;
    b. vagrants and therefore of little biological significance since they did not represent locations at which the taxon might persist; or
    c. collected at such a coarse scale that the centre point of the grid in which collected fell outside the expert-derived definition of the range.

Any deemed to be in these categories were excluded from the analysis and the polygon redrawn.

2.2.1.1.3 Definition of geographic range for terrestrial and inland waters birds

Geographic range was defined for all continental Australian birds using minimum convex polygons encompassing all valid records. This produced an estimate of the Extent of Occurrence (EOO) which is a commonly used measure of species and subspecies spatial distributions (Gaston 1991; Gaston and Fuller 2009; IUCN 2001). Creation of current range maps followed the steps described above by excluding from the EOO all areas known to be unoccupied. However this was not as constrained as the IUCN Red List Area of Occupancy since it was not confined to all occupied 1 km^2 pixels based on a 4 km^2 grid. For a few taxa historical ranges were used for the purpose of modelling as it was considered that these were more representative of the climates in which taxa were previously capable of existing before extirpation as a result of environmental change since European colonisation. Subspecies’ ranges and hybrid zones (for sympatric and parapatric taxa) were based largely on Schodde and Mason (1997), Schodde and Mason (1999) and Ford (1987a,b). Where an observation occurred in a hybrid zone it was effectively allocated to all taxa occurring in that hybrid zone (most hybrid zones involved two taxa but a small number involved three or four taxa). For 31 taxa both breeding and non-breeding ranges could be modelled separately. For the purpose of modelling, records of irruptive species away from a core range defined by experts were classified as vagrants and not included in models since irruptive species, by definition, do not persist in the habitat to which they irrupt.

2.2.1.2 Models

2.2.1.2.1 Selection of climate scenarios

For this project, we sourced coarse resolution (0.5x0.5 degree or ~50kmx50km) climate projections from Drs Rachel Warren and Jeff Price, Tyndall Centre, University of East Anglia, UK (available at http://climascope.wwfus.org). Here, we specifically accessed 18 General Circulation Models (GCMs) for RCP 8.5 (Appendix 1.1). This is a high emission scenario which we considered justified since climate change is occurring at rates tracking the highest of IPCC emission scenarios (Rahmstorf *et al*. 2007). Representative Concentration Pathways (RCPs; Appendix 1.2) have been adopted by the IPCC to replace the Special Report on Emissions Scenarios (SRES) used in the AR4 report (Solomon *et al*. 2007); RCPs are to be used in the AR5 IPCC report due in 2014. Although new GCM runs for RCPs have not been fully completed, several research groups have implemented methods to utilize knowledge gained from SRES predictions to recreate predictions for the new RCPs using AR4 GCMs (e.g., Meinshausen *et al*. 2011a, Meinshausen *et al*. 2011b, Rogelj *et al*. 2012). The methods used to generate the GCM predictions for the RCP emission scenarios are defined at http://climascope.wwfus.org and in associated publications (e.g., Mitchell and Jones 2005, Warren *et al*. 2008, Meinshausen *et al*. 2011a).

2.2.1.2.2 Downscaling of global models

Monthly data on temperature (min and max) and precipitation were downscaled to 0.05 degrees (~5km resolution) and 0.01 degrees (~1km resolution) using a cubic spline of the anomalies (deviance from modelled current and modelled future); these anomalies were applied to a current climate baseline of 1976 to 2005 – climate average centred on 1990 (Appendix 1.3). The current climate for ~5km data was sourced from the Australia Water Availability Project (AWAP; http://www.bom.gov.au/jsp/awap/) and for ~1km data was sourced from Anuclim v6.1 (McMahon *et al*. 1995). The downscaled monthly temperature and precipitation values were used to create 19 standard bioclimatic variables (Appendix 1.4). All downscaling and bioclimatic variable creation was done using the climates package in R (http://www.r-project.org/; J.VanDerWal unpublished data).

2.2.1.2.3 Climate space and summed suitability

Once vetted, the observation records were used to model the current distributions of the ultrataxa prior to projecting into the future onto the AR5 climate data. Here we used Maxent (Phillips *et al*. 2006) as the presence-only distribution modelling algorithm to correlate information about where a species was actually observed to climatic information. Maxent outperforms other modelling approaches for this type of study (Elith *et al*. 2006, Hernandez *et al*. 2006) and is more capable of dealing with small sample sizes than other modelling methods such as Bioclim, Domain or GARP (Hernandez *et al*. 2006). Geographically unique occurrence data were correlated using Maxent to a taxon-specific target group background as recommended by Phillips and Dudik (2008).The background was created for all represented unique geographic localities for bird observation records. For 59 taxa from topographically diverse areas where climatic gradients are steep (Appendix 2), we used climate data calculated for grids at a scale of ~1 km. For all other species we used a climate grid scale of ~5 km. Species were only modelled across continental Australia, Tasmania, the Tiwi Islands and Kangaroo Island. The models were run 11 times; a 10-fold cross-validation for model accuracy statistics was followed by the final model that used all observations of a species. Models were then projected onto the spatial layers representing continental Australia for current and future climates. The models produce a continuous measure of environmental suitability from 0 to 1; not all of this is suitable for the species and thus a threshold was selected that identified the minimum level of environmental suitability in which the species would survive. The method used to select this threshold was one that equates the entropy of the thresholded and original distributions to assess binary presence/absence of suitable climate. This threshold was used as it was assess to best reflect an environmental suitability limit that was within known ranges of the species. For broad ranging species (i.e., species whose distributions were greater than ~80% of the continent), this threshold was divided by two so that the range was more inclusive. This was done to account for biases in model accuracy and threshold values for broad-ranged species using presence-only climate envelope models (Lobo *et al.* 2008; VanDerWal *et al.* 2009).

Realised distributions are often much smaller than what has been modelled – modelled distributions include all potentially suitable climate for a species. In other cases realised distributions were larger than predicted by the models, or a combination of the two – the modelled climate space extended beyond the boundaries of the realised distribution in some areas but other parts of the realised distribution were predicted as having very low suitability or being below the lowest suitability threshold (Figure 1). Where modelled distributions are larger than the realised distribution it may be because they are potential distributions of species that have not taken into account biotic interactions, dispersal limitations, biogeographic barriers both now and over the habitat fluctuations of the Quaternary or other factors. Where it is the reverse it may be that the areas predicted to have low or no suitability are occupied only by transient or dispersing individuals or that they are only fleetingly suitable, allowing birds to occupy them temporarily or tenuously. Despite corrections, models can also be biased towards areas with the highest density of observations while definitions of the limits to climatic suitability are particularly influential at the boundaries of modelled distributions. All model summaries and statistics were calculated on both potential and realised distributions whereby the realised distributions were the suitable climate within the observation vetting polygons. All model summaries and statistics were done using the SDMTools package in R (http://www.r-project.org/; J.VanDerWal unpublished data).

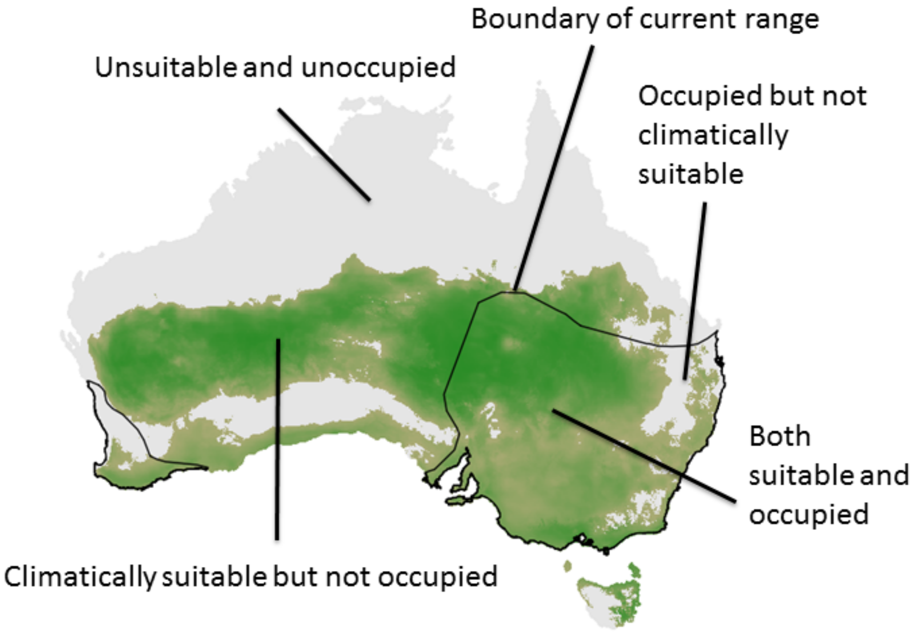

Figure 1. Diagrammatic representation of the relationships between modelled climate space and realised distribution.

In addition, for each modelled distribution, a climate suitability score was calculated for each grid cell by comparing the climate metrics of each cell with those of cells with the highest density of records. The score for each cell is thus a proportion with zero being completely dissimilar and 1.0 being the 90% of cells with the highest density of records. These scores were then summed to calculate a total suitability score for a taxon. For some taxa the summed suitability score is proportional to the population of that taxon (VanDer Wal *et al.* 2009) so that changes in summed suitability represent a change in population size.

From these data it was possible to calculate the following statistics as measures of exposure to shifts in climate space.

i. the area of modelled climate space or summed suitability currently inside the current range – this is the area known to be occupied currently by the taxon and modelled as having a climate that exceeds suitability thresholds
ii. the area of modelled climate space or summed suitability currently outside the current range – this is the area which is currently unoccupied by the taxon but, for a variety of reasons, may not be. The ratio of inside to outside provides a crude correlative measure of the extent to which climate is influencing the current distribution, i.e. the higher the ratio, the greater the influence.
iii. % of the climate space or summed suitability predicted to remain inside the current range in 2085 under RCP 8.5 (i.e. the current rates of emission remaining unchanged) – this represents the extent to which the climate, or the suitability of the climate, changes within the current range. The median score for the 18 GCMs was chosen for calculating exposure, with the 10th and 90th percentile giving a measure of uncertainty around models. A very low percentage indicates that the climate is predicted to become largely unsuitable by 2085.
iv. % of the current climate space or summed suitability predicted to occur outside the current range in 2085 under RCP 8.5 compared to that currently inside the current range – this is a measure of the area of suitable climate into which a taxon could move in 2085, all else being equal. However such areas may be isolated from the current range or may already be climatically suitable but are unoccupied for a variety of reasons, many of which are likely to remain in 2085.

Metrics iii and iv were then translated into a comparative measure of exposure (Table 2). These are arbitrary but are designed to provide an indicative measure of exposure that can be refined with greater knowledge of the relationship between exposure and vulnerability. Given that some areas outside the range may already be considered suitable but are unoccupied, we considered loss of climate space within a taxon's current range as potentially being more threatening than loss outside. Overall we have been very conservative about assessing which taxa are very highly exposed because of the uncertainty around model predictions. Taxa for which the median scores met the criteria for very highly exposed were considered for the development of adaptation strategies.

Table 2. Categories of exposure calculated from the percentage of climate space predicted to be inside or outside each taxon's current range in 2085 based on current rates of greenhouse gas emission.

	% Inside			
% Outside	0	1-10	11-20	>20
0	Very high	Very high	High	Low
1-10	Very high	Very high	High	Low
11-20	Very high	High	Medium	Low
>20	High	High	Medium	Low

2.2.1.3 Non-modelled exposure

2.2.1.3.1 Sea-level rise

The effect of sea-level rise on coastal habitats is complex, with modelling requiring very high-resolution digital elevation data along with detailed local knowledge of coastal geomorphology, coastal vegetation, coastal built structures and adjacent land uses, a level of detail that is not available at a national scale. Each bird taxon was therefore assessed subjectively against their reliance on coastal habitats, assuming that sea level is likely to rise by up to a metre in the next century (Church and White 2011). Assessments were based on the extent to which natural adaptation to geomorphological processes that have been occurring for millennia, such as rapid sea level rise (Stanford *et al*. 2006) and higher sea levels than today (Kopp *et a.* 2009; Lewis *et al.* in press), are thought likely to interact with human impacts in Australia that are likely to disrupt that adaptation, like coastal development and increased nest failure rates because of introduced predators. Taxa for which this is occurring were considered very highly exposed; all others were considered to have low exposure.

2.2.1.3.2 Marine environments

The exposure of Australian marine birds to climate change has been reviewed recently by Chambers *et al.* (2011). They note that the effects of climatic variation on top marine predators are poorly known. However, because most seabirds are apex predators, they may be particularly sensitive to changes in climatic and oceanic dynamics, with reduced breeding success and altered timing of breeding. Not all Australian seabirds are affected similarly, with responses varying among species and locations. In addition, the paucity of information on the distribution and biology of seabird prey, foraging patterns and movements of seabirds, and the ability of seabirds to switch between prey species or adjust timing of life-cycles make generalisations about potential effects of future climate change and adaptive capacity in seabirds difficult. This applies both within Australia and elsewhere, where data are similarly sparse. Here we have based exposure on modelled changes in productivity (Steinacher *et al.* 2010), while recognising that the capacity of seabirds to obtain sufficient food is based on the interaction between marine productivity and other mobile and fixed oceanographic features, such as currents, thermoclines and sea mounts, the interactions between their prey and other fish species etc.

Marine taxa were divided into two categories – near shore and distant feeders with 200 nautical miles (370 km) selected as an arbitrary cutoff between the two as this is the limit of the Australian fishing zone and hence the limit over which Australian authorities have direct jurisdiction for the imposition of mitigation strategies. For some seabirds, such as petrels (Baduini and Hyrenbach 2003), the 200 NM limit may be a realistic reflection of a feeding strategy whereby relatively short chick-provisioning flights are interspersed with much longer flights during which the adult replenishes its reserves. Other seabirds, such as many albatrosses, often fly much greater distances while many coastal species feed much closer to breeding colonies. The coarseness of the modelling data precluded finer scale specification with changes in near coastal productivity in particular being likely to vary greatly from the predictions of global marine models.

Current productivity, projected change to it to 2100, and productivity in 2100 was assessed for a 200 NM radius of each breeding site for each taxon based on maps of current productivity and projected change to it in Steinacher *et al*. (2010). Productivity in 2100 was estimated by summing current and projected change for each relevant pixel. Two metrics were calculated for each taxon: the mean change per pixel (±standard error) and the change in the maximum assuming that many seabirds will concentrate feeding within the areas of maximum available productivity. Predicted productivity declines of ≥10% were considered very highly exposed, of 5-9% highly exposed, 1-4% a medium level of exposure and ≤0% a low level of exposure.

2.2.1.3.3 Fire

Changes to the frequency and intensity of fire will be influenced by changes in a range of climate parameters (e.g. rainfall, temperature and wind speed), by the response of fuels present in differing vegetation types to rainfall and drought (Bradstock 2010; O'Donnell *et al*. 2011), and by management (Williams & Bowman 2012). The different climate parameters may influence the growth and drying of vegetation (Bradstock 2010), in turn influencing fire regimes which are critical for a number of Australian bird species (Woinarski & Recher 1997; Garnett *et al*. 2011). Ecosystems in southern Australia in particular, where the fuel includes substantial live woody plant material, can expect increases in the frequency, intensity and areal extent of wildfires with warmer and drier conditions (Bradstock 2010). This generates serious exposure for specialist old-growth inhabitants of these environments such as scrub-birds *Atrichornis* spp., bristlebirds *Dasyornis* spp., the Ground Parrots *Pezoporus* spp., Malleefowl *Leipoa ocellata* and Black-eared Miner *Manorina melanotis*. The outlook for hummock grasslands dominated by *Triodia* spp. is less certain and likely to vary across the continent with different climates, patterns of climate change, and associated fuels. Fire frequency may decrease in central Australia (King *et al.* 2013), but is likely to increase in southern areas where hummock grasses occur interspersed with shrubs (e.g. in mallee and mallee heathland).*et al*. Any resultant exposure is of concern for old-growth spinifex specialists such as most members of the genera grasswrens *Amytornis* spp. and emu-wrens *Stipiturus* spp., and especially for the Mallee Emu-wren *Stipiturus mallee*.

Some breeding colonies of marine birds may also be exposed to an increase in fire frequencies (Chambers *et al.* 2011). Fire sensitivity was determined on the basis of published information on each species.

2.2.2 Sensitivity

Treatment of sensitivity was structured around three processes: Specialisation, Low genetic diversity and Slow life history (Table 3). Metrics used to quantify each trait are described below along with aggregation methods. Dispersal ability is not used as a predictive trait since exposure modelling allows an assessment of the likely requirements for movement by each species, from which it is possible to calculate whether movement is likely to be achieved with or without assistance.

All metrics have been scaled from 0 to 1 where 0 = not or least sensitive and 1 = highly or most sensitive. ENFA specialisation scores were log-transformed because of an extreme skew, with the lower 50% of taxa scoring between 0.38 and 1.58, the lower 90% below 6.56 but 17 scoring >100 to a maximum of 384. Scaling is unavoidably arbitrary because experimental data are unavailable but reflects discussion among team members about the relevant weighting of levels for each metric, and the contraction of high values so that scaling was not structured by a few outliers and a moderate number of taxa were rated as having either the minimum or maximum for each metric under consideration.

Table 3. Sensitivity metrics: source, form and scaling.

Metric	Data source	Data form and type	Scaling of sensitivity
#habitats	HANZAB*	31 categories (13 terrestrial, 6 inland waters, 6 coastal, 6 marine)	0 = >3 habitats 0.33 = 3 habitats 0.67 = 2 habitats 1 = 1 habitat
#food types	HANZAB*	10 categories	0 = >3 food types 0.33 = 3 food types 0.67 = 2 food types 1 = 1 food type
#foraging substrates	HANZAB*	9 categories	0 = 4 or 5 substrates 0.33 = 3 substrates 0.67 = 2 substrates 1 = 1 substrate
ENFA** climate specialisation (Hirzel *et al.* 2002)	Distributional and climatic data collated for exposure analysis	Continuous: taxa with small climatic ranges have high ENFA specialisation scores	$\log_{10}$-transformed. Re-scaled from min.(0.142) – 1 to 0 – 1; taxa with $\log_{10}$ (ENFA) > 1 scored

Metric	Data source	Data form and type	Scaling of sensitivity
			as 1.
Relative brain size (RBS)	Andrew Iwaniuk: brain volume (ml) for 519 Australian bird species, converted to brain mass (g) using constant 1.036 (refs in Sol *et al.* 2005)	Continuous: RBS calc'd as residuals from $\log_{10}$-$\log_{10}$ regression on body mass; extrapolated to missing taxa using mean of nearest relatives	re-scaled from min.–max. to 0 to 1 and inverted so that: 0 = largest RBS 1 = smallest RBS
Population size (2 x no. of adults of limiting sex; approximates *effective population size*)	Garnett *et al.* (2011) and miscellaneous sources	Continuous for most small populations; mostly categoric (10,000+) for remainder	0 = 10,000+ 0.2 = 2,500 – <10,000 0.4 = 1,000 – <2,500 0.6 = 250 – <1,000 0.8 = 50 – <250 1 = <50
Annual r_{max}***	HANZAB* and Beruldsen (2004)	Continuous: max. clutch size by max. no. of broods per year****	0 = 11+ 0.2 = 6 – 10 0.4 = 3 – 5 0.6 = 2 0.8 = 1 1 = <1

* HANZAB = *Handbook of Australian, New Zealand & Antarctic Birds* (Marchant and Higgins 1990, 1993; Higgins and Davies 1996; Higgins 1999; Higgins *et al.* 2001; Higgins and Peter 2002; Higgins *et al.* 2006a, b) unless new data available.

** ENFA = Ecological Niche Factor Analysis.

*** Annual r_{max} = the maximum number of young that can be raised in a year.

**** assumed to be two broods per year where a taxon is known to be at least occasionally multi-brooded but no quantitative data are available; annual r_{max} for parasitic cuckoos was assumed to be 5–10.

2.2.2.1 Specialisation

In a recent comprehensive review of the relationship between specialisation and climate change, Devictor *et al.* (2010) proposed that the realised niche can be quantified using diversity indices such as of habitat classes. We measure habitat specialisation among Australian birds in three dimensions:

1. number of habitat types
2. number of foraging substrate types
3. number of food types

We conducted Ecological Niche Factor Analysis (Hirzel *et al.* 2002) for terrestrial and inland waters taxa whereby climate parameters are weighted by the climate envelope model for that taxon with the national standard deviation for those parameter weights compared with the taxon standard deviation. Taxa with small climatic ranges have high scores.

We also include a measure of relative brain size since birds with larger relative brain size are demonstrably better able to adapt to change (Sol *et al.* 2002, 2005, 2007, 2008; Schuk-Paim *et al.* 2008; Vall-llosera & Sol 2009; Carrete & Tella 2011; Maklakov *et al.* 2011; Moussus *et al.* 2011; Reif *et al.* 2011).

2.2.2.2 Low genetic diversity

While the link between genetic diversity and evolutionary potential remains unproven, small populations are less likely to be able to adapt to change and very small populations, particularly of species that were once numerous, are likely to suffer from inbreeding depression (Jamieson & Allendorf 2012). Very small populations are also prone to extinction induced by random demographic and environmental events and the Allee effect in which the reproductive rate diminishes as the population declines. Random environmental events more likely to occur as a result of climate change are droughts, heat waves, wildfire, severe tropical cyclones and other extreme or unusual weather events. Estimates have been made of the population size of most rare (and thus threatened) Australian bird taxa (Garnett *et al.* 2011). We have made estimates for the population size of any others that we think likely to have fewer than 10,000 mature individuals.

2.2.2.3 Slow life history

The ability to colonise new areas, to recover from climate-induced population shocks, to avoid loss of allelic diversity, inbreeding and demographic stochasticity, is directly related to fecundity. In birds low fecundity is associated to a high extinction risk (Lee & Jetz 2011) and high fecundity with successful colonisation (Duncan *et al.* 1999, 2001), a process with clear parallels to the ability to colonise shifting habitat and exploit new opportunities. While avian clutch size has been employed as a proxy for fecundity in many studies (e.g. Duncan *et al.* 1999; Angert *et al.* 2011; Lee & Jetz 2011), many Australian species have small clutches but are multi-brooded (Yom-Tov 1987; Rowley & Russell 1991). We have therefore used the number of young a female can potentially raise in a year in good conditions, annual r_{max},, as an index of fecundity.

2.2.2.4 Aggregation of data types

Three data types for the sensitivity analyses are categorical and four are continuous. Categories were summed and converted to ordinal data. One continuous data source (relative brain size) was retained in fully quantitative form, one in semi-quantitative form (ENFA climate specialisation), and the remaining two converted to ordinal classes. All were scaled from 0 to 1 where 0 = not or least sensitive and 1 = highly or most sensitive. Multicollinearity among sensitivity metrics was tested and found to be relatively low. The five specialisation metrics were aggregated into a specialisation measure, then three measures (specialisation, genetic diversity and life history) into an overall measure of sensitivity. Each metric was weighted and measured equally *a* *priori* at each step. Specialisation and life history measures were then re-scaled from 0 to 1 before a second aggregation was undertaken. Aggregation was undertaken by taking the Euclidean distance from the origin:

$S = (x^2 + y^2 \ldots n^2)^{1/n}$

where S = the sensitive measure, the metrics are x, y ... n and *n* is the number of metrics.

This aggregation method emphasizes and thus weights high scores for any one metric, thus emphasising features of high sensitivity.

2.2.2.5 Categorization

Terrestrial and inland waters taxa, for which Ecological Niche Factor Analysis (ENFA) specialisation (climate specialisation) was available, were ranked from 1 to 1,230 with 1 being the taxon having the highest aggregated sensitivity score. The 100 most sensitive taxa were then arbitrarily allocated to the category “very highly sensitive”, the next 100 to “high”, the next 100 to “medium” and the remaining 1018 as “low”. All 1,658 taxa, including the marine, coastal, small island and mangrove taxa, were then ranked based on their aggregated scores but without considering the ENFA metric. Any marine, coastal, small island or mangrove taxa that had an aggregated sensitivity score higher than the 100th ranked terrestrial or inland waters taxon was categorised as “very highly sensitive” inland waters

2.3 Adaptation strategies

Management actions to deal with the consequences of climate change are often collectively referred to as “adaptation strategies” (Smithers and Smit 1997). This reflects a key reality that the goals of management need to be re-set to incorporate climate change, as a failure to do so will very likely ultimately lead to failure (Lawler *et al.* 2010).

For wildlife managers, developing strategies that incorporate climate change presents multiple challenges, particularly the great uncertainty about how the environment will respond. Possible management responses to ecological uncertainty include focussing on actions that are most robust to the state of our knowledge and thus inherently less risky (Groves *et al.* 2012), on actions commensurate with the risk to the taxon, and on actions that do not require detailed local projections of climate change and its impacts (Cross *et al.* 2012). For example, assisted colonisation is generally inherently more risky than improving the quality of existing habitat but may become necessary in more extreme cases of climate change stress (Morecroft *et al.* 2012). Cross *et al.* (2012) offer a flow-chart for making management decisions. Where detailed climate change projections are available, these may usefully be represented for incorporation into simple heuristic models of management (e.g. Lawler *et al.* 2010). More quantitative approaches to dealing with uncertainty of costs and benefits of management actions are also available (e.g. Conroy *et al.* 2011, 2012).

In conceptual terms, the goals of conservation management under climate change may be three-fold: to avoid the impacts of climate change (*resistance*), to promote *resilience* to those impacts, or to facilitate *response* to novel situations (Table 4).

Many management strategies are now pitched in terms of these three concepts (e.g. Millar *et al.* 2007; Galatowitsch *et al.* 2009; Prober *et al.* 2012).

Table 4. Conceptual approaches to the management of wildlife in the face of climate change (modified from Millar *et al.* 2007 and CCWAPWG 2009).

Management goals	Explanation and example
Promote *resistance*	Actively manage to maintain the *status quo*, or to a previous more desirable state, and forestall impacts of climate change - control competitive invasive species (could involve controlling climate change refugees) - revegetate to historical habitat states
Promote *resilience*	Improve the capacity of populations to recover from disturbance - ensure reserves contain viable populations able to recover after drought, wildfire or cyclone - create or maintain corridors between similar environments
Facilitate *response*	Enable transition to new conditions - create or maintain corridors between contrasting environments - assist migration so that species can track shifting climate envelopes - enhance climate-adaptedness of population gene pool with stock from other climate zones - create or modify habitat to suit changed climatic conditions - allow fire regimes to trigger vegetation change appropriate to the new climate

Biodiversity management commonly occurs at the level of landscapes, ecosystems or protected areas, and manipulation of habitat is rarely undertaken with the interests of just a single species in mind. Yet habitat issues remain at the core of both biodiversity and species management (Table 5). Response to climate change may at times require an emphasis on ecosystem processes and function rather than species (Cumming and Child 2009; Heller and Zavaleta 2009). For example, a key process for the maintenance and enhancement of ecosystem *resilience* is to ensure functional redundancy in which many species occupy similar and potentially overlapping niches. At a broad level, biodiversity richness alone has important links to ecosystem processes (Cardinale *et al*. 2012, Hooper *et al.* 2012). A forest is more likely to be robust to climate-induced change in insect populations if it contains many rather than just a few insectivores. The pay-off for species management is that diverse ecosystems by definition support more species, and resilient ecosystems provide a greater buffer for populations (Karp *et al.* 2011).

Table 5. Management options for the conservation of birds in a climate-change world (modified extensively from Mawdsley *et al.* 2009; see also Shoo *et al.* in press).

Type of management	**Practical options**
do nothing	–
maintain and enhance habitat	• expand the protected area network • maintain and improve habitat quality • identify, protect and expand refugia • maintain and extend landscape connectivity • create new habitats
facilitate the response of wild populations (intensive species management)	• assist colonisation by translocation • enhance the genetics of subspecies • enhance intrinsic population growth rate and manage other threatening processes, e.g. by predator control, habitat manipulation, captive breeding
preserve populations – the last resort	• save species in captivity • store germplasm
understand what is happening and may happen	• monitor bird populations - general surveys (e.g. Atlas) - targeted species-specific monitoring - monitor habitats and threatening processes • investigate the ecology of species and communities • model habitat and climate envelopes in more detail • model management options

A key decision to be made in the management of species is whether it is possible and appropriate to manage them where they are, including where they might move too without assistance (*in situ*), whether it is necessary or desirable to manage them somewhere in the wild where they do not occur (assisted colonisation) or, should extinction in the wild be deemed inevitable, whether *ex situ* management such as captive breeding is necessary, desirable and possible. The answers to these questions may change over time, and a species management strategy may involve positive answers to more than one of these questions simultaneously. Species may be managed within part of their existing range and some individuals translocated outside their current range. Assisted colonisation may occur within the former or current range. Species may establish in new areas unassisted, raising a different set of management questions. Captive breeding may be employed to assist *in situ* management or migration, in addition to a last resort option.

There is yet another management option – to do nothing. For many species, this may be a realistic and appropriate option, but it can only be appropriate under three conditions:

1. after (at least generic) consideration of the consequences;
2. with on-going monitoring in at least a generic manner, e.g. Bird Atlas (Barrett *et al.* 2003); and
3. the flexibility to recognise and respond to changed circumstances in a timely manner.

Given uncertainty about the response of species to climate change, and in particular the possibility of synergistic effects with other stressors (Brook *et al.* 2008), ecological surprises are inevitable (Doak *et al.* 2008), and if we are to conserve Australia's birds we must be able to both detect and respond to both incremental and abrupt change.

Based on the above, the following adaptation strategies were considered for each of the taxa that were both:

- very highly exposed to
  - a shift in a modelled climate space or climatic suitability
  - sea level rise
  - a reduction in marine productivity near breeding sites (marine species only)
  - increases in fire frequency and/or intensity
- very highly sensitive based on the rankings described above

A narrower range of potential strategies was considered for taxa that were either very highly exposed or very highly sensitive but not both.

2.3.1 In-situ management

2.3.1.1 Expand the protected area network

In the face of climate change, protected areas will play a key role in the maintenance of biodiversity in general (Hannah *et al.* 2007; Monzon *et al.* 2011) and of bird populations in particular (Hole *et al.* 2009; Şekercioğlu *et al.* 2012), this notwithstanding the need for a major shift in thinking about the goals of protected areas to one that takes better account of climate change. The interaction between climate change and fragmentation means that a greater proportion of fragmented landscapes must be set aside for conservation to maintain current levels of biodiversity (see 2.3.1.4 below). A key adaptation strategy will be to retain habitat not just where species are currently but also where they are predicted to move to. Geographic shifts in climate may require the establishment of protected areas in regions where none currently exist (Hole *et al.* 2011). It is even conceivable, and perhaps even likely, that novel habitats may need to be created in areas currently committed to other purposes. Methods for identifying optimal placement of protected areas under climate change have already been developed, some of which include birds among the elements in need of protection (Pyke and Fischer 2005; Carvalho *et al.* 2011; Hole *et al.* 2011; Davison *et al.* 2012).

2.3.1.2 Maintain and improve habitat quality

Because of the synergistic effect of climate change and other stressors, efforts to maintain, restore and improve habitat quality are key to conservation of many species in the face of climate change. Management actions may include a range of traditional methods such as control of weeds and feral animals and management of fire, as well as novel management actions such as the creation of new habitats. Traditional actions need to reflect the realities of climate change. For example, fire management needs explicit biodiversity goals that incorporate both the effect of climate change on fire regimes and the changing needs of biodiversity. These will involve local decisions informed by both local context and wider spatial and temporal priorities (Heller and Zavaleta 2009). Lemieux and Scott (2011) and Prato (2012) provide perspectives on the decision-making process for protected area managers.

2.3.1.3 Identify, protect and expand refuges

Refugia to which species may retreat have facilitated their survival during past climatic changes (Taberlet *et al.* 1998; Tzedakis *et al.* 2002; Byrne 2008; Binney *et al.* 2009; Carnaval *et al.* 2009) and will doubtless again prove critical. They are effective due to the decoupling of the refugial climate from the regional climate, allowing species to persist in an otherwise hostile environment. Crucial properties of refugia include: 1) their ability to protect species from the impact of climate change; 2) their size to account for evolutionary processes and long-term population viability (Ovaskainen 2002); 3) availability (accessibility) to species; and 4) their long-term stability (Jansson 2003; Carnaval *et al.* 2009; Mosblech *et al.* 2011).

Three approaches can be taken to identify refugia. The first is to identify areas that show the greatest buffering from extreme conditions of temperature, water, fire and biotic interactions. Refugia in the face of extreme events include areas that buffer species from cyclones (Murphy and Legge 2007) or heat waves (Welbergen *et al.* 2008). Terrain can help decouple local climates from that experienced by the region by three main mechanisms: cold air drainage, elevation, and slope and aspect effects (Dobrowski 2011). Riparian areas across Australia are particularly important for maintaining a large variety and abundance of wildlife in an otherwise mostly water-limited environment (Williams *et al.* 1994; Bentley and Catterall 1997; Mac Nally *et al.* 2000; Soderquist and Mac Nally 2000; Woinarski *et al.* 2000; Lynch *et al.* 2002; Klein *et al.* 2009); mountainous areas often have higher rainfall, generating local run-off and concentration of water into valleys, as well as providing micro-climates that protect species from high and low temperatures, temperature fluctuations and fire

(Wood *et al.* 2011); rock outcrops are refuges for many species in Australia, providing greater water availability and refuge for fire-sensitive species (Bowman *et al.* 2000; Woinarski *et al.* 2006).

The second approach is to relate species records to climate and environmental data projected onto future climate scenarios (Pearson and Dawson 2003). The advantage of this approach is that perceptions about the importance of the climate of refugia are determined by the needs of species rather than generalised preconceptions. This approach is only as reliable as the species distribution models employed so use of fine-scale environmental variables including topography is essential.

The third approach is to identify past refugia (Eeley *et al.* 1999; Pearson 2006). It has been suggested that areas with the highest level of endemism represent past climatic stability and will change the least with future climate change (Jansson 2003). This approach will be most useful if the threats that drive species into future refugia are the same as in the past, and will also identify refugia that in need of protection.

2.3.1.4 Maintain and extend ecological connectivity

Connectivity describes the structure of landscapes that enable birds and other wildlife including plants to move through them to reach new habitat patches or refugia. Connectivity may be provided by continuous habitat, or as “stepping stones” including scattered trees (Manning *et al.* 2006) and feeding sites for migratory shorebirds that may be separated by thousands of kilometres (Battley *et al.* 2012) with continuous habitat for one species being a barrier for another.

Ecological connectivity serves two climate change adaptation goals (Opdam and Wascher 2004):

- to enhance the *resilience* of populations by the formation of metapopulations (Van Teeffelen *et al.* 2012), and
- to facilitate change in the range of populations in *response* to changed circumstances (Travis 2003).

The first goal may be met by habitat corridors at local scales particularly in fragmented landscapes or where habitat is naturally patchy (Saunders and Hobbs 1991), whereas the latter involves connectivity along ecological gradients often at much larger scales of width and distance. Whilst in some situations connectivity may increase the spread of disease and fire, Reed (2004) found that the value of connections among populations outweighed the risk.

Connectivity along major ecological gradients (Whitten *et al.* 2011) may be addressed by projects such as the Alps to Atherton (Great Eastern Ranges) Initiative (DECC 2007a), the Gondwana Link project in Western Australia (Gondwana Link 2012), the Territory Eco-link project in the Northern Territory (PWCNT 2012), the Trans-Australia Eco-link, an extension of the Territory Eco-link through South Australia to the south coast of the continent (DSEWPC 2012), the Habitat 141° Ocean to Outback project along the border between South Australia, Victoria and New South Wales (Habitat 141° 2012); and by re-establishing altitudinal links in the Wet Tropics of north Queensland.

In practice, management to improve connectivity will be of most value to those species for which the pre-management level of connectivity was marginal (Johst *et al.* 2011) with improving connectivity and assisted colonisation being complementary strategies for the spatial management of birds in the face of climate change.

2.3.1.5 Create new habitats

The need for new habitats under climate change is perhaps most obvious when the climate envelope suitable for a species moves to areas where no suitable habitat currently exists. Given the time lag involved in the creation of habitats such as forest or woodland, the early identification of target species and areas such as undertaken preliminarily in this study, is imperative. A more conceptually challenging context for the creation of new habitats will arise within existing natural areas where, as climate changes, some vegetation will become maladapted and need modification or replacement. The possible facilitation of forest transitions has already been flagged in a forestry context (Millar *et al.* 2007) and similar thinking may also be necessary for biodiversity conservation. Traditional emphases on local provenance will in many climate change circumstances prove less than optimal for biodiversity conservation (Sgro *et al.* 2011), and use of non-local species is an extension of this perspective. Australian perspectives on use of non-local provenance for revegetation in the face of climate change have already emerged (Booth and Williams 2012; Booth *et al.* 2012; Hancock and Hughes 2012).

2.3.2 Assisted colonisation

As climate changes, situations will undoubtedly arise in which the choice for wildlife managers and society is stark: assist colonisation of new locations or lose – or risk losing – a species (or subspecies) (Minteer and Collins 2010; Thomas 2011; Schwartz *et al.* 2012). More subtle, but perhaps equally important situations will arise in which the choice will be between assisted colonisation and loss – or risk of loss – of ecosystem function (Hutton *et al.* 2007; Kreyling *et al.* 2011; Lunt *et al.* 2013). Assisted colonisation (defined broadly to include reintroduction) already plays an important role in the conservation of threatened species in Australia (Short 2009; Sheean *et al.* 2012) and elsewhere, and its application to mitigation of the impacts of climate change on biodiversity is a logical extension of this practice (Thomas 2011). Its potential role in dealing with climate change impacts on taxa is threefold:

- to reduce extinction risk by creating additional populations (the insurance policy);
- to restore populations following catastrophic local events (reintroduction); and
- to facilitate change in the range of populations in *response* to changed circumstances.

Of these, only the third raises new and largely untested challenges because it is more or less unique to climate change mitigation. In Australia, significant legislative and administrative impediments will need to be overcome and cooperation across state boundaries will often be necessary (Burbidge *et al.* 2011).

Notwithstanding, there are substantial ethical and practical concerns with assisted colonisation. While there are risks of assisted colonisation to the source population, the founder individuals and the recipient ecosystem (Schwartz *et al.* 2012), prior evaluation of the risks should also include those of not undertaking the assisted colonisation (Hoegh-Guldberg *et al.* 2008), and of alternatives to assisted colonisation (Loss *et al.* 2011). Assisted colonisation may be of most value for narrow endemics which are generally neither invasive nor highly competitive and therefore unlikely to be problematic (Thomas 2011).

Enhancement of genetic adaptedness of a population by translocation into it of individuals from another population or even subspecies is a special case of assisted colonisation. This raises questions about local adaptation, outbreeding risks and the integrity of subspecies or populations, as well as disease transmission, although these may be tractable (Weeks *et al.* 2011), and numerous potential problems may be avoided or minimised by moderating the rate of genetic influx typically to little more than one genetically-effective individual per generation.

2.3.3 Ex-situ management

2.3.3.1 Save species in captivity

As climate changes become more extreme, some species and many populations will go extinct in the wild even where the resources are available for intensive management. Captive breeding has played a key role in the intensive management in the wild of some threatened species (Butchart *et al.* 2006) but is considered very much an option of last resort among the tools available for conservation biology (Snyder *et al.* 1996). As a response to climate change it is recommended only where no-other option is available and where a taxon is unlikely to persist in the wild.

Where there is a reasonable prospect of either preventing extinction in the wild with captive breeding as a contribution, or of restoring a population to the wild from captivity, a range of management considerations arise. Snyder *et al.* (1996) listed the following challenges: (1) establishing self-sufficient captive populations, (2) poor success in reintroductions, (3) high costs, (4) domestication, (5) pre-emption of other recovery techniques, (6) disease outbreaks, and (7) maintaining administrative continuity. Captive breeding can have profound effects on the fitness of subsequent generations when they are released to the wild (Araki *et al.* 2007). In birds, the expression of phenotypic traits in long-term captive populations are at least as different from their expression in wild populations as the differences between subspecies (Tschirren *et al.* 2009).

Captive breeding is usually expensive (e.g. Restani and Marzluff 2001; Walters *et al.* 2010) though high establishment costs can be amortised across time. Costs may also be mitigated through private breeding, including mixed public/private cooperative strategies (Cannon 1996). The involvement of private individual breeders may allow a much larger effective population size to be maintained, but genetic management is likely to be more difficult (El Alqamy *et al.* 2012). It is envisaged that, if birds are taken into captivity because the climate in the wild is no longer suitable then there will be ethical issues about release of excess breeding stock. Populations will therefore need to be managed to match the capacity of the breeding facilities.

2.3.3.2 Store germplasm

Genome resource banks have long been thought of as the last option for the conservation of biodiversity (Wildt *et al.* 1997) but new technologies for cryogenic storage of avian germplasm (Glover and McGrew 2012) are making the possibility of using germplasm storage a practical option in the future (Wernery *et al.* 2010). While not suggested for any taxa in this plan, the possibility may exist in future as the technologies continue to improve.

2.3.4 Monitoring and research

Understanding existing trends and how they might play out in the future relies on sustained monitoring combined with fine-scale modelling (Morecroft *et al.* 2012). Various frameworks have been developed to help make decisions under uncertainty (Polasky *et al.* 2011) but all are improved on a sound knowledge of states, interactions and trends in the existing system allowing decisions to be based on optimising the resources available (Wintle *et al.* 2011).

2.3.4.1 Monitor bird populations

Monitoring is essential as the basis for action (Lindenmayer *et al.* 2012a,b), particularly for decisions about the timing of action (McDonnell-Madden *et al.* 2012). For birds much can be achieved through continuing engagement of citizen science through the Australian Bird Atlas (Franklin 1999; Blakers *et al.* 1984; Barrett *et al.* 2002, 2003; Joseph *et al.* 2009; Szabo *et al*. 2011). The costs of monitoring can also be reduced by targeting regions where exposure to climate change is expected to be particularly intense, either through dedicated surveys or by encouraging volunteers to search for target taxa in particular regions. For some taxa, however, only dedicated surveys are likely to provide enough data that can be used to detect trends from a climatic background that may not only be changing but is naturally highly variable at inter-annual and inter-decadal scales.

2.3.4.2 Monitor habitats and threatening processes

Ideally any monitoring of individual taxa should be accompanied by or linked to monitoring of both habitat and threats, particularly slow-moving trends that may not be easily reversed and are likely to be exacerbated by climate change (Lindenmayer and Likens 2010). This can be as simple as remote sensing to detect habitat loss (Zerger and McDonald 2012). At other times it will require intense research to detect change in a threatening process as part of adaptive management of a threat. Some monitoring of habitat may detect a threat long before there is any decline in the species (e.g. Manning *et al.* in press), allowing time for prophylactic management.

2.3.4.3 Investigate the ecology of species and communities

Many communities are temporary aggregations of interacting species that may disassemble as the constituent species move along different gradients of change (Gilman *et al.* 2010). The ranges of many species are constrained by biotic interactions (Pigot and Tobias 2013) which are likely to change as membership of communities alters. Thus, there is an imperative to be aware of the nature and trend of interactions among species, not just of trends in populations, their landscapes and their threats, and long-term monitoring of the strength of interactions (e.g. Krebs *et al.* 2001) may provide key information about the likely effects of climate change. The complex nature of interactions means they have great potential to produce ecological surprises.

2.3.4.4 Model habitat and climate envelopes

Modelling to locate microrefugia must be undertaken at a very fine scale, with the modelling taking into account not just the climate of the niches but also the habitat availability (Gillingham *et al.* 2012; Shoo *et al.* 2011). When the locations of potential refugia can be identified in advance of climate change, appropriate land planning and management can be initiated. Fine-scale modelling can also show the extent to which concern for taxa is justified. However such an approach requires much more detailed information on how species use the environment, and how that use is likely to change in response to climate change.

2.4 Costs

Like Joseph *et al.* (2008), we have attempted to use current costs to identify what may be needed over the next 50 years, using the costs as indicative rather than definitive to illustrate the relative expenditure that might be required for the actions that might be required. Unlike Joseph *et al.* (2008), however, we have not applied a future discount rate because there is dispute on the most appropriate rate to apply (Stern 2006; Nordhaus 2007) and minor variations in the rate can cause major discrepancies in the eventual costs.

All costs are in Australian dollars. The methods used to estimates costs of each of the actions described above (except the more extreme forms of *ex situ* conservation) are as follows:

2.4.1 Defined actions

2.4.1.1 Expand the protected area network

Land purchase costs or the cost of developing covenants over private land were estimated very approximately on the basis of local rural real estate values in the regions where land will need to be secured for future use by taxa. There are numerous potential mechanisms for land and sea protection, with the most appropriate protection strategy needing to be tailored for each taxon.

2.4.1.2 Identify, protect and expand refuges

Modelling of terrestrial refuges was estimated for each region as the cost of one technical officer ($60K) for one year. Identification of more mobile marine refugia will require more detailed research, including tracking of individual seabirds. It is assumed that this will cost $150k for a standard PhD plus $50K for satellite tracking. These costs will need to be compared with the greater efficiencies that will be achievable at higher cost from employing professional modellers.

2.4.1.3 Create new habitats

Costs/ha of restoration published for different habitats (e.g. Louis Berger and Associates 1997 for saltmarsh) were used to calculate restoration costs up to an area thought likely to contain a self-sustaining population of the species concerned.

2.4.1.4 Assisted colonisation

Costs of assisted colonisation and of enhancing the genetics of wild populations by adding individuals from another population were estimated separately for each taxon because some taxa have proven track records for reintroduction (e.g. Black-eared Miner *Manorina melanotis*; Clarke *et al*. 2003) and likely to be relatively inexpensive to move to another new site given the skills required are available and the birds breed readily in captivity, while for others it is likely to prove extremely difficult (e.g. Glossy Black-Cockatoo *Calyptorhynchus lathami*; Crowley *et al.* 1995). In each case post-release monitoring costs are included in the total package. Costs also include funds for feasibility studies to ensure not only the practicality of moving to a new site but also that the receiving community fully supports the project (Burbidge *et al.* 2012). Standard costs cover employment of a social scientist plus those of mailouts to members of the receiving community and other interested parties.

2.4.2 On-going actions

2.4.2.1 Maintain and improve habitat quality

Land management was costed as the wages of one person plus on-costs ($60,000) and running costs for field expenses at $40,000 per species. Groups of geographically co-located species were costed in units of $100,000 depending on the area and number of taxa to be managed and the complexity of the human landscape.

2.4.2.2 Species management

Many species already have active conservation programs or are likely to require them. These were mostly standardised to $100,000 each as for habitat management above. Some species management is going to require research. These were generally attributed to a PhD stipend of $150,000 over three years including supervision costs.

2.4.2.3 Captive breeding

To estimate captive breeding costs we sought advice from managers of three captive breeding facilities (Alice Springs Desert Park, Healesville Sanctuary, Priam Australia Pty Ltd) on the costs of establishing and maintaining a facility with 100 pairs of a taxon while maintaining a stud book to ensure genetic variability. On the basis of this we estimated the following costs:

Aviary building costs:	$20,000/breeding unit = $2,000,000 = $40,000 p.a. for 50 yrs
Food and expenses:	$30,000 p.a.
Veterinary:	$10,000 p.a.
Staff x 2	$140,000 p.a. (including on-costs)
TOTAL	$220,000 p.a.

2.4.2.4 Monitoring

Costs of monitoring include the costs of accessing sites, counting birds, data management, analysis and reporting. The estimate for any monitoring program, whether for a single taxon or for multiple taxa from a geographically defined area that could be monitored simultaneously, was standardised at US$30K. Costs were lower where there has historically been a high level of involvement from volunteers or where the monitoring requires very little time or travel. They were higher where time and travel costs are likely to be much greater than for standard monitoring (e.g. remote or marine taxa). The Atlas of Australian Birds had a single cost estimate of $200K to cover coordination of records of multiple taxa provided by volunteers.

2.5 Timing

Some actions must begin immediately; others can be delayed until there is greater certainty about trends. Timing for most taxa was standardised as follows:

2.5.1 Immediate actions

2.5.1.1 Defined actions

2.5.1.1.1 Land purchase

Where there is high certainty about a need to acquire habitat for conservation purposes (e.g. coastal locations where inundation is inevitable), land needs to be acquired now before it is alienated for other purposes even if it is not used for the purpose for which it is acquired until a later date.

2.5.1.1.2 Land and species management

Many aspects of land management need to be undertaken immediately regardless of climate change or taxa will not persist long enough for climate change to affect them. Thus management of existing threats (e.g. Garnett *et al.* 2011) can be seen as an aspect of climate change adaptation because, without it, adaptation will not be possible.

2.5.1.1.3 Surveys

Surveys, which are separate from monitoring, are needed for some little known taxa to create a baseline for subsequent monitoring and action. Surveys required will either count taxa that are already known or are needed to locate populations of species that can then be managed.

2.5.1.1.4 Refugia modelling

Fine-scale modelling to identify refugia at a fine scale is becoming increasingly sophisticated. The earlier probable refugia are identified, the sooner their requirements can be incorporated into land use planning and appropriate management of them be initiated.

2.5.1.1.5 Assisted colonisation

For a few species assisted colonisation is already occurring as part of conservation programs (e.g. Eastern Bristlebird *Dasyornis brachypterus*; Baker 2009). Given this is occurring there is an opportunity to consider immediate adaptation of the assisted colonisation process to incorporate climate change predictions.

2.5.1.2 Ongoing actions

Actions that must continue indefinitely are costed over the full 50 year period under consideration. These should either start immediately or be continued from existing programs

2.5.1.2.1 Monitoring

The sooner monitoring begins the sooner it will be possible to determine when or if action must be taken. Many bird taxa may not need future action so decisions are contingent on there being a solid monitoring baseline that shows trends through a range of recent climatic perturbations so that climate change signals can be detected from the noise. The scale, detail and difficulty of monitoring will need to be determined on a case by case basis. In the current exercise, the level of intensity is reflected in the cost for each taxon.

2.5.1.2.2 Captive breeding

Several Australian bird species already have an insurance population in captivity, have captive populations that are already being employed as part of reintroduction programs, or need to have insurance populations created as soon as possible to prevent extinction. These are, and are likely to be held mostly by zoological institutions, but in some cases may involve private aviculturists. It is assumed that these captive populations will need to be maintained for the next 50 years.

2.5.1.2.3 Species management

Where threatened taxa already have recovery programs and/or management actions identified in the *Action Plan for Australian Birds 2010* (Garnett *et al.* 2011) it is assumed that these will need to be continued, and probably intensified, as climate changes. As the implications of climate change become apparent many of these recovery plans will need to be revised.

2.5.2 Future actions

2.5.2.1 Defined actions

2.5.2.1.1 Assisted colonisation and genetic augmentation

For most taxa assisted colonisation and genetic augmentation are considered to be distant events and the only action postulated is research on their feasibility, with the actual costs being deferred until after the next 50 years have elapsed.

2.5.2.1.2 Establish new habitat

Some new habitat may need to be established in areas that are not yet suitable (e.g. coastal sites awaiting inundation). Establishment is thus a future action. It is assumed that this will happen at some time in the next 50 years.

2.5.2.1.3 Marine refugia modelling

Marine refugia are likely to shift location as marine features that result in patches of high productivity (upwellings, thermoclines etc.) change location. It is assumed that information on their location will be obtained at a time decided from monitoring through detailed research undertaken by PhD students.

2.5.2.2 Ongoing actions

2.5.2.2.1 Captive breeding

We have assumed that, for taxa where captive breeding is a reasonable possibility, it will be needed in 40 years' time. This figure can only be refined with more detailed research but the possibility of this expense needs to be anticipated. Even if populations persist in the wild, captive breeding has been recommended for taxa for which the climate space disappears on the basis that genetic variability needs to be captured before the population gets too small.

2.5.2.2.2 Refugia management

We have assumed that additional management of refugia will be needed in 25 years and will then continue indefinitely. While not needed immediately, it is likely to be required before captive breeding is essential.

2.5.2.2.3 Species management

Future ongoing species management may include provision of supplementary food at sites where natural food supplies may be reduced by climate change, management of coastal nests that may face unsustainable rates of inundation and irrigation of food trees that may be affected by drought. Here we have assumed such actions will not be needed for 25 years, if at all.

3. RESULTS AND OUTPUTS

3.1 Data sets

Twenty-nine databases were used to source locational data (Table 6). Together this database consisted of over 29 million locality records – the most comprehensive set of Australian bird records ever assembled for a single project. Of these 16.5 million were considered both valid and unique at a 2 km x 2 km grid size.

Table 6. Summary of data collated for the project.

Source of data	No. of unique records	Percentage
BirdLife Australia New Atlas Surveys	7,955,512	48
BirdLife Australia First Atlas Data (1977-81)	2,712,581	16
New South Wales Dept. of Environment, Climate Change and Water (Atlas of NSW Wildlife)	1,275,204	8
Victorian Department of Sustainability and the Environment (Atlas of Victorian Wildlife)	907,628	5
BirdLife Australia Historical Atlas Data (pre-1977)	749,338	5
Northern Territory Department of Natural Resources, Environment, the Arts and Sport	615,173	4
BirdLife Australia Shorebirds 2020 database	560,320	3
BirdInfo	235,820	1
Cumberland Bird Observers	208,617	1
Canberra Ornithologists Group	174,083	1
Queensland Department of Environment and Resource Management (Wildnet)	170,000	1
Tasmanian Department of Primary Industries, Parks, Water and Environment	162,755	1
Eremaea Birds	143,246	1
South Australia Department of Environment and Heritage	105,804	1
BirdLife Australia Australian Bird Count	100,592	1
BirdLife Australia Nest Record Scheme	88,511	1
CSIRO Townsville Biodiversity Group	70,015	<1
Melbourne Water/Arthur Rylah Institute Werribee Treatment Plant counts	60,904	<1
Nature Map - Western Australia	51,194	<1
Victorian Waterbird Database	50,164	<1

Source of data	No. of unique records	Percentage
Heather Gibbs data	39,548	<1
Rhythms of Life	39,065	<1
Murray-Darling Database	31,798	<1
Melbourne Water data - William Steele	11,041	<1
Incidental observations from *Action Plan for Australian Birds 2010* compilation	3,886	<1
BirdLife Australia Regent Honeyeater Database	3,111	<1
Museum and Art Gallery – Tasmania	2,795	<1
Birdpedia	2,185	<1
BirdLife Australia Orange-bellied Parrot Winter Census and Resights Database	1,727	<1
BirdLife Australia Australian Painted Snipe Database	1,180	<1
BirdLife Australia Carnabys Black-Cockatoo database	1,054	<1
Eastern Mainland Hooded Plover biennial count 2010	584	<1
David Parker Plains-wanderer surveys	220	<1
Sally Bryant Forty-spotted Pardalote surveys	129	<1
Ian Gynther Double-eyed Fig-Parrot (southern, Coxen's) records	95	<1
Murphy, Burbidge *et al*. Night Parrot data	45	<1
Houston and Melzer 2010 - Capricorn Yellow Chat recovery plan	20	<1
Andrew Black *in litt*; Black *et al.* 2010 grasswren data	16	<1
Atlas of Living Australia OZCAM	2	<1
Total	**16,535,962**	

3.2 Exposure

3.2.1 Taxa of terrestrial environments and inland waters

3.2.1.1 Climate space and summed suitability

3.2.1.1.1 Ultrataxa

Levels of exposure are summarised in Table 7 with details for each taxon in Appendix 3. Summaries are presented in Appendix 9 and maps in Appendix 10. For 75 taxa the median model suggested that there would be no suitable climate space remaining in 2085, either inside or outside the current range, on current rates of greenhouse gas emissions. Even the 10th percentile for the 18 GCMs predicts that 25 taxa lose all their climate space. All but two of these currently occur on the Tiwi Islands, King Island or Cape York Peninsula.

Table 7. Exposure of Australian bird taxa of terrestrial environments and inland waters to shifts in climate space by 2085 under current rates of greenhouse gas emissions

Data are the median no. taxa from 18 climate models (range from 10th and 90th percentiles). "% Inside" and "% Outside" are the percentage of the current range estimated to be climatically suitable in 2085 inside and outside the current range respectively; very highly' exposed categories highlighted.

	% Inside				
% Outside	<1	1-10	11-20	>20	Total
<1	75 (25-165)	8 (1-19)	10 (0-26)	25 (0-22)	118 (26-232)
1-10	5 (3-51)	34 (2-65)	17 (0-33)	123 (0-144)	179 (2-293)
11-20	0 (0-7)	27 (22-22)	6 (0-15)	109 (0-136)	142 (25-180)
>20	21 (1-36)	9 (0-23)	33 (2-31)	482 (189-928)	545 (279-931)
Total	101 (29-259)	78 (25-129)	66 (2-105)	739 (491-928)	984

The picture is similar for summed suitability with the numbers of taxa predicted to be exposed being slightly higher than for climate space alone (Table 8).

Table 8. Exposure of Australian bird taxa of terrestrial environments and inland waters to shifts in summed climate suitability by 2085 under current rates of greenhouse gas emissions.

Data are the median no. taxa from 18 climate models (range from 10th and 90th percentiles). "% Inside" and "% Outside" are the percentage of the summed suitability within the current range estimated to be climatically suitable in 2085; very highly' exposed categories highlighted**.**

	% Inside				
% Outside	<1	1-10	11-20	>20	Total
<1	53 (20-189)	11 (3-27)	13 (3-26)	3 (2-28)	80 (54-244)
1-10	13 (23-103)	84 (8-102)	34 (18-29)	147 (85-186)	278 (145-409)
11-20	0 (2-8)	9 (5-10)	2 (2-15)	133 (70-77)	144 (79-110)
>20	68 (3-58)	10 (8-33)	46 (12-26)	358 (110-662)	482 (213-699)
Total	134 (48-358)	114 (172-24)	95 (60-71)	641 (375-845)	984

Using the categories from Table 2, 122 taxa, or 12.4% of all terrestrial or inland waters bird taxa in Australia, are predicted to be very highly exposed to either a loss of climate space or reduction in climatic suitability using the median of 18 climate models, with 31 taxa being very high highly exposed at the 90th percentile of all models (Table 9).

Table 9. Exposure of Australian bird taxa of terrestrial environments and inland waters to shifts in climate space, summed suitability or either by 2085 under current rates of greenhouse gas emissions.

Data are the median no. taxa from 18 climate models (range from 10th and 90th percentiles); very highly' exposed categories highlighted.

	Climate space	Summed suitability	Overall
Very High	122 (31-307)	161 (56-429)	162 (302-429)
High	84 (23-140)	134 (48-145)	135 (138-145)
Medium	39 (2-46)	48 (27-28)	48 (27-46)
Low	739 (491-928)	641 (375-845)	639 (375-491)

There is substantial clustering of many of the very highly exposed taxa into broad regions (Table 10). Cape York Peninsula stands out but 35 of the species there are represented by subspecies that also occur in New Guinea. Similarly, the climate space for a number of other subspecies is predicted to disappear but the modelling suggests that the same areas become, or remain, suitable for other subspecies occurring elsewhere in Australia.

Table 10. Regional affiliations of the 167 Australian bird taxa of terrestrial environments and inland waters that are considered most exposed to climate change.

	Exposed taxa		No. taxa where climate space could be filled by other subspecies	No. taxa where replacement unlikely
Region	Number	%		
Cape York Peninsula	49	29	35	10
South-west Victoria and southern South Australia	39 (Kangaroo Island 17)	23 (10)	10(7)	13 (3)
Arid zone	28	17	13	15
Top End and Tiwi Islands	18 (Tiwis 8)	11 (5)	11 (3)	7 (2)
Tasmania and King Island	13 (King Island 10)	8 (6)	8(7)	5(3)
Wet Tropics	10	6	0	10
Other	10	6	3	5

3.2.1.1.2 Species

Many of the most exposed taxa are subspecies. Species with multiple subspecies are more widespread than the subspecies themselves and are thus less likely to be heavily exposed. Exposure of species to either loss of climate space or a reduction in the suitability of that climate space is summarised in Table 11. A list of the 39 considered to have the highest level of exposure is provided in Table 12.

Table 11. Exposure of Australian bird taxa of terrestrial environments and inland waters to shifts in climate space or summed suitability by 2085 under current rates of greenhouse gas emissions.

Data are the median no. taxa from 18 climate models (range from 10th and 90th percentiles); very highly' exposed categories highlighted.

	% Inside				
% Outside	<1	1-10	11-20	>20	Total
<1	15	5	3	1	24
1-10	3	16	7	139	165
11-20	0	6	1	100	107
>20	23	4	12	202	241
Total	41	31	23	442	537

Table 12. List of the 39 terrestrial and inland waters Australian bird species most exposed to either a loss of climate space or a reduction in climatic suitability

Chestnut-quilled Rock-Pigeon *Petrophassa rufipennis*

Banded Fruit-Dove (Australian) *Ptilinopus cinctus alligator*

Papuan Frogmouth *Podargus papuensis*

Sarus Crane (Australian) *Grus antigone gillae*

Oriental Plover *Charadrius veredus*

Oriental Pratincole *Glareola maldivarum*

Palm Cockatoo (Australian) *Probosciger aterrimus macgillivrayi*

Major Mitchell's Cockatoo *Lophochroa leadbeateri*

Eclectus Parrot *Eclectus roratus*

Red-cheeked Parrot *Geoffroyus geoffroyi*

Princess Parrot *Polytelis alexandrae*

Swift Parrot - breeding only *Lathamus discolor*

Golden-shouldered Parrot *Psephotus chrysopterygius*

Hooded Parrot *Psephotus dissimilis*

Chestnut-breasted Cuckoo (Australian) *Cacomantis castaneiventris castaneiventris*

Yellow-billed Kingfisher (Australian) *Syma torotoro flavirostris*

Fawn-breasted Bowerbird *Ptilonorhynchus cerviniventris*

Mallee Emu-wren *Stipiturus mallee*

Short-tailed Grasswren *Amytornis merrotsyi*

White-throated Grasswren *Amytornis woodwardi*

Chestnut-quilled Rock-Pigeon *Petrophassa rufipennis*

Thick-billed Grasswren *Amytornis modestus*

Dusky Grasswren *Amytornis purnelli*

Eyrean Grasswren *Amytornis goyderi*

Tropical Scrubwren *Sericornis beccarii*

Chestnut-breasted Whiteface *Aphelocephala pectoralis*

Forty-spotted Pardalote *Pardalotus quadragintus*

Grey-headed Honeyeater *Lichenostomus keartlandi*

Black-eared Miner *Manorina melanotis*

Grey Honeyeater *Conopophila whitei*

Gibberbird *Ashbyia lovensis*

Tawny-breasted Honeyeater *Xanthotis flaviventer*

Cinnamon Quail-thrush *Cinclosoma cinnamomeum*

Chirruping Wedgebill *Psophodes cristatus*

Red-lored Whistler *Pachycephala rufogularis*

Black-backed Butcherbird (Cape York Peninsula) *Cracticus mentalis kempi*

Trumpet Manucode *Phonygammus keraudrenii*

Magnificent Riflebird (Australian) *Ptiloris magnificus alberti*

White-faced Robin (Australian) *Tregellasia leucops albigularis*

Northern Scrub-robin (Australian) *Drymodes superciliaris superciliaris*

Thick-billed Grasswren *Amytornis modestus*

Dusky Grasswren *Amytornis purnelli*

3.2.1.2 Fire

Based on Bradstock (2010) and knowledge of the ecology of species, 61 taxa were listed as being highly exposed to fire (Table 13). These are taxa for which the postulated increase in fire frequency and intensity in shrubby habitats is likely to have greatest effect. It also assumes that spinifex, itself a shrubby grass, will also be affected by increases in shrub growth between spinifex patches.

Table 133. Australian bird taxa considered likely to be exposed to increases in the frequency and intensity of fires as a result of climate change.

Orange-bellied Parrot *Neophema chrysogaster*

Western Ground Parrot *Pezoporus flaviventris*

Eastern Ground Parrot (Tasmanian) *Pezoporus wallicus leachi*

Eastern Ground Parrot (mainland) *Pezoporus wallicus wallicus*

Rufous Scrub-bird (southern) *Atrichornis rufescens ferrieri*

Rufous Scrub-bird (northern) *Atrichornis rufescens rufescens*

Noisy Scrub-bird *Atrichornis clamosus*

Southern Emu-wren (Kangaroo Island) *Stipiturus malachurus halmaturinus*

Southern Emu-wren (Dirk Hartog Island) *Stipiturus malachurus hartogi*

Southern Emu-wren (Fleurieu Peninsula) *Stipiturus malachurus intermedius*

Southern Emu-wren (Tasmanian) *Stipiturus malachurus littleri*

Southern Emu-wren (eastern) *Stipiturus malachurus malachurus*

Southern Emu-wren (Eyre Peninsula) *Stipiturus malachurus parimeda*

Southern Emu-wren (Glenelg) *Stipiturus malachurus polionotum*

Southern Emu-wren (western) *Stipiturus malachurus westernensis*

Mallee Emu-wren *Stipiturus mallee*

Rufous-crowned Emu-wren *Stipiturus ruficeps*

Eastern Bristlebird (southern) *Dasyornis brachypterus brachypterus*

Eastern Bristlebird (northern) *Dasyornis brachypterus monoides*

Western Bristlebird *Dasyornis longirostris*

Rufous Bristlebird (Coorong) *Dasyornis broadbenti broadbenti*

Rufous Bristlebird (Otways) *Dasyornis broadbenti caryochrous*

Scrubtit (King Island) *Acanthornis magnus greenianus*

Chestnut-rumped Heathwren (Mount Lofty Ranges) *Hylacola pyrrhopygia parkeri*

Chestnut-rumped Heathwren (Flinders Ranges) *Hylacola pyrrhopygia pedleri*

Chestnut-rumped Heathwren (eastern) *Hylacola pyrrhopygia pyrrhopygia*

Shy Heathwren (eastern mallee) *Hylacola cauta cauta*

Shy Heathwren (Kangaroo Island) *Hylacola cauta halmaturina*

Shy Heathwren (Riverina) *Hylacola cauta macrorhyncha*

Shy Heathwren (western) *Hylacola cauta whitlocki*

Rufous Fieldwren (Nullarbor) *Calamanthus campestris campestris*

Rufous Fieldwren (Dorre Island) *Calamanthus campestris dorrie*

Rufous Fieldwren (Lake Eyre basin) *Calamanthus campestris isabellinus*

Rufous Fieldwren (Dirk Hartog Island) *Calamanthus campestris hartogi*

Striated Grasswren (Opalton) *Amytornis striatus rowleyi*
Striated Grasswren (sandplain) *Amytornis striatus striatus*
Striated Grasswren (Pilbara) *Amytornis striatus whitei*
Short-tailed Grasswren (Flinders Ranges) *Amytornis merrotsyi merrotsyi*
Short-tailed Grasswren (Gawler Ranges) *Amytornis merrotsyi pedleri*
White-throated Grasswren *Amytornis woodwardi*
Carpentarian Grasswren *Amytornis dorotheae*
Rufous Fieldwren (western wheatbelt) *Calamanthus campestris montanellus*
Rufous Fieldwren (west coast) *Calamanthus campestris rubiginosus*
Rufous Fieldwren (upper Murchison) *Calamanthus campestris wayensis*
Rufous Fieldwren (Murray mallee) *Calamanthus campestris winiam*
Black-eared Miner *Manorina melanotis*
Helmeted Friarbird (Top End sandstone) *Philemon buceroides ammitophila*
Western Whipbird (Kangaroo Island) *Psophodes nigrogularis lashmari*

Dusky Grasswren *Amytornis purnelli*
Kalkadoon Grasswren *Amytornis ballarae*
Eyrean Grasswren *Amytornis goyderi*
Black Grasswren *Amytornis housei*
Western Whipbird (eastern) *Psophodes nigrogularis leucogaster*
Western Whipbird (western heath) *Psophodes nigrogularis nigrogularis*
Western Whipbird (western wheatbelt) *Psophodes nigrogularis oberon*

3.2.2 Mangrove taxa

Climatic models could not be developed for mangrove taxa so only exposure to sea level rise and increased storm frequency and intensity were considered. Given that mangroves and their associated fauna have successfully followed sea level changes over millennia, including to higher levels than currently and at faster rates, we considered that mangrove taxa were only likely to be affected where a significant portion of their landward habitat had been developed in a way that would prevent landward expansion as sea levels rise. It was considered that none of the mangrove taxa are likely to be seriously exposed to deleterious effects of sea level rise within the next 100 years because all endemics are in northern Australia where there is ample room for mangrove migration. Similarly, given the periodicity of storms and their localised effect, it was felt that any increase in storm frequency or intensity would still be unlikely to be a substantive threat to any Australian mangrove bird taxon.

3.2.3 Marine taxa

Climatic models could not be developed for marine taxa so exposure was assessed on the basis of changes in marine primary productivity in the vicinity of breeding islands. Current primary productivity, anticipated changes and resultant predicted productivity for waters around Australia are shown in Figure 2.

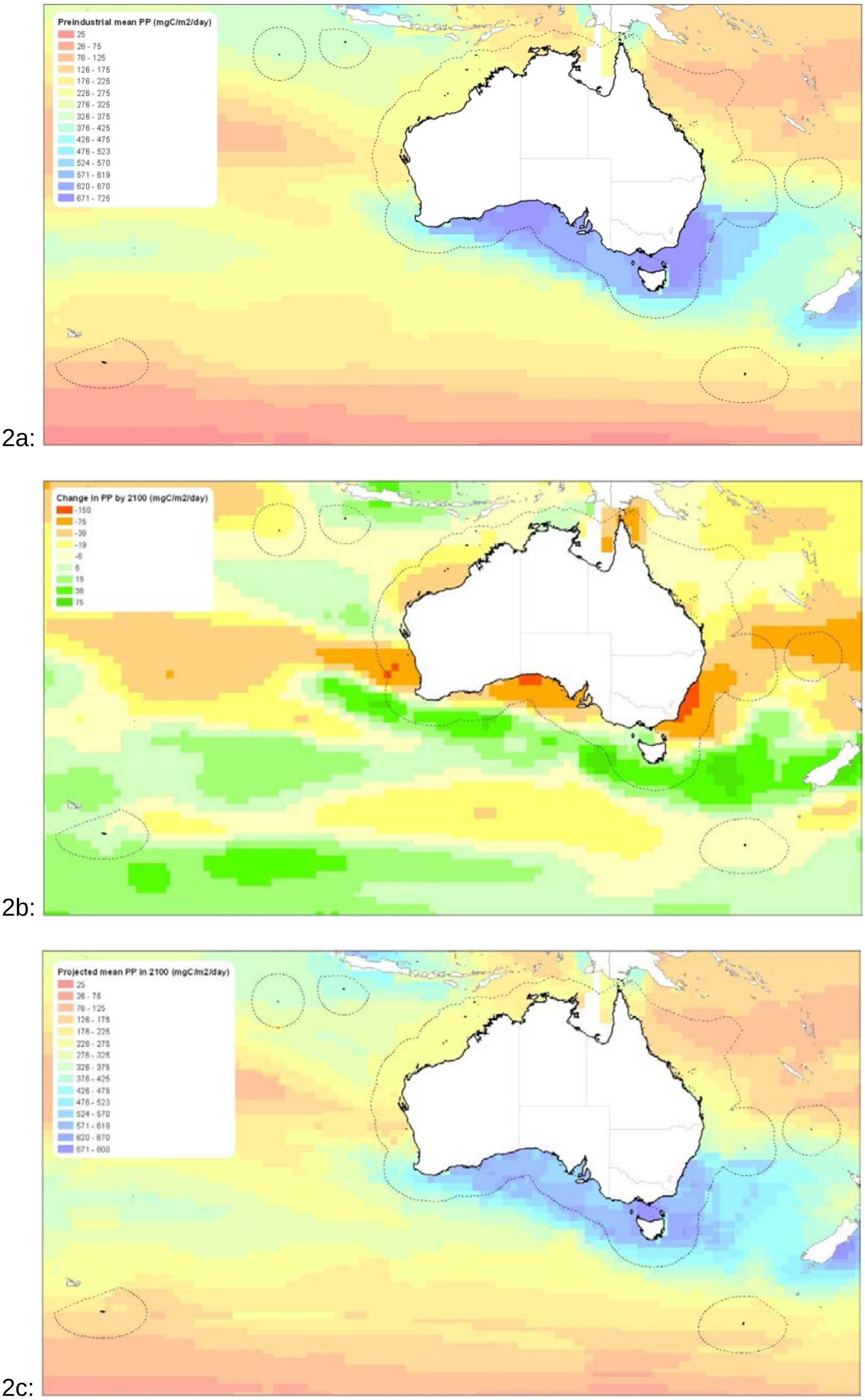

Figure 2. Primary productivity (mg/C/m^2/day) in waters around Australia (adapted from Steinacher *et al.* 2010) showing the Australian Fishing Zone (dotted lines): a. preindustrial levels; b. anticipated changes by 2100; c. 2100 revised primary productivity.

On the basis of this it is possible to calculate for all marine bird taxa the predicted change in primary productivity for waters in the vicinity of known breeding sites on Australian territory (including offshore islands). The pattern of change to current levels of productivity near breeding sites is shown for marine taxa in Figure 3. For details see Appendix 4. For maps see Appendix 10.

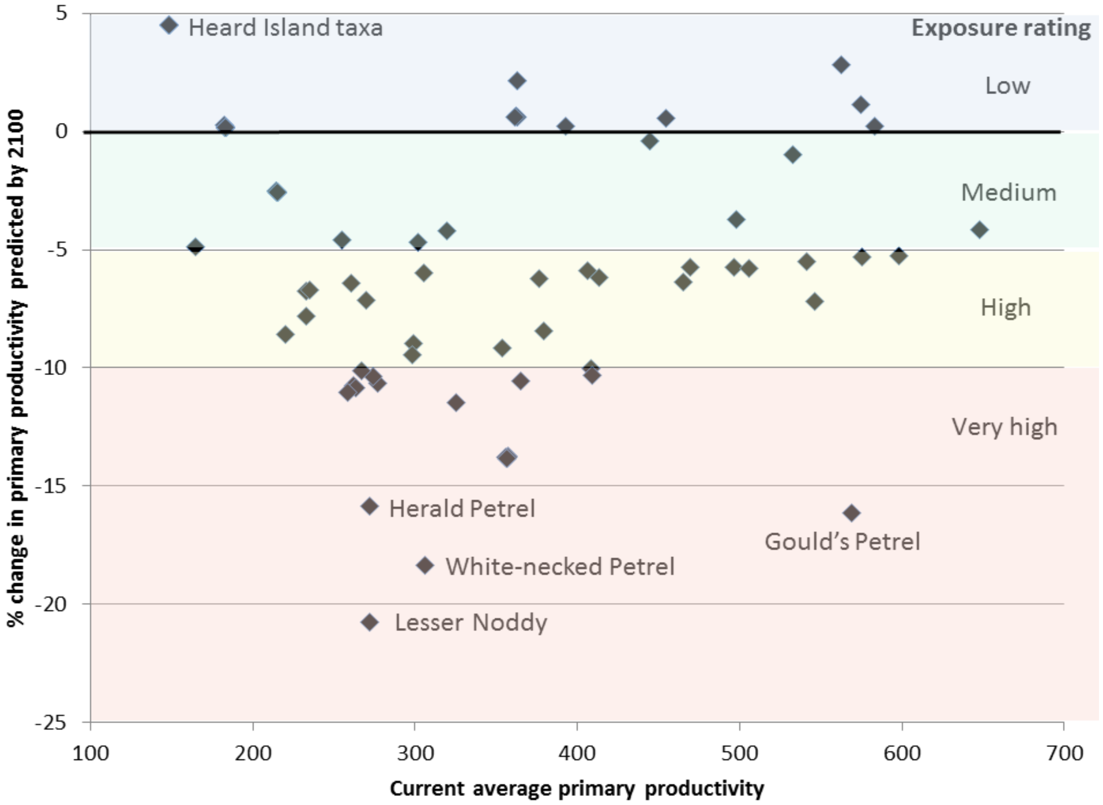

Figure 3. Change in average primary productivity (mg/C/m^2/day) anticipated for 2100 within 200 nautical miles (Australian Fishing Zone) of breeding colonies of Australian seabird breeding taxa, and the exposure rating applied (data from Steinacher *et al.*2011).

For the purposes of the current exercise, taxa deemed highly exposed to reductions in marine productivity resulting from climate change were those that feed primarily in the Australian fishing zone while provisioning young. All species were assessed where possible and, if appropriate, assumed to be sensitive unless there was evidence to the contrary. This included two taxa that fit this category but were nevertheless excluded from the list of highly exposed marine taxa. The White Tern *Gygis alba* was excluded because research has shown that it breeds more successfully when marine productivity is low because there is less competition (Catry *et al.* 2009). The Roseate Tern *Sterna dougallii* was excluded because, although breeding success is greatly affected by local changes in marine productivity (Ramos *et al.* 2002), adult terns can shift at least 400 km between successive breeding sites (Spendelow *et al.* 2010). The greatest declines in marine productivity are predicted to occur off eastern Australia so the seabirds breeding in eastern Australia, on Lord

Howe and Norfolk Islands and on parts of the Great Barrier Reef are predicted to be most exposed based on this metric.

The 12 taxa that meet the criteria for being highly exposed are listed in Table 14. Nearly all are tropical taxa. Very recent data on White-necked and Gould's Petrels suggests that they are capable of foraging well beyond the 200 NM limit while breeding (N.Carlile and D Priddel pers.comm.) but it is not known which of these longer trips result in food provisioning for the chicks.

Table 14. Highly exposed Australian marine bird taxa based on predicted changes to inshore marine productivity.

White-bellied Storm-Petrel (Tasman Sea) *Fregetta grallaria grallaria*	Masked Booby (Tasman Sea) *Sula dactylatra tasmani*
Wedge-tailed Shearwater *Ardenna pacifica*	Common Noddy (Indo-Pacific) *Anous stolidus pileatus*
Little Shearwater (Tasman Sea) *Puffinus assimilis assimilis*	Black Noddy (Indo-Pacific) *Anous minutus minutus*
Herald Petrel *Pterodroma heraldica*	Lesser Noddy (Houtman Abrolhos) *Anous tenuirostris melanops*
Gould's Petrel (Australian) *Pterodroma leucoptera leucoptera*	Grey Ternlet (western Pacific Ocean) *Procelsterna cerulea albivitta*
White-necked Petrel (southern) *Pterodroma cervicalis cervicalis*	Sooty Tern (Pacific Ocean) *Onychoprion fuscata serrata*

3.2.4 Coastal taxa

Climate modelling was not possible for coastal taxa so assessments considered only exposure to sea level rise. Given the history of sea level rise, it is likely that only birds relying on coasts that are backed by built infrastructure are unlikely to be able to shift their use of the environment in line with changing coastal processes. Nevertheless such adaptation has not yet been proven so any taxon that breeds predominantly near the high tide level may suffer from increased nest loss. Given that introduced predators and the human use of coasts may have increased since European arrival, beach-nesting birds may not have the leeway to adapt to rising sea levels that they presumably had during the last sea level rise events. Birds that rely primarily on saltmarshes are also likely to be affected by sea level rise if there is no ground further inland on which new saltmarshes can develop. For non-breeding shorebirds, however, it was assessed that the level of exposure in Australia is likely to be low relative to that of other bird taxa, especially given that the high rate of development along the migratory pathway is likely to mean that Australian shorebird environments are likely to be well below carrying capacity for many decades to come. On the basis of the above, eight taxa were listed as having a very high exposure to sea level rise (Table 15). Of these, the Herald Petrel and the three terns are seabirds and the thornbill is terrestrial. Two other terrestrial taxa, the Orange-bellied Parrot *Neophema* *chrysogaster* (Loyn *et al.* 1986) and the Cape York subspecies of Star Finch *Neochmia ruficauda clarescens* (Garnett *et al.* 2003), rely on coastal saltmarsh at certain times of year but both have access to large areas of coastline where new marshes can develop without impedance.

Table 15. Australian bird taxa considered highly exposed to sea level rise.

Herald Petrel *Pterodroma heraldica*
Beach Stone-curlew *Esacus giganteus*
Australian Pied Oystercatcher *Haematopus longirostris*
Hooded Plover (eastern) *Thinornis rubricollis rubricollis*
Little Tern (western Pacific Ocean) *Sternula albifrons sinensis*
Fairy Tern (New Caledonian) *Sternula nereis exsul*
Fairy Tern (Australian) *Sternula nereis nereis*
Slender-billed Thornbill (Gulf St Vincent) *Acanthiza iredalei rosinae*

3.2.5 Small island taxa

Climate modelling is not yet possible for small islands so the only assessment of exposure was based on predicted changes to the marine environment in which the islands sit, following Steinacher *et al.* (2010). On this basis Lord Howe and Norfolk Islands and the Houtman Abrolhos, of those islands with endemic terrestrial bird taxa, appear likely to have substantial declines in marine productivity in their vicinity. Whether this indicates climatic changes that will affect the ecology of the islands themselves is unknown. However there are some predictions that the cloud layer on Lord Howe Island may lift up Mts Gower and Lidgbird (DECC 2007b), which could reduce rainfall, and that there is likely to be a reduction in rainfall and an increase in storm frequency on Norfolk Island (DNP 2011).

On this basis, 17 taxa are considered highly exposed to climate change (Table 16).

Table 16. Australian bird taxa from small islands considered highly exposed to climate change.

Orange-footed Scrubfowl (Papuan) *Megapodius reinwardt reinwardt*

Lord Howe Woodhen *Gallirallus sylvestris*

Painted Button-quail (Houtman Abrolhos) *Turnix varius scintillans*

Rainbow Lorikeet (Papuan) *Trichoglossus haematodus caeruleiceps*

Tasman Parakeet (Norfolk Island) *Cyanoramphus cookii cookii*

Pheasant Coucal (Papuan) *Centropus phasianinus thierfelderi*

Southern Boobook (Norfolk Island x New Zealand) *Ninox novaeseelandiae undulata*

Sacred Kingfisher (Norfolk Island) *Todiramphus sanctus norfolkiensis*

Sacred Kingfisher (Tasman Sea) *Todiramphus sanctus vagans*

Norfolk Island Gerygone *Gerygone modesta*

Golden Whistler (Lord Howe Island) *Pachycephala pectoralis contempta*

Golden Whistler (Norfolk Island) *Pachycephala pectoralis xanthoprocta*

Pied Currawong (Lord Howe Island) *Strepera graculina crissalis*

Grey Fantail (Norfolk Island) *Rhipidura fuliginosa pelzelni*

Scarlet Robin (Norfolk Island) *Petroica multicolor multicolor*

Silvereye (Lord Howe Island) *Zosterops lateralis tephropleurus*

Slender-billed White-eye *Zosterops tenuirostris*

3.3 Sensitivity

3.3.1 Sensitivity metrics

A summary of sensitivity metrics is provided in Appendix 5. A full list of sensitivity metrics is provided in Appendices 6-8. For overall rankings see Appendix 9. There were no very strong correlations among sensitivity metrics, the strongest being between *annual* r_{max} and *#habitats* – $r_s = 0.45$ (Table 17). Among the 457 terrestrial species for which the additional metric *ENFA specialisation* was available, correlations were of similar magnitudes as in Table 17 except that *ENFA specialisation* was moderately correlated with *#habitats* ($r_s = 0.64$) – species with a limited climate range occupy fewer habitats. We concluded that multicollinearity among sensitivity metrics was not strong enough to be of concern and therefore used all seven metrics.

Table 17. Matrix of Spearman's rank correlations among six sensitivity metrics for 705 Australian bird species

ENFA climatic specialisation has been excluded because it is available for only a sub-set of species (see text).

	#food types	#substrates	relative brain size	annual r_{max}	population
#habitats	0.36	0.071	-0.032	0.451	0.311
#food types		0.199	0.072	0.307	0.056
#substrates			0.19	-0.079	0.022
RBS				-0.03	-0.002
annual r_{max}					0.133

3.3.2 Most sensitive taxa

Marine taxa were rated more sensitive on average, with shoreline, mangrove and inland waters taxa least (Figure 4).

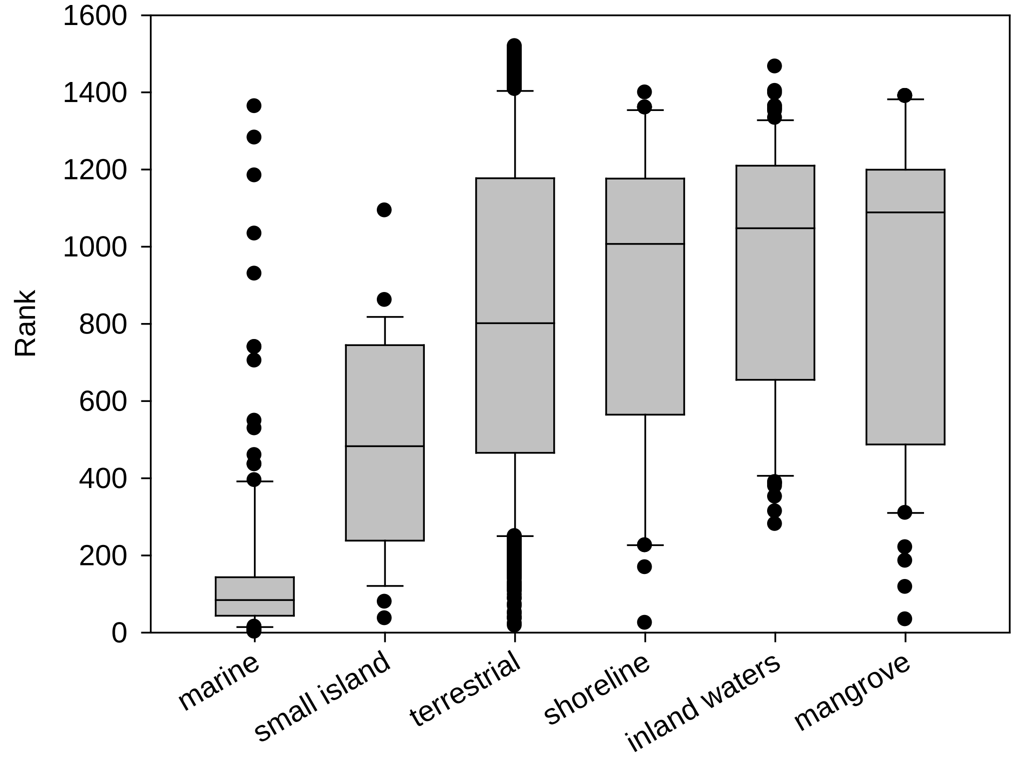

Figure 4 Rankings for sensitivity to climate change for Australian bird taxa by habitat class (ranks include all sensitivity measures except ENFA)

The most sensitive taxa in each group are listed in Table 18. and the most sensitive species in Table 19. It should be noted that, where there are breeding and non-breeding populations of the same taxon occurring in Australia, as is the case with many seabirds, only the breeding population is considered.

Table 18. List of Australian bird taxa rated most sensitive to climate change in each habitat class

(sensitivity rank in brackets based on all taxa without ENFA, see Appendix 9)

Mangroves	Coastal	Inland waters	Marine	Small islands	Terrestrial
Collared Imperial-Pigeon (Papuan) *Ducula mullerii mullerii* (33)	Beach Stone-curlew *Esacus giganteus* (24)	Little Bittern (Australo-Papuan) *Ixobrychus minutus dubius* (283)	Wandering Albatross *Diomedea exulans* (1)	Southern Boobook (Norfolk Island x New Zealand) *Ninox novaeseelandiae undulata* (36)	Glossy Black-Cockatoo (Kangaroo Island) *Calyptorhynchus lathami halmaturinus* (17)
Eclectus Parrot (Papuan) *Eclectus roratus polychloros* (117)	Asian Dowitcher *Limnodromus semipalmatus* (168)	Cotton Pygmy-goose (Australian) *Nettapus coromandelianus albipennis* (313)	Herald Petrel *Pterodroma heraldica* (2)	Lord Howe Woodhen *Gallirallus sylvestris* (79)	Double-eyed Fig-Parrot (southern, Coxen's) *Cyclopsitta diophthalma coxeni* (23)
Barking Owl (Papuan) *Ninox connivens assimilis* (185)	Sooty Oystercatcher (southern) *Haematopus fuliginosus fuliginosus* (228)	Australasian Shoveler (Australian) *Anas rhynchotis rhynchotis* (351)	Soft-plumaged Petrel *Pterodroma mollis mollis/dubia* (2)	Glossy Swiftlet (Christmas Island) *Collocalia esculenta natalis* (121)	Yellow-tufted Honeyeater (Helmeted) *Lichenostomus melanops cassidix* (35)
Singing Starling *Aplonis cantoroides* (223)	Sooty Oystercatcher (northern) *Haematopus fuliginosus ophthalmicus* (228)	Pink-eared Duck *Malacorhynchus membranaceus* (378)	Fairy Prion (southern) *Pachyptila turtur subantarctica* (4)	Painted Button-quail (Houtman Abrolhos) *Turnix varius scintillans* (180)	Red-tailed Black-Cockatoo (south-eastern) *Calyptorhynchus banksii graptogyne* (37)

Mangroves	**Coastal**	**Inland waters**	**Marine**	**Small islands**	**Terrestrial**
Brown Goshawk (Papuan) *Accipiter fasciatus dogwa* (309)	Wandering Tattler *Tringa incana* (320)	Black-fronted Dotterel *Elseyornis melanops* (4385)	Kermadec Petrel (western) *Pterodroma neglecta neglecta* (5)	Pied Currawong (Lord Howe Island) *Strepera graculina crissalis* (190)	Thick-billed Grasswren (north-western New South Wales) *Amytornis modestus obscurior* (38)
Dusky Gerygone (southern) *Gerygone tenebrosa christophori* (310)	Hooded Plover (eastern) *Thinornis rubricollis rubricollis* (460)	Red-kneed Dotterel *Erythrogonys cinctus* (386)	White-necked Petrel (southern) *Pterodroma cervicalis cervicalis* (5)	Emerald Dove (Christmas Island) *Chalcophaps indica natalis* (212)	Western Whipbird (western heath) *Psophodes nigrogularis nigrogularis* (47)
Dusky Gerygone (northern) *Gerygone tenebrosa tenebrosa* (310)	Eastern Reef Egret (eastern) *Egretta sacra sacra* (485)	Hoary-headed Grebe *Poliocephalus poliocephalus* (389)	White-tailed Tropicbird (Pacific Ocean) *Phaethon lepturus dorotheae* (7)	Christmas Island Hawk-Owl *Ninox natalis* (234)	Brown Thornbill (King Island) *Acanthiza pusilla archibaldi* (52)
Peaceful Dove (Papuan) *Geopelia striata papua* (317)	Australian Pied Oystercatcher *Haematopus longirostris* (501)	Zitting Cisticola (eastern) *Cisticola juncidis laveryi* (406)	White-tailed Tropicbird (Indian Ocean) *Phaethon lepturus lepturus* (7)	Black-faced Sheathbill (Heard Island) *Chionis minor nasicornis* (236)	Topknot Pigeon *Lopholaimus antarcticus* (67)
Red-cheeked Parrot (Papuan) *Geoffroyus geoffroyi aruensis* (375)	Red-capped Plover *Charadrius ruficapillus* (755)	Zitting Cisticola (Top End) *Cisticola juncidis leanyeri* (406)	White-bellied Storm-Petrel (Tasman Sea) *Fregetta grallaria grallaria* (9)	Southern Emu-wren (Dirk Hartog Island) *Stipiturus malachurus hartogi* (246)	White-throated Nightjar (eastern) *Eurostopodus mystacalis mystacalis* (73)
Mangrove Gerygone (eastern) *Gerygone levigaster cantator* (421)	Greater Sand Plover (Mongolian) *Charadrius leschenaultii leschenaultii* (785)	Zitting Cisticola (Normanton) *Cisticola juncidis normani* (406)	Grey-backed Storm-Petrel *Garrodia nereis* (10)	Scarlet Robin (Norfolk Island) *Petroica multicolor multicolor* (247)	Scrubtit (King Island) *Acanthornis magnus greenianus* (87)

Table 19. List of Australian bird species rated most sensitive to climate change by habitat class (overall rank)

Mangroves	**Coastal**	**Inland waters**	**Marine**	**Small islands**	**Terrestrial**
Collared Imperial-Pigeon *Ducula mullerii* (33)	Beach Stone-curlew *Esacus giganteus* (24)	Little Bittern *Ixobrychus minutus* (283)	Wandering Albatross *Diomedea exulans* (1)	Lord Howe Woodhen *Gallirallus sylvestris* (79)	Topknot Pigeon *Lopholaimus antarcticus* (67)
Singing Starling *Aplonis cantoroides* (223)	Asian Dowitcher *Limnodromus semipalmatus* (168)	Cotton Pygmy-goose *Nettapus coromandelianus* (313)	Herald Petrel *Pterodroma heraldica* (2)	Glossy Swiftlet *Collocalia esculenta* (121)	White-throated Nightjar *Eurostopodus mystacalis* (73)
Dusky Gerygone *Gerygone tenebrosa* (310)	Sooty Oystercatcher *Haematopus fuliginosus* (242)	Australasian Shoveler *Anas rhynchotis* (351)	Soft-plumaged Petrel *Pterodroma mollis* (2)	Christmas Island Hawk-Owl *Ninox natalis* (234)	Red Goshawk *Erythrotriorchis radiatus* (97)
Mangrove Gerygone *Gerygone levigaster* (421)	Wandering Tattler *Tringa incana* (320)	Pink-eared Duck *Malacorhynchus membranaceus* (378)	Kermadec Petrel *Pterodroma neglecta* (5)	Black-faced Sheathbill *Chionis minor* (236)	Banded Fruit-Dove *Ptilinopus cinctus* (106)
Broad-billed Flycatcher *Myiagra ruficollis* (428)	Eastern Reef Egret *Egretta sacra* (485)	Black-fronted Dotterel *Elseyornis melanops* (385)	White-bellied Storm-Petrel *Fregetta grallaria* (9)	Christmas Island Imperial-Pigeon *Ducula whartoni* (273)	Noisy Scrub-bird *Atrichornis clamosus* (109)
Chestnut Rail *Eulabeornis castaneoventris* (475)	Hooded Plover *Thinornis rubricollis* (492)	Red-kneed Dotterel *Erythrogonys cinctus* (386)	Grey-backed Storm-Petrel *Garrodia nereis* (10)	Variable Goshawk *Accipiter hiogaster* (308)	Superb Fruit-Dove *Ptilinopus superbus* (110)

Mangroves	**Coastal**	**Inland waters**	**Marine**	**Small islands**	**Terrestrial**
Great-billed Heron *Ardea sumatrana* (503)	Australian Pied Oystercatcher *Haematopus longirostris* (501)	Hoary-headed Grebe *Poliocephalus poliocephalus* (389)	Grey Petrel *Procellaria cinerea* (11)	Norfolk Island Gerygone *Gerygone modesta* (372)	Wompoo Fruit-Dove *Ptilinopus magnificus* (111)
Mangrove Grey Fantail *Rhipidura phasiana* (539)	Red-capped Plover *Charadrius ruficapillus* (755)	Zitting Cisticola *Cisticola juncidis* (406)	Abbott's Booby *Papasula abbotti* (12)	Tasman Parakeet *Cyanoramphus cookii* (482)	White-rumped Swiftlet *Aerodramus spodiopygius* (123)
Large-billed Gerygone *Gerygone magnirostris* (553)	Greater Sand Plover *Charadrius leschenaultii* (785)	Banded Stilt *Cladorhynchus leucocephalus* (416)	Christmas Island Frigatebird *Fregata andrewsi* (13)	Slender-billed White-eye *Zosterops tenuirostris* (712)	Albert's Lyrebird *Menura alberti* (125)
Red-capped Flowerpecker *Dicaeum geelvinkianum* (774)	Grey-tailed Tattler *Tringa brevipes* (787)	Darter *Anhinga melanogaster* (462)	King Penguin *Aptenodytes patagonicus* (15)	Island Thrush *Turdus polio*cephalus (752)	Spotted Nightjar *Eurostopodus argus* (127)

3.3.3 What drives the sensitivity of very highly sensitive taxa?

Among ultrataxa rated as very highly sensitive, Principal Components Analysis (PCA) of sensitivity metrics revealed two factors that are most informative (Fig. 5):

- Factor 1: positively related to genetic constraints (population size) and negatively to food types specialisation (#food types) and reproductive constraints (annual r_{max}).
- Factor 2: positively related to habitat specialisation (#habitats) and reproductive constraints (annual r_{max}) and negatively to small relative brain size (RBS) and foraging substrate specialisation (#substrates);

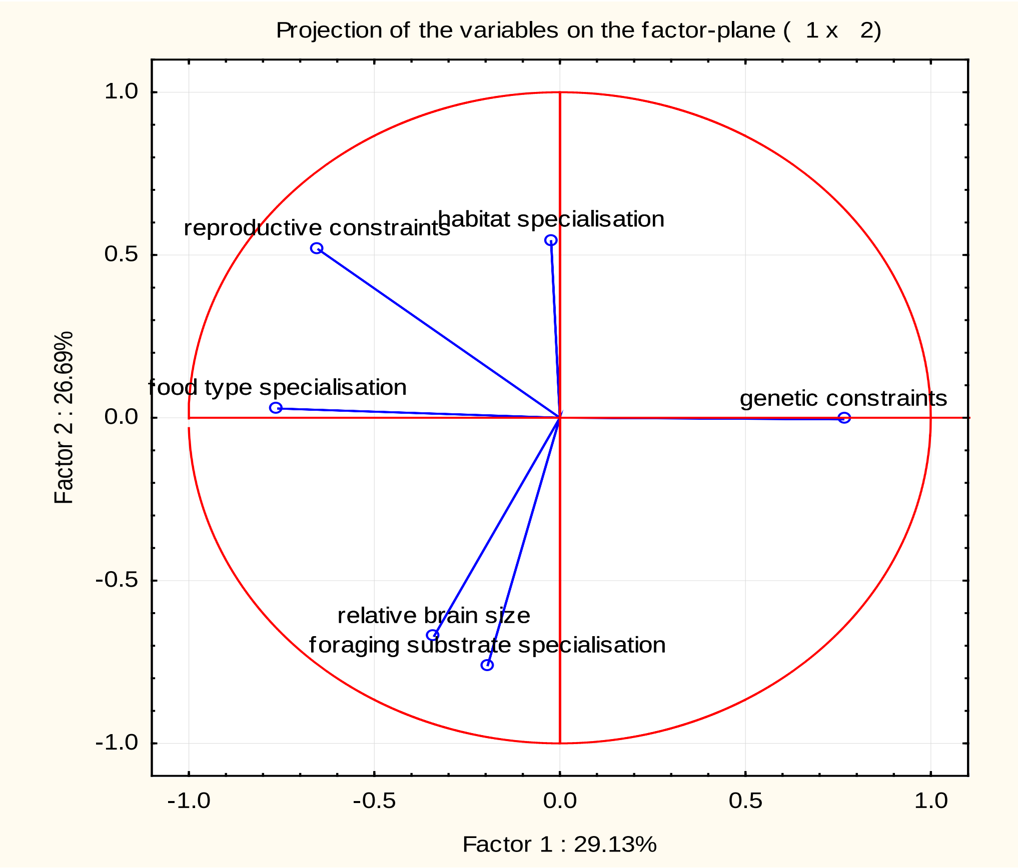

Figure 5. The first two factors of a Principal Components Analysis of sensitivity metrics for 218 ultrataxa that are rated "very highly sensitive".

All metrics have been scaled from 0 to 1 where 0 = least sensitivity and 1 = most sensitivity. Climate specialisation has been excluded because it is not available for all taxa. The first two factors accounted for 55.8% of the variance, with remaining factors each accounting for no more than a further 15% of the variance.

There were marked differences in scores for the first two PCA factors, and especially Factor 1, between groups of taxa (terrestrial, small island, mangroves, shoreline, marine – no inland water taxa were rated as very highly sensitive; one-way ANOVA: Factor 1 – $F_{4,213} = 22.6$, $P << 0.001$; Factor 2 – $F_{4,213} = 4.1$, $P = 0.003$). Terrestrial taxa displayed a wide range of sensitivities (i.e. were widely dispersed across the ordination) but feature a number of potentially genetically-constrained (rare) taxa showing as high scores for Factor 1 (Fig. 6A). The few very highly sensitive mangrove specialists tended weakly to feature because of genetic constraints, small brains and foraging substrate specialisation (Fig. 6B). Very highly sensitive shoreline taxa showed little variation with regard to Factor 2 and an even but wide spread of scores for Factor 1 (Fig. 6C). Small island taxa that are very highly sensitive featured particularly because of genetic constraints (rarity) and displayed a wide range of scores for Factor 2 (Fig. 6D). Very highly sensitive marine taxa displayed a wide range of sensitivity attributes but with a heavy concentration of taxa that were slow breeders with specialisation to food type and habitat (Fig. 6E).

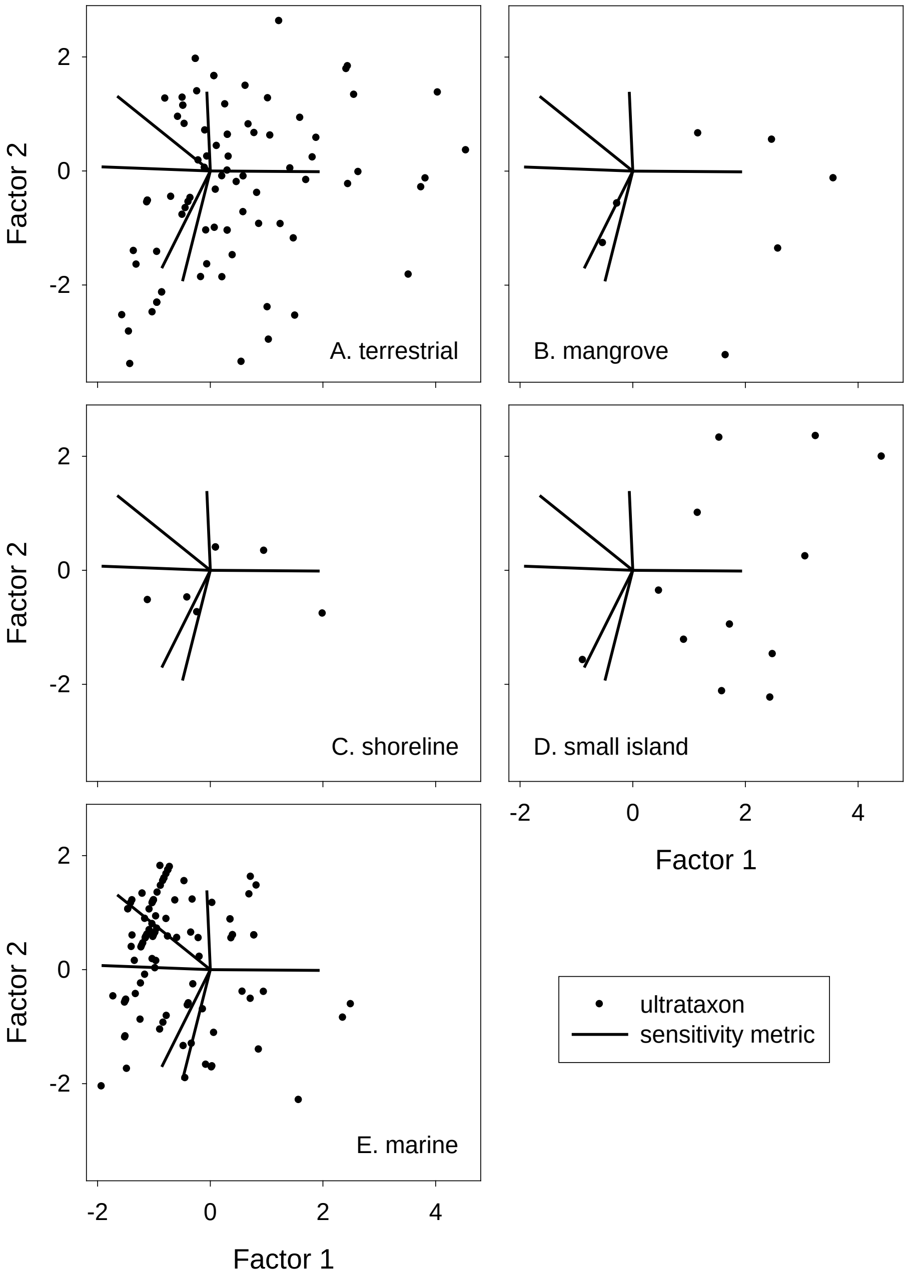

Figure 6 Position of very highly sensitive ultrataxa in five groups relative to sensitivity metrics in the Principal Components Analysis of Fig. 5.

(The factor scores for sensitivity metrics in Fig. 5 have been multiplied by 2.5.)

3.4 Exposure and Sensitivity

Very highly sensitive taxa were more likely to be marine whereas very highly exposed taxa were more likely to be from small islands (Figure 7A,B). Small island taxa were most likely to be both very highly sensitive and very highly exposed (Figure 7C). No mangrove or inland water taxa were rated as both very highly sensitive and very highly exposed.

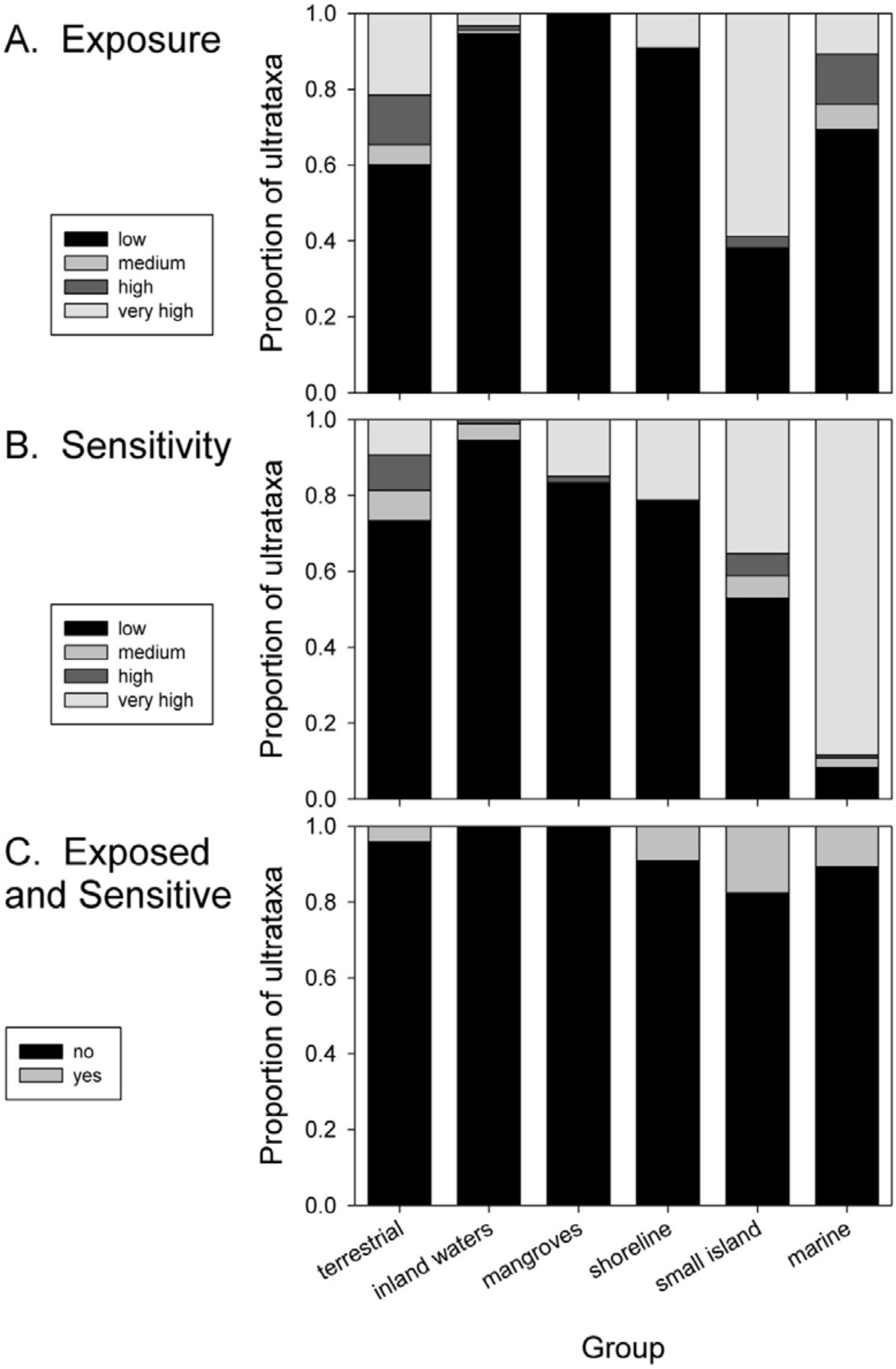

Figure 7. Proportion of Australian bird taxa in sensitivity and exposure classes by habitat class.

3.5 Threatened taxa

As shown in Figure 8, the more threatened a taxon, the more likely it is to be considered either sensitive or exposed to climate change, or both.

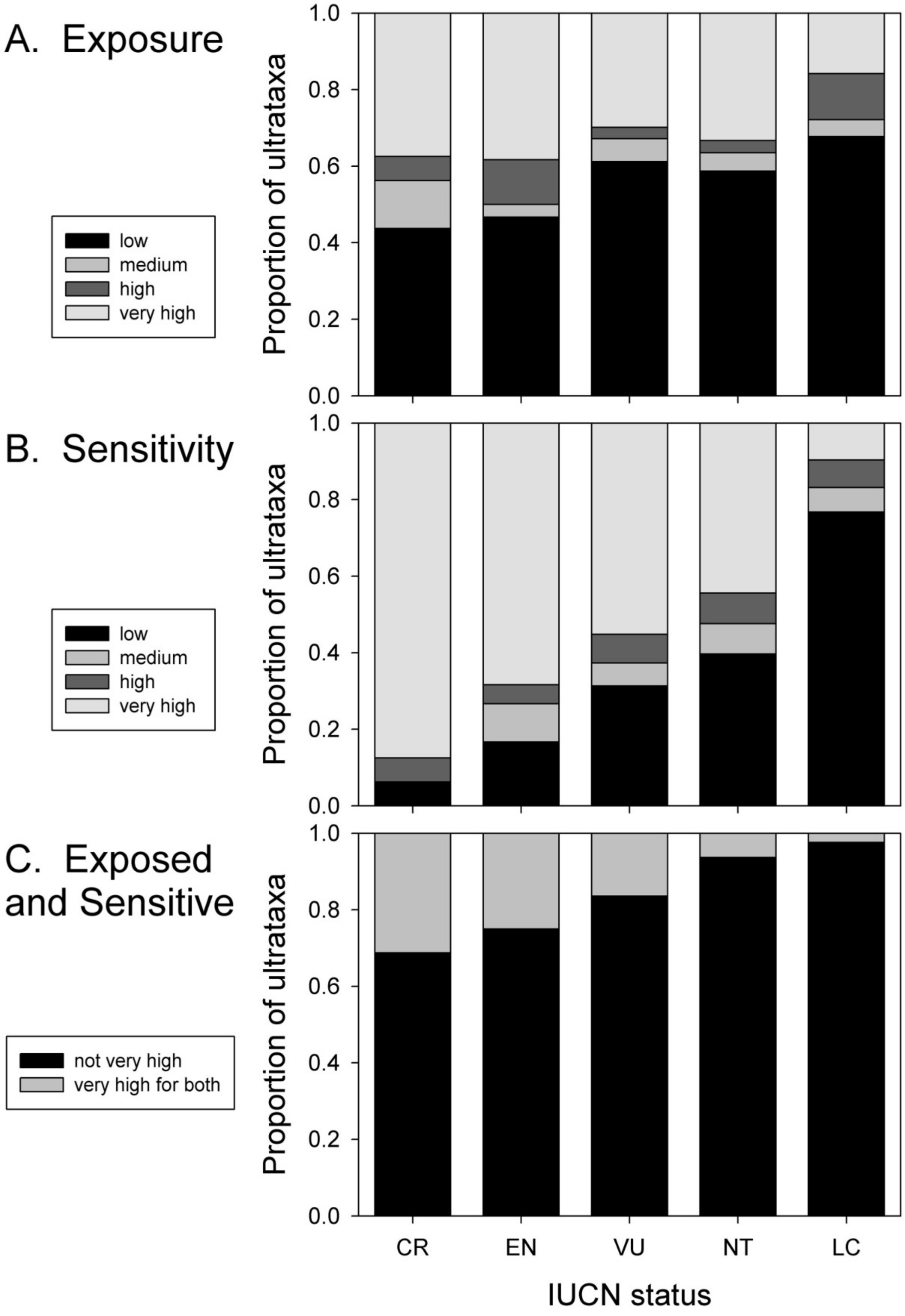

Figure 8. Proportion of Australian bird taxa in sensitivity and exposure classes by five IUCN Red List categories.

3.6 Adaptation strategies and associated costs

Full adaptation strategies were developed for only those birds considered to be both highly sensitive to climate change and very highly exposed. Less intensive actions were developed for those that were either very highly sensitive or very highly exposed but not both. The source of funds in each case is not known but, as currently, is likely to consist of a portfolio of government, private and volunteered input that differs for each taxon.

3.6.1 Immediate actions

3.6.1.1 Defined actions

3.6.1.1.1 Modelling of refugia

Fine scale modelling is needed for multiple areas to identify which sites need protection or conservative management so that can be available as refuges in the future (Table 19). Costs of modelling are averaged across all sensitive and exposed taxa likely to benefit, not just those that are both. The total cost for all modelling is $785,000 if each region is done separately, as is likely to be necessary if local knowledge is going to be incorporated and local planners involved in the modelling process, though this is only $6,000 per taxon. For four taxa fine scale modelling is recommended to identify potential sites for assisted colonisation outside the current range should the need arise. This will also require local knowledge and involvement to identify sites that are not only climatically suitable but potentially already have suitable habitat and secure tenure.

Table 19. Costs of fine scale modelling to identify terrestrial refugia for Australian birds exposed and/or sensitive to climate change (costs AU$'000)

		Cost				
	No. taxa	Exposed only	Sensitive only	Both exposed and sensitive	Total	Cost/ taxon
Detailed modelling within region						
Arnhem Land	4	30	0	30	60	15
Border Ranges	4	0	15	45	60	15
Cape York Peninsula	56	41	9	11	60	1
Gawler Ranges/Flinders ranges	2	30	0	30	60	30
Kangaroo Island	17	53	0	7	60	4
North-west Cape	1	0	0	60	60	60
Tiwi Islands	8	45	0	15	60	8
Western Victoria	4	45	0	15	60	15
Wet Tropics	24	25	32	3	60	3
Detailed modelling of potential refugia outside current range						
Noisy scrub-bird	1	0	0	60	60	60
Black-eared Miner	1	0	0	60	60	60
Orange-bellied Parrot	1	0	0	30	30	30
Slender-billed Thornbill (Gulf St Vincent)	1	0	0	30	30	30
Total	124	269	51	400	720	6

3.6.1.1.2 Surveys

Baseline surveys are required for two taxa before planning for climate change can take place. For the Brown Thornbill (King Island) *Acanthiza pusilla archibaldi*, any management can only take place if the continued existence of the subspecies is confirmed. A thorough survey for the subspecies is estimated to cost $60,000. For the Southern Boobook (Norfolk Island) *Ninox novaeseelandiae undulata* baseline numbers need to be re-established for the population if change is to be detected. Such a survey is estimated to cost $10,000.

3.6.1.1.3 Baseline taxon management and research

For three taxa, basic research and management is needed before the effects of climate can be managed. The Forty-spotted Pardalote *Pardalotus quadripunctatus* recently suffered a substantial decline, even in its stronghold on Maria Island off Tasmania, for reasons that are not understood (Bryant 2010). An understanding of the reasons for current declines is essential if the effects of climate change are to be recognised and managed. While more knowledge is desirable on nearly all taxa, for others the basic drivers of population trends are understood sufficiently well that the first steps in climate change adaptation are possible. The cost, estimated at $150,000, would cover a PhD on the species.

For two King Island subspecies, the Scrubtit *Acanthornis magnus greenianus*, which occurs as a single declining population of about 50 individuals in the centre of a single swamp (Donaghey 2011) and the Brown Thornbill *Acanthiza pusilla archibaldi*, which has not been seen since 2003 (Garnett *et al.* 2011), intensive management is required over the next decade if they are to persist at all. This may require cross-fostering to other species to increase the population size, reintroduction to places from which it has disappeared and intensive fire management. The cost is estimated at $100,000/yr for 10 years to cover both subspecies.

3.6.1.1.4 Assisted colonisation

For one species, the Eastern Bristlebird *Dasyornis brachypterus*, there is already a successful program of reintroduction of the southern subspecies *D. b. brachypterus* (Baker 2009), though this is not related to climate change. The tiny, isolated populations of the northern subspecies, *D. b. monoides*, are occasionally monitored but there is no active management, although vacant habitat exists (Garnett *et al.* 2011). If the subspecies is to persist then reintroductions will be needed, as well as assisted colonisation of new sites where habitat is suitable and where climate modelling predicts that the climate space will remain suitable for an extended period. Unlike assisted colonisation for most taxa however, where extended planning and proof of the necessity is prudent, delaying assisted colonisation of *D. b. monoides* may prove fatal. The project is estimated to cost $300,000, which is the cost of labour and field expenses for translocations. The techniques perfected for *D. b. brachypterus* are directly applicable to this subspecies, reducing research costs. The modelling suggests that areas of north-eastern NSW already known to contain suitable climate space will retain that suitability until at least 2085.

3.6.1.1.5 Land management

Most land management cannot be undertaken until there is more evidence of the way in which climate change will affect management choices. On Norfolk Island, however, five taxa in the rainforest of the national park will benefit from the immediate removal of a trial eucalypt plantation and its replacement with rainforest. This will not only reduce the risk of fire should the island dry out but will provide additional habitat for native species (DNP 2011). The cost is estimated to be $750,000 (25 ha at $30,000/ha), $15,000 per taxon.

3.6.1.1.6 Land purchase

For most taxa, land purchase in anticipation of climate change is premature. Either there is excessive uncertainty about whether taxa will respond to climate change in the ways predicted, there is currently ample land, much of it protected or unlikely to be alienated in the foreseeable future, in the areas likely to contain refugia, or any areas likely to contain refugia in fragmented landscapes (e.g. western Victoria, Kangaroo Island) are already secured for conservation purposes. This is the case with most of the areas where refugia modelling is suggested. However two taxa, Orange-bellied Parrot *Neophema chrysogaster* and Slender-billed Thornbill (Gulf St Vincent) *Acanthiza iredalei rosinae*, rely on saltmarshes in areas where not only are human populations growing but settlement is already pressed hard against the coast. Such areas are likely to offer an increasingly limited range of options for creating alternative habitat as sea level displaces the habitat they currently use. For each taxon a nominal one million dollars has been allocated for land purchase. For the thornbill, which is sedentary, modelling should be able to identify areas for potential purchase fairly readily, and parts of Clinton Conservation Park may already be suitable. Farmland in the region is currently on sale at $1,000/ha (http://www.realestate.com.au). For the Orange-bellied Parrot, which is almost extinct in the wild and migratory, identifying habitat which could be acquired for saltmarsh habitat may simply be too difficult and uncertain to warrant the expenditure, especially as it is questionable whether a shortage of saltmarsh is actually threatening this species. On the assumption that the most likely bottleneck for saltmarsh habitat will be King Island in Bass Strait, $1 million could purchase 300 ha at current prices (http://www.realestate.com.au).

3.6.1.2 Ongoing actions

3.6.1.2.1 Captive breeding

For most taxa, captive breeding is not yet necessary even if it is the best strategy. However, for two taxa identified as climate exposed and sensitive, the Orange-bellied Parrot and the Western Ground Parrot *Pezoporus flaviventer*, captive breeding is already under way and must continue indefinitely. This is estimated to cost $220,000 per year when aviary construction costs are averaged over the 50 year period. A captive population of Orange-bellied Parrots was established several decades ago and has recently been expanded to maximise its genetic variability. The species is maintained at seven separate institutions and is subject to best practice husbandry and genetic management. Three juvenile Western Ground Parrots are currently in captivity, where they have bred but not raised young, and 110 are believed to be in the wild at one location, the species having disappeared from all other locations over the last decade (Garnett *et al.* 2011; J. Blyth *in litt.*). Unless a captive insurance population is established in the next few years, climate change adaptation will not be necessary because it is likely to be extinct.

3.6.1.2.2 Monitoring

Knowledge of trends is essential for informing action. The total cost of monitoring is estimated to be about $1.5 million per year, of which two thirds would need to be spent on marine or small island taxa.

As noted above some taxa, especially rare taxa, need specialised techniques for monitoring. More widespread taxa can be monitored using general surveys, such as the Atlas of Australian Birds. Targeted regional monitoring is recommended for areas where substantial numbers of taxa are identified as exposed, sensitive or both. As with refugial monitoring, costs are averaged for all taxa confined to a region (Table 21), not just those that are both sensitive and exposed.

Table 20. Annual costs (AU$'000s) of monitoring Australian bird taxa that may be sensitive or exposed to the effects of climate change, or both.

		Cost				
Monitoring class	No. taxa	Exposed only	Sensitive only	Both exposed and sensitive	Total	Cost/ taxon
Terrestrial, inland water, mangrove and coastal taxa						
Arnhem Land	4	15	0	15	30	7.5
Beach nesting taxa	7	0	9	21	30	4.3
Border Ranges	4	0	8	15	23	5.6
Cape York Peninsula	56	20	4	5	30	0.5
Eungella	6	5	25	0	30	5.0
Kangaroo Island	17	26	0	4	30	1.8
King Island	10	21	0	9	30	3.0
South Australian ranges	11	22	0	8	30	2.7
Tiwi Islands	8	23	0	8	30	3.8
Wet Tropics	24	13	16	1	30	1.3
Dedicated single taxon monitoring	12	15	0	188	232	19.3
Atlas of Australian birds	1060	28	10	6	44[2]	0.04
Subtotal	1217	187	69	283	539	0.4
Marine and small island taxa						
Christmas Island	12	0	30	0	30	2.5
North Keeling Island	10	0	27	3	30	3.0
Coral Sea islands	6	0	15	15	30	5.0
Dirk Hartog Island	2	15	0	15	30	15.0
Cabbage Tree Island	1	0	0	30	30	30.0
Heard Island[1]	15	0	160	0	160	10.7
Heron Island	2	0	0	30	30	15.0
Houtman Abrolhos	6	0	15	15	30	6.0
Lord Howe Island	17	5	7	18	30	1.8
Macquarie Island	22	0	250	0	250	11.4
Marine non-breeding	39	0	200	0	200	5.1
Michaelmas Cay	2	0	0	30	30	15.0
Norfolk Island seabirds	7	0	4	26	30	4.3
Norfolk Island terrestrial birds	8	23	0	8	30	3.8
Raine Island	10	0	18	12	30	3.0

Monitoring class	No. taxa	Cost Exposed only	Sensitive only	Both exposed and sensitive	Total	Cost/ taxon
South-west Western Australian islands	5	0	30	0	30	6.0
Subtotal marine and small islands	139	43	752	201	1000	7.2
Total	396	230	814	496	1540	3.9

1. Heard Island costs are for once every 10 years only as it lacks threats and primary productivity in the vicinity is predicted to increase by 2100.
2. Full Atlas costs, which cover 1045 less exposed or sensitive Australian bird taxa, are estimated at $200K/yr

3.6.1.2.3 Species management

For threatened taxa, existing programs will need to be continued or intensified. None currently have explicit climate change adaptation provisions included within them. Across the 18 taxa for which this is thought to be needed, the cost is $1.26 million/yr, or $70,000 per taxon/yr (Table 22).

Table 21. Costs (AU$ '000s) of ongoing management of Australian bird taxa needed to sustain them in the face of climate change.

Taxon	Cost/yr
Red-tailed Black-Cockatoo (south-eastern) *Calyptorhynchus banksii graptogyne*	100.0
Glossy Black-Cockatoo (Kangaroo Island) *Calyptorhynchus lathami halmaturinus*	100.0
Orange-bellied Parrot *Neophema chrysogaster*	100.0
Western Ground Parrot *Pezoporus flaviventris*	200.0
Tasman Parakeet (Norfolk Island) *Cyanoramphus cookii cookii,* Southern Boobook (Norfolk Island x New Zealand) *Ninox novaeseelandiae undulata,* Golden Whistler (Norfolk Island) *Pachycephala pectoralis xanthoprocta,* Scarlet Robin (Norfolk Island) *Petroica multicolor multicolor,* Slender-billed White-eye *Zosterops tenuirostris*	100.0
Noisy Scrub-bird *Atrichornis clamosus,* Western Bristlebird *Dasyornis longirostris,* Western Whipbird (western heath) *Psophodes nigrogularis nigrogularis*	150.0
Southern Emu-wren (Fleurieu Peninsula) *Stipiturus malachurus intermedius*	100.0
Southern Emu-wren (Eyre Peninsula) *Stipiturus malachurus parimeda*	100.0
Black Grasswren *Amytornis housei* [1]	14.9
Eastern Bristlebird (northern) *Dasyornis brachypterus monoides*	100.0
Forty-spotted Pardalote *Pardalotus quadragintus*	100.0
Black-eared Miner *Manorina melanotis*	100.0

1. Costs from Carwadine *et al.* (2011) shared across all beneficiary taxa

3.6.2 Future actions

3.6.2.1 Defined actions

3.6.2.1.1 Establish new habitat

Given the rate of sea level rise new saltmarsh may need to be created deliberately for the Orange-bellied Parrot and the Slender-billed Thornbill (Gulf St Vincent). Using relatively old data from Louis Berger and Associates (1997), costs are estimated at $50K/ha so 100 ha would cost $5 million. Timing will depend on need, land availability and the rate of sea level rise. For other saltmarsh taxa it is assumed that appropriate habitat will be available in some form as climate changes and that no other new habitat will have to be created to accommodate birds as they shift across the landscape.

3.6.2.1.2 Feasibility study of potential management

For several marine taxa for which the productivity of waters near their breeding sites is predicted to decline, a number of actions can be undertaken to help them adapt to climate change. We therefore recommend a feasibility study to determine which strategy is most cost-effective – e.g. what is the feasibility of augmenting food for seabirds by reducing fishing intensity in areas where they obtain food while breeding? Could there be other ways of augmenting local food supplies? Alternatively, could new colonies be established in more productive waters if the birds are failing to move there themselves (c.f. Priddel *et al.* 2006; Miskelly *et al.* 2009). The cost of this feasibility study is estimated at $100,000 shared across 10 seabird taxa.

3.6.2.1.3 Marine refugia modelling

The identification of marine refugia needs to be undertaken in the future because their location is likely to change, so this is not captured under 3.6.1.1.1. They may also differ for different species. Thus, identification of refugia is assumed to require a separate study of each taxon, which gives a cost of $2.2 million for 11 marine taxa. Costs are those of a PhD scholarship, associated supervisory costs, and the costs of tracking devices that would be used to locate the sites where the seabirds feed most frequently while provisioning young. Once located, these areas can be the subject of local management (e.g. fishing regulations etc.). For seven taxa, knowledge is required of the basic biology, so it is recommended that the relationship between foraging and breeding success, population density and productivity of surrounding seas is investigated, including tracking to determine use of marine habitat in space and time. For four taxa, much original research has been undertaken so it may only be necessary to investigate the locations and characteristics of key feeding sites during breeding and the means to retain their value under climate change.

3.6.2.1.4 Assisted colonisation

Three classes of action related to assisted colonisation were considered.

Feasibility studies of genetic supplementation

For many species the climate space that is predicted to be lost by one subspecies is predicted to be filled by another subspecies. However, the potential replacement subspecies are likely to be prevented from such replacement by the same barriers that led to the evolution of subspecies in the first place. This may mean that the resident subspecies already have the capacity to cope with the new climate but this has never been tested. However, it may also mean that there has been local adaptation to slightly differing climates and the transfer of this genetic capacity could lead to persistence of the species in the landscape even if the subspecies is no longer ‘pure’ because it now has additional genetic material. There were four cases where it was felt that feasibility studies could be warranted in the future to consider the practicality and social acceptability of moving some individuals of climate-adapted taxa to augment the populations of taxa for which the climate space is predicted to disappear. These are described below. A cost of $100,000 is estimated for each feasibility study.

Cape York Peninsula: Of the 56 exposed or sensitive taxa on Cape York Peninsula, 41 also occur in New Guinea, in some cases as the same subspecies but mostly as separate subspecies. This includes all the rainforest specialists but also six savannah taxa. All but one of the savannah species also has subspecies in the Top End or the Kimberley for which the climate space is predicted to expand into Cape York Peninsula by 2085. Another four savannah subspecies predicted to lose climate space have endemic Australian subspecies from the Top End with climate space distributions that may extend into the Peninsula.. It is not known whether the climate space of any of the New Guinea taxa is likely to extend over Cape York Peninsula but it may be worth investigating, as is the social acceptability of such genetic transfer among the people of Cape York Peninsula.

Tiwi Islands: For seven of the eight endemic Tiwi Island taxa for which it is predicted that the climate space will disappear entirely, there are potentially replacement taxa on the mainland living in very similar habitat as is widespread on the island. The main consideration would appear to be whether the Tiwi Island people would consider genetic augmentation of their fauna with mainland genetic material. $100,000 is estimated as the cost of a feasibility study to be undertaken should local populations of the endemic subspecies decline. It should be noted that one climatically isolated Tiwi island subspecies, the Tiwi Hooded Robin *Melanodryas cucullata melvillensis*, has already gone extinct (Garnett *et al.* 2011).

Kangaroo Island: all of the 17 subspecies endemic to Kangaroo Island have equivalents on the mainland that could be used to augment the local genetic pool, possibly to their benefit as climate changes.

Hooded Plover: While it was not possible to model the climate space of the beach-reliant eastern subspecies of Hooded Plover *Thinornis r. rubricollis*, it is under substantial pressure from beach users, pressure that may be exacerbated by rising sea levels. The Western Australian *T. r. tregellasi*, however, nests beside inland salt lakes. It is predicted to have suitable climate space in western Victoria by 2085. The introduction of some *T. r. tregellasi* to Victoria could result in eastern birds nesting away from vulnerable beaches and taking advantage of the fringes of western Victoria’s salt lakes. Again, such a proposal would need to be assessed for technical and social feasibility, not least among the many volunteers who protect the beach nests of *T. r. rubricollis.*

Brown Thornbill: The King Island subspecies *Acanthiza pusilla archibaldi* may already be extinct, and is predicted to have no climate space by 2085. Introduction of the mainland subspecies *A. p. pusilla*, for which King Island is predicted to remain climatically suitable, could augment any remaining *A. p. archibaldi* on King Island and the increased population restore whatever ecological function *A. p. archibaldi* was fulfilling before it declined. Where possible genetic augmentation should be undertaken long before a population reaches near extinction to maximise retention of locally-adapted variation.

Feasibility studies for assisted colonisation

For three groups of birds assisted colonisation was considered as an adaptation strategy for the taxon being moved:

Norfolk and Lord Howe Islands: the creation of additional populations of Norfolk Island land birds on Lord Howe Island once rats have been eradicated. Lord Howe Island lost five taxa to rats early in the 20th century for which Norfolk Island has closely-related equivalents: the Southern Boobook *Ninox novaeseelandiae undulata*, Tasman Parakeet *Cyanoramphus cookii cookii*, Norfolk Island Gerygone *Gerygone modesta*, Grey Fantail *Rhipidura fuliginosa pelzelni* and the Slender-billed White-eye *Zosterops tenuirostris*. Their establishment on Lord Howe Island would not only help restore that island's biological functionality but would also act as an insurance against climate change induced declines on Norfolk Island.

Border Ranges: five taxa from the rainforests of south-eastern Queensland and north-east New South Wales are predicted to lose their climate space by 2085. All five, Coxen's Fig-Parrot *Cyclopsitta diophthalma coxeni*, both subspecies of Rufous Scrub-bird, *Atrichornis rufescens ferrieri* and *A. r. rufescens*, the northern subspecies of Eastern Bristlebird *Dasyornis brachypterus monoides* and Albert's Lyrebird *Menura alberti*, are predicted to have new climate space available in southern Australia, particularly north-west Tasmania. Such a move could have many consequences and should not proceed without completion of a full risk assessment.

Assisted colonisation:

Assisted colonisation may be an option for a range of taxa. For four Endangered or Critically Endangered taxa, it is recommended that this be considered as soon as there is an indication of climate-driven decline in the source population and there is agreement from the receiving community that it should occur. The total cost is estimated at $2.82 million for four taxa. Costs for different taxa vary greatly.

For the Glossy Black-Cockatoo from central Queensland, *Calyptorhynchus lathami erebus*, the Mount Lofty Ranges is already predicted to be climatically suitable and is predicted to become increasingly so. This area already contains suitable habitat and was occupied by *C. l. halmaturinus* in the 19th century before its range retracted to Kangaroo Island. However Glossy Black-Cockatoos are highly specialised, raise one young each year at most and remain dependent on their parents for a long time after they fledge as they learn how to feed on casuarinas and, presumably, where to find food trees. Captive breeding and release is therefore likely to be slow and expensive (Crowley *et al.* 1999). Here, the cost is estimated at $10,000 per bird with 100 birds being required to ensure a population of sufficient size as founders. It should be noted that this action aims to retain this species in its former South Australian range – for *C. l. erebus* itself suitable CS expands within the northern part of the current range of *C. l. lathami.*

The risks of losing the Southern Boobook on Norfolk Island (*N. n. undulata*) to climate change or other causes could be greatly reduced by reintroducing it to Lord Howe Island. Assuming the social acceptability survey for multiple taxa has a favourable response for the boobook, the process would involve captive breeding of *N. n. undulata* to increase numbers ($220K/yr for 5 years using refurbished existing aviaries) and subsequent release and monitoring ($100K/yr x 3 yrs).

Given the high probability that the local subspecies of Brown Thornbill on King Island, *A. p. archibaldi*, is either extinct or so scarce that none can be found, there is potential to introduce individuals of *A. p. pusilla* from the mainland since the island is predicted to retain a suitable climate for this subspecies under climate change. The subspecies is common on the mainland so reintroduction, if agreed to by King Island residents, is expected to involve the capture of 100 individuals of *A. p. pusilla* on the mainland and transferring them directly to an appropriate site on King Island, a process that would be followed by three years of research and monitoring to ensure their survival. This is costed at one full-time salary plus field costs for one staff member ($100k/yr for 3 yrs).

The techniques for translocating Black-eared Miners to new locations are well-known (Clarke *et al.* 2003). We suggest that two additional translocations be trialled, but this time to sites for which there is no historical record of occupation but where fine scale refugia modelling suggest will be suitable under climate change, which makes them assisted colonisation. The cost of doing so is estimated at $50K/site/yr for three years.

3.6.2.2 Ongoing actions

3.6.2.2.1 Maintain and improve habitat quality

Most actions that will be taken to maintain or improve habitat quality are actions that are or should be undertaken to counter current threats to habitat integrity, though with greater intensity. A summary of the investment likely to be required for different regions and the types of actions that are likely to be required are described in Table 23. Fire management is likely to be a key activity in most regions, along with feral animal and weed control.

Table 223. Additional investment (AU$'000s) required to manage threats to Australian bird taxa exacerbated by climate change with respect to region, and their attributes.

Region	No. taxa	Area	Landscape complexity	Potential principal tasks	Units allocated	Cost p.a.
Arnhem Land	4	Large	Low	Fire management, feral herbivore control	4	400
Border Ranges	4	Small pockets	High	Fire management, feral predator control, weed control	1	100
Cape York Peninsula	56	Pockets within large area	Medium	Fire management, feral herbivore control	10	1,000
Dirk Hartog Island	2	Small	Low	Fire management	0.5	50
Kangaroo Island	16	Medium	High	Fire management, native herbivore control, connectivity retention/restoration	5	500
Marine habitat key sites	5	Very large	High	Fishing management, location of key sites, reduction of threats at nest sites	20	2,000
North-west Cape	1	Small	Low	Fire management, fig protection	0.5	50
Gawler and north Flinders Rangers	2	Small pockets	Low	Fire management, feral predator control, reintroductions after local extinctions	1	100
Tiwi Islands	8	Medium	Low	Fire management, feral herbivore control, weed control	3	300
Wet Tropics	24	Large	High	Fire management, feral predator control, weed control, connectivity retention/restoration, reintroductions after local extinctions, management of competition for refugia from common native taxa	10	1,000

3.6.2.2.2 Species management

While habitat management must necessarily take into account the needs of particular components of that habitat, some specific actions have been identified as necessary for individual taxa that cannot easily be grouped under regions. Detailed actions may also become necessary for other taxa as climate change progresses but, for most, too little is known about their current ecology let alone their interactions with the environment under an altered climate for recommendations to be made now.

Supplementary feeding

The most likely result of climate change for the Lord Howe Woodhen *Gallirallus sylvestris*, the Lord Howe subspecies of Pied Currawong *Strepera graculina crissalis* and the Houtman Abrolhos subspecies of Painted Button-quail *Turnix varia scintillans* is a shortage of food that may occur if there is less rain. It is therefore suggested that the most efficient strategy for maintaining the taxa extant will be provision of food for at the nominal cost of $1,000 per year. For the button-quail an alternative might be to introduce to the islands food plant species that are better suited to an altered climate (c.f push-pull assisted colonisation; Lunt *et al.* 2013), depending on the acceptability of the other ecological consequences of such an introduction.

Active nest site protection

Many Australian beach nesting birds are already the subject of extraordinary volunteer effort to protect them from humans, their pets and introduced predators. Sea level rise may mean these efforts will have to include active protection against exceptionally high tides and storm events. Seven taxa may benefit: five are considered very highly exposed to sea level rise: Beach Stone-curlew *Esacus giganteus*, Australian Pied Oystercatcher *Haematopus longirostris*, the eastern subspecies of Hooded Plover *Thinornis rubricollis rubricollis*, western Pacific Ocean subspecies of Little Tern *Sternula albifrons sinensis* and the Australian subspecies of Fairy Tern *Sternula nereis nereis*. Two others, the southern and northern subspecies of Sooty Oystercatcher *Haematopus fuliginosus fuliginosus* and *H. f. ophthalmicus*, nest rather higher on beaches than the Pied Oystercatcher but may still warrant special attention because rocky coastlines are less malleable than beaches so the capacity of birds that rely on rocky areas for nesting to adapt may be more limited than those using beaches which may move inland as the sea rises. Most of the effort protecting nests will probably continue to be undertaken by volunteers, but additional investment in part-time employment may be needed to link the volunteer activity with the areas most threatened by sea level rise. A single half time position of $30,000 per year is estimated as being required in about 25 years' time.

Irrigation of food trees

The Glossy Black-Cockatoo on Kangaroo Island eats the seeds of only one tree *Allocasuarina verticillata*. Seeding of this tree is affected by water and nutrient availability (Cameron 2006; Chapman and Paton 2007). Should food shortage become a problem then select trees could be provided with additional food and water to increase seed productivity. The cost is estimated at $30,000 per year, starting in 2037.

Alternatively the funds could be used for establishing other *Allocasuarina* species that can produce seed under the altered conditions.

Intensified fire management

For most regions extra fire management is likely to be necessary as the climate changes. Additional fire management, in the form of e.g. greater protection burning, more intense burning across the season to retain a mosaic of fire ages and accelerated response times to fire outbreaks, is thought likely to be required for several individual taxa, though this is often only to focus existing fire management that is already occurring as standard management practice on areas most important for the taxa in question. Taxa for which some form of additional fire management is anticipated are the Western Ground Parrot *Pezoporus flaviventris*, Chestnut-rumped Heathwren from the Flinders Ranges *Hylacola pyrrhopygia pedleri*, and the Western Whipbird from both eastern Australia, *Psophodes nigrogularis leucogaster*, and the western wheatbelt, *Psophodes nigrogularis oberon*. For each, the cost of additional fire planning is nominally set at $20,000 per year starting in 25 years' time.

3.6.2.2.3 Captive breeding

Captive breeding is considered the option of last resort for 29 taxa in addition to the two for which it is already being undertaken (Table 24). For most taxa it is suggested that captive breeding will not be needed for at least 40 years, by which time the extent of their response to climate change and risks to their persistence, particularly from catastrophic events, may be apparent. For the very rare Brown Thornbill from King Island and the Black-eared Miner it is thought that insurance populations may need to be established within the next ten years while, for Forty-spotted Pardalote, captive populations may be needed within 25 years if current trends continue. On this timing, given a cost of $220,000 per taxon per year, the total cost would be $1.56 million per year for 50 years. However this expense will be punctuated by the high cost of aviary construction if 25 taxa have to be taken into captivity in 40 years (Figure 9). By the end of 2053 annual costs to maintain 30 taxa in captivity indefinitely would be $5.4 million per year at today's prices.

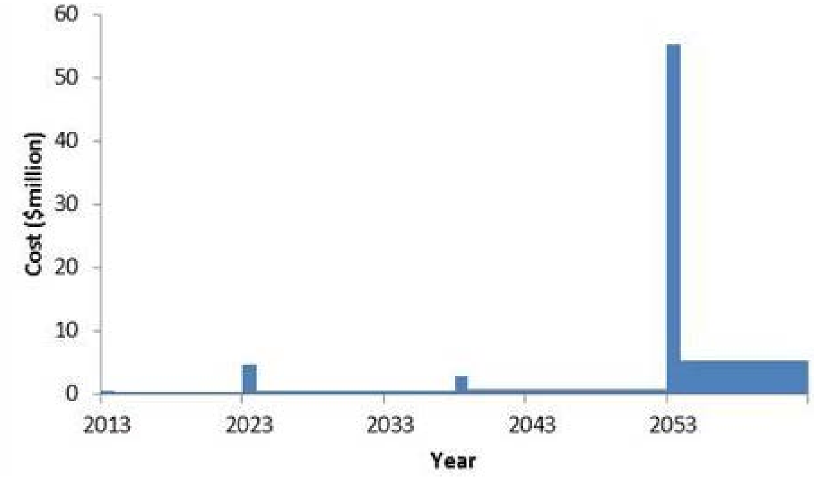

Figure 9. Annual costs of captive breeding of the 30 Australian taxa that or may have to be kept in captivity indefinitely should they be unable to persist in the wild under new climatic conditions.

Table 23. Australian bird taxa for which captive breeding may be necessary should they prove as sensitive and exposed to climate change as predicted and adaptation actions fail to stem declines.

Brown Cuckoo-Dove (Cape York Peninsula) *Macropygia amboinensis quinkan*
Chestnut-quilled Rock-Pigeon *Petrophassa rufipennis*
Wompoo Fruit-Dove (Cape York Peninsula) *Ptilinopus magnificus assimilis*
White-rumped Swiftlet (Chillagoe) *Aerodramus spodiopygius chillagoensis*
Palm Cockatoo (Australian) *Probosciger aterrimus macgillivrayi*
Red-tailed Black-Cockatoo (south-eastern) *Calyptorhynchus banksii graptogyne*
Glossy Black-Cockatoo (Kangaroo Island) *Calyptorhynchus lathami halmaturinus*
Double-eyed Fig-Parrot (Cape York Peninsula, Marshall's) *Cyclopsitta diophthalma marshalli*
Eclectus Parrot (Cape York Peninsula) *Eclectus roratus macgillivrayi*
Noisy Pitta (Cape York Peninsula) *Pitta versicolor simillima*
Spotted Catbird (Cape York Peninsula) *Ailuroedus melanotis joanae*
Western Bowerbird (North-west Cape) *Ptilonorhynchus guttatus carteri*
Southern Emu-wren (Dirk Hartog Island) *Stipiturus malachurus hartogi*
Southern Emu-wren (Fleurieu Peninsula) *Stipiturus malachurus intermedius*
Southern Emu-wren (Eyre Peninsula) *Stipiturus malachurus parimeda*
Short-tailed Grasswren (Gawler Ranges) *Amytornis merrotsyi pedleri*
Scrubtit (King Island) *Acanthornis magnus greenianus*
Brown Thornbill (King Island) *Acanthiza pusilla archibaldi*
Forty-spotted Pardalote *Pardalotus quadragintus*
Yellow-tinted Honeyeater (Tiwi Islands) *Lichenostomus flavescens melvillensis*
Black-eared Miner *Manorina melanotis*
Chowchilla (northern) *Orthonyx spaldingii melasmenus*
Western Whipbird (Kangaroo Island) *Psophodes nigrogularis lashmari*
Black Currawong (King Island) *Strepera fuliginosa colei*
Frilled Monarch (Cape York Peninsula) *Arses telescopthalmus lorealis*
Yellow-breasted Boatbill (Cape York Peninsula) *Machaerirhynchus flaviventer flaviventer*
Northern Scrub-robin (Australian) *Drymodes superciliaris superciliaris*
Horsfield's Bushlark (Tiwi Islands) *Mirafra javanica melvillensis*

3.6.3 Total costs

The total costs of climate change adaptation for Australian birds based on the assumptions and methods described in this report are summarised in Table 25. In today's dollars, with no future discounting, the annual cost would be $18.8 million per year or $47,500 per taxon that is considered exposed or sensitive to climate change, or both. For the full 50 years it would be $941 million, or $2.4 million per taxon. The most expensive items are the ongoing costs of refugia management once those are identified, secured and managed for climate change adaptation, captive breeding for a relatively small number of taxa should their survival in the wild become untenable, monitoring and the management of individual taxa, and management of threatened taxa that need individual attention if they are to persist long enough for climate change adaptation to be necessary.

Table 24. Costs/yr (AU$'000s) of climate change adaptation for the next 50 years for Australian bird taxa that are highly sensitive, highly exposed or both (total taxa 396: exposed 177, sensitive 151, both 68)

	Exposed	Sensitive	Both	Total	Cost/taxon
Immediate costs					
Defined projects					
Assisted colonisation	-	-	120	120	0.30
Land management	450	-	300	750	1.89
Land purchase	-	-	2,000	2,000	5.05
Modelling	268	56	456	780	1.97
Surveys	-	-	70	70	0.18
Species management	-	-	1,150	1,150	2.90
Ongoing costs					
Captive breeding	-	-	440	440	1.11
Monitoring	230	646	467	1,344	3.39
Species management	60	-	1,205	1,265	3.19
Potential future costs					
Defined projects					
Assisted colonisation			2,800	2,800	7.07
Establish new habitat			1,400	1,400	3.54
Feasibility study for genetic supplementation	230	64	407	700	1.77
Feasibility study of potential management			100	100	0.25
Marine refugia modelling			2,000	2,000	5.05
Ongoing costs					
Captive breeding	-	-	1,606	1,606	4.06
Refugia management	1,009	388	820	2,217	5.60
Species management	-	-	73	73	0.18
Total	2,247	1,154	15,414	18,815	
No. taxa	176	154	66	396	
Cost/taxon	13	7	234	47.5	

4. DISCUSSION

4.1 In situ *adaptation*

In identifying the actions required to assist birds to adapt to climate change, the principal message is do more of the same, much more. This message is not new, and may be applicable to most intact landscapes – generally the best adaptation to climate change will be to enhance the resistance and resilience of taxa *in situ* (Millar *et al.* 2007). Most threats are likely to intensify, not change in nature. Fire, weeds, feral herbivores, predators and over-fishing are all likely to need continued management regardless of the climate. It should also be noted that, while threatened birds were more likely to be exposed or sensitive to climate change, many were not. Continued management of threatened species will be needed regardless of climate change – for the most part climate change only intensifies some threats by acting synergistically with them. Only for beach-nesting and saltmarsh-dependent taxa does climate change provide a certain threat, though even then the severity of sea level rise as a threat is uncertain and the birds and their habitat may shift more easily than we anticipate, as they have during earlier phases of sea level fluctuation.

One threat that, surprisingly, seems to be relatively unimportant with respect to climate change adaptation is the effects of clearance and habitat fragmentation that has already taken place. For the intensively used parts of eastern and south-western Australia the climate change models suggest that the climate space of resident birds will shift towards the coast but largely to areas with relatively intact natural environments. This does not mean that there may not be substantial local extinctions as the inland habitats in particular become climatically unsuitable, but the taxa themselves are likely to have climate space remaining within or adjacent to their current ranges. This may be partly an artefact of the very high cutoff we placed on classifying taxa as extremely exposed to climate change, which meant that taxa on the fringes of the continent that lost all or most of their climate space were more likely to be included. Nevertheless none of the very highly sensitive taxa were birds of the habitats that have been favoured for development. Thus, it is in the relatively intact landscapes of Cape York Peninsula, the Wet Tropics uplands, Kangaroo Island and the Tiwi Islands where most *in situ* adaptation will need to occur, and where climate change refugia will need to be identified.

The other surprising absence among the *in situ* management options was the need for the retention of corridors for conservation of entire taxa, although they are an essential part of the conservation of taxa within fragmented habitats (Chambers *et al*. 2005). Almost all taxa requiring refugia are already occurring in the habitats where the refugia are likely to persist. A small number do lose all their climate space but may have climatically suitable areas develop in other parts of the country. In each case, however, corridors will not play a part in linking new and old climate space – the transfer will need to be through assisted colonisation.

4.2 Assisted colonisation and genetic augmentation

4.2.1 Genetic augmentation

There are many cases where the climate space for one subspecies will entirely disappear from an area but that of a sibling subspecies will entirely encompass it. The importance of environment in the expression of genetic traits is an area of intense research (e.g. Andrew *et al.* 2010) and the risk of compromising the capacity of local populations to adapt can be of concern (Laikre *et al.* 2010; Byrne *et al.* 2011). The challenge is that conservation managers are caught between the dangers of both inbreeding depression in which, when populations shrink deleterious genes are expressed, and outbreeding depression in which local adaptation is overwhelmed (Edmands 2006). Thus, before any genetic augmentation is contemplated, feasibility studies will need to be undertaken that include assessment of the acceptability to the local human community who ultimately will live with the consequences and participate in the management of the new genetic material (Burbidge *et al.* 2011).

For the most part, the nature of the adaptations that may be lacking in one subspecies but appear to be present in the other are not known. For the Hooded Plover, however, the adaptation would appear to be behavioural – one subspecies nests beside saline lakes across south-western Australia and has low exposure or sensitivity to climate change. The other nests only on beaches where it is beset not only by a wide range of existing threats but will now have to cope with sea-level rise in areas where coastal development is most intense. There would appear to be many advantages of introducing the traits of one subspecies to the other in terms of conserving the species in eastern Australia. However the new entity would not be the same – it would be in a habitat not currently used by eastern Hooded Plover and have different genetic material. The philosophical underpinnings of the purpose of conservation would need to be quite clear before such genetic augmentation was contemplated and the ultimate decision will necessarily be political, a judgement on how society values such novel entities. Curiously, were the eastern Hooded Plover to move to lakes for breeding of their own accord, it would probably be seen as a remarkable adaptation to climate change.

4.2.2 Assisted colonisation

Assisted colonisation is recommended for very few taxa. For just one, the Critically Endangered northern subspecies of Eastern Bristlebird, we recommend that it occur immediately. For another four we suggest it should be considered seriously if local adaptation proves unlikely. In two cases, the area into which the taxon would be transferred is small and isolated (King Island, Lord Howe Island) and in three cases the taxon being assisted to colonise would be fulfilling the ecological functions of close relatives that have disappeared in the recent past (c.f. Lunt *et al.* 2013). In the final case, that of the Black-eared Miner, the proposed assisted colonisation would be a extension of recent management to areas where climate modelling suggest the species' climate space will persist. In no case do any of the taxa have biological characteristics that suggest they would pose any threat to the receiving environment, though all would need to be assessed thoroughly before any movement occurred. Similarly, the taxa for which assisted colonisation feasibility studies are recommended, those from Norfolk to Lord Howe Islands and from the rainforests of the Border Ranges to areas identified by fine scale modelling further south, are all taxa with low fecundity and highly specialised habitat. However such movement may not prove necessary for three of the mainland taxa – Albert's Lyrebird and the two subspecies of Rufous Scrub-bird. Their current habitat is intact and protected and they are among the most ancient of Australian passerines, suggesting they have had the capacity to weather much climate change in the past.

4.3 **Ex situ** ***conservation***

We recommend captive breeding only as a last resort option. While recognising it is currently essential for two parrot species, and may be for a few other very scarce taxa in the near future, we share the view of those managing the breeding programs that they are insurance populations just in case management of wild birds fails, and that the ultimate objective is to retain wild populations or restore them as soon as possible after threatening processes are ameliorated. However we have necessarily included captive breeding as an option should society wish to invest in retention of taxa where attempts to retain them in the wild are unlikely to succeed. And we have suggested that the captive breeding be initiated in about 40 years, several decades before the time when the models predict all their climate space will be gone, so that the captive populations have a realistic chance of persistence with a full complement of the wild genetic diversity.

In many ways, the number of taxa for which captive breeding could be contemplated in the next 50 years is relatively small. Several bird taxa that are facing threats other than climate change probably have higher priority for captive breeding resources than those listed here.

In the meantime, there probably needs to be public debate about the extent to which all genetic variation needs to be retained and whether retention of captive populations of subspecies for which the species is secure warrants the investment. Just three of the taxa recommended for captive breeding are species (Chestnut-quilled Rock-Pigeon, Forty-spotted Pardalote, Black-eared Miner) in addition to the two parrots already in or mooted to be kept (Orange-bellied and Western Ground Parrot). The remaining 25 are subspecies of species that are likely to persist in the wild, even if not in Australia for some of the Cape York Peninsula taxa. Quite apart from the resources required, the technical challenge of retaining any semblance of the original form past a few generations in captivity will be formidable, if not prohibitive (Araki *et al.* 2009).

4.4 *Uncertainty*

Predicting the consequences of climate change for birds is somewhat analogous to projecting a regression line beyond the data points used to fit the line in the first place. The underlying assumption is that trends into the future will be simple linear extrapolations of existing relationships, for example of taxa to climate even if mediated by food supply, vegetation or other factors including the complex web of ecological interactions. Whilst there is considerable evidence that some species are already tracking their climate envelopes (Parmesan and Yohe 2003), and that the ability or need to do so is related to species-specific traits such as ecological generalism (Pöyry *et al.* 2009; Reif and Flousek 2012) which we have approximated with our assessment of sensitivity, it is also possible that the predictive power of this conceptual model is limited and will decline with time. Evidence of geographic responses to past climate change, notably during and since the last glaciation that peaked c. 18,000 years ago, is mixed (e.g. Graham *et al.* 1996; Roberts and Hamann 2012) – and places particular emphasis on the role of refugia (Hilbert *et al.* 2007; Byrne 2008). Even if extrapolation were robust, limits to the accuracy of predictions would also arise due to inevitable quirks and constraints of the modelling process, including assumptions about projected climate change itself.

Uncertainty reinforces the need for monitoring, frequent revision of outlooks, and flexibility in management responses.

4.4.1 Sensitivity

We have devoted considerable energy to developing a measure of sensitivity. There is no justified benchmark or standard available; notwithstanding a few applications, the notion of sensitivity is at best moderately developed conceptually and weakly developed metrically. The choice of metrics, their quantification and conversion to sensitivity indices, and their aggregation into an overall measure all involve best judgement and compromise to facilitate generalisation across a wide range of taxa. Further, our study is probably the first to apply a consistent measure of sensitivity to an entire avifauna, imposing constraints on data availability and relevance in rating and comparing, for example, small forest passerines with nomadic desert waterbirds and seabirds nesting on coral cays.

Dispersal ability is a key species-specific trait that we were unable to generalise and formally incorporate into our sensitivity measure. In assessing individual taxa, we were surprised how limited its relevance appeared, as indicated by the relatively few taxa for which we recommended assisted colonisation. The general mobility of birds, along with an evolutionary history of long-term climate change in a flat landscape (necessitating long-range responses) and seasonal and interannual climate fluctuations, may have predisposed most Australian species to adapt to change by moderate- to long-distance dispersal (Keast 1960; Kingsford and Norman 2002). However, exceptions are likely to be frequent and almost certainly under-rated by our study because of our emphasis on the threat of national rather than regional extinction and that we didn’t quantitatively incorporate the effect of human pressure on habitat. The focus for dispersal is likely to be species that have or are persistent only in refugia, and those reduced to refugia by human- or climate-change-induced fragmentation of habitat. The degree of habitat specialisation in the Australian avifauna may add to the importance of refugia.

4.4.2 Exposure

We have already explored the assumptions of climate space models in the methods section. The relationship between climate and the realised, potential and fundamental niche of taxa remains a vexed question (Soberón and Nakamura 2009). Further, in Australia, relationships to climate may be less relevant than more direct relationships to vegetation type compared to higher latitudes of the northern hemisphere where much work in testing climate space models has been undertaken. These higher latitudes were largely glaciated in recent geological time and the vegetation that has developed since lacks the local and regional variation evident in Australia and other warmer temperate and tropical regions that were not glaciated. On the other hand, both a recent history of glaciation and environmental change at high latitudes, and a history of climatic vicissitude in Australia suggest the promotion of a generalist avifauna in both places that may respond similarly to climate change – the contrast being with the diverse and specialised rainforest avifaunas of Africa, South-East Asia and central and South America.

Climate envelope models are either not available for, or not very relevant to, marine, coastal and small island taxa, and we have made more subjective judgements about the exposure of these taxa. Change to marine productivity, as used in this study, provide a marine analogy to climate space but the exposure of marine taxa to climate change is far more complex and would need to be explored at a local and taxon level over time to understand its full implications. It is unclear how effective a proxy change to marine productivity is for other processes likely to generate exposure for marine birds, for example latitudinal and other geographic shifts in sea surface temperatures and the food sources that track these changes.

4.4.3 Vulnerability

Though the conceptual model of vulnerability (Williams *et al.* 2008; Dawson *et al.* 2011), of which we have employed a variant, requires that taxa be both exposed and sensitive, it is possible that extreme vulnerability may arise without very high levels of both. It is for this reason that we have provided lists of taxa with very high ratings for either one in the absence of the other. For example, if a taxon has strong habitat specificity and no dispersal capacity because the next suitable habitat patch is too far away, it may be seriously adversely affected by even mild exposure to climate change that generates a tipping point for its habitat.

The conceptual model also fails to incorporate the complexity of ecological webs (McMahon *et al.* 2011) except insofar as climate provides a useful generalised proxy for them. It is not possible to incorporate this complexity across a wide range of taxa, though some progress has been made in doing so for single taxa that are relatively well-understood (e.g. Harris *et al.* 2012). This complexity suggests that non-linear responses are likely to be frequent, providing an important qualifier to extrapolation.

The vulnerability of taxa we have identified, along with that of many taxa we have not, should be reviewed on a case-by-case basis in due course. We flag here a few key regional uncertainties in the vulnerability assessment of Australian birds.

Our modelling has flagged the possibility that the climate to support rainforest on Cape York Peninsula will be replaced by a climate suitable for savanna, potentially driving a suite of rainforest-specialist birds to extinction. Assisted colonisation of a few to the Wet Tropics may provide a feasible conservation measure (Anderson *et al.* 2012), though the recent models we have applied here do not corroborate Anderson *et al.*'s findings. In any case the presence of close relatives and other likely competitors may render this inappropriate for many of the Cape York Peninsula rainforest taxa. However, our modelling runs counter to the observation that rainforests in the area are currently expanding at the expense of savanna, an effect attributed to exclusion of traditional fire regimes (Russell-Smith *et al.* 2004a,b). A CO_2 fertilisation effect may also favour rainforest over savanna. How these conflicting trends will resolve may not become apparent for decades, but we flag the possibility of transition of rainforest to a more seasonal and drought-tolerant monsoon forest, a habitat not currently well-developed in Australia but which may continue to support some, but probably not all of the Cape York rainforest specialists.

Another major source of uncertainty in vulnerability arises with fire regimes in spinifex-dominated landscapes and their effect on the number of taxa that depend on old-growth spinifex environments. The outlook for southern spinifex landscapes with heavy interspersion of woody vegetation (e.g. mallee) is not bright. However, the outlook for central and north Australian spinifex landscapes and their birds is much less certain, and there appears to be a reasonable prospect for successful interventions in the form of fire management, tempered however by the remoteness of many of these landscapes.

The vulnerability of beach-nesting taxa to rising sea-levels is also a major source of uncertainty. We have flagged a number of species for more intensive monitoring – both of the birds and of coastal geomorphological processes – but it is possible that some will prove quite able to track rising coastlines successfully as they have done at a massive scale since the last glaciation.

On the other hand, some vulnerabilities are likely to have gone undetected in this study. Of particular concern are those where biotic interactions may play a key role. As possible examples, we note that speciose Australian granivore and honeyeater assemblages commonly involve fine partitioning of resources within seemingly homogenous landscapes. Subtle changes to resource availability are already implicated in the decline of rich-patch specialists such as the Gouldian Finch *Erythrura gouldiae* (Woinarski 1999) and Regent Honeyeater *Anthochaera phrygia* (Ford 2011a). We anticipate further shifts within these and similarly diverse assemblages under climate change with positive impacts for some taxa and negative effects for others that are difficult to predict.

4.4.4 Actions

Uncertainty with the actions needed for management arises not only with the need for action but also its timing and outcomes.

In some environments, change may come incrementally and be detected in time for an adequate response provided that monitoring is frequent and robust. In others, we envisage ecosystem tipping points that may occur abruptly and unpredictably. Laurance *et al.* (2011) identify the Australian ecosystems most prone to tipping points. In either situation, distinguishing change with consequences for management (whether attributable to climate change or other stressors) from variation in populations and processes that will be self-correcting is an additional challenge. For example, drought is a normal, occasional feature of most Australian environments to which species are well-adapted and from which populations and ecosystems can be expected to recover. However, and especially in parts of Australia where rainfall is expected to decrease, become more seasonal or even just change in seasonality (in combination, that is virtually everywhere), droughts are also likely to be major ecosystem tipping points – events that generate new states that may be more ecologically matched to a changed climate – but which may drive populations and taxa to extinction. Thresholds of tolerance will vary among taxa (and ecosystems) and will be lowered (potentially massively so) by other stressors. The key to dealing with this uncertainty is *not* to concentrate on the question: *is this drought [or other event] a normal drought [or other event]?* but rather *is this a potential tipping point for a population, taxon or ecosystem?* Droughts, for instance, appear already to have been tipping points driving populations of some birds in remnant woodlands of south-eastern Australia to extinction (Ford 2011b; Watson 2011). However the tipping points arising for other birds and from other stresses are little understood.

Given uncertainty in the detection of population change, identification of its cause and extrapolation of the trend, the timing of management responses is a key issue. Whilst in general, a precautionary and early response is desirable, limited resources will doubtless drive a decision-making process involving the setting of priorities and there are at least some circumstances where delaying the response is desirable even in the absence of resource constraints (McDonald-Madden *et al.* 2011). McDonald-Madden *et al.* (2011) specifically address the optimal timing of assisted colonisation, but the principles outlined have potential for application to other management issues.

Given that the outcomes of management are also uncertain, and at risk of labouring the point, management must operate in an adaptive manner (Walters 1986). This is considerably more than just monitoring of populations – it requires that management be treated as an experiment so that the success or failure of management can be attributed to a process and management amended appropriately. This is true “learning by doing”, a further development of which is the “adjustive management” paradigm of Maris and Bechet (2010) which incorporates both scientific uncertainty (which management will work?) and normative uncertainty (which biodiversity to conserve and why?).

4.4.5 Cost uncertainties

Costings aim to allow comparisons between classes of action and give some indication of the scale of the cost of climate change adaptation. Most studies of future expenditure included a future discount rate to calculate net present value. Here we have not done so because the uncertainties are so great that the figures are only representative of relative costs rather than appraisals of required expenditure. By 2053, when most captive breeding is postulated to begin, the world will be an entirely different place in terms of society, technology, the wealth of nations and the availability of resources. Even immediate costs are highly variable.

That said, the cost of $47,700 per taxon per year is not greatly dissimilar to the $120,000 spent on each of 111 threatened bird species in Australia during 1990-2000 (Garnett *et al.* 2003) or the median annual cost/taxon estimated as required for long-term persistence of threatened and at risk species in New Zealand ($130,205; McCarthy *et al.* 2012). McCarthy *et al.* (2012) do calculate a much higher annual cost for downlisting all birds on the IUCN Red List over a ten year period

($848,000/taxon/year) but that was without looking at synergies across taxa. Here we have found that great savings can be made by monitoring, modelling and managing groups of taxa in areas likely to be subject to the greatest climate change.

4.5 Costs of climate change adaptation

A billion dollars over 50 years for conserving Australia’s birds in the face of climate change is paltry compared to the costs of biodiversity loss. Of course, this figure is on top of the management that is already occurring, or should be, to manage protected areas, support threatened species, and reduce biodiversity loss from private lands. Nevertheless it is not prohibitive, especially as more than half of the costs are necessarily postponed until the results of monitoring are known.

Of the immediate costs, monitoring is the largest, followed by existing commitments to species management that aims to retain taxa that are already threatened. Of the monitoring costs, two-thirds are for monitoring marine birds. This is an area where there could be efficiency gains through consolidation of results and better direction of monitoring programs to answer particular questions relating to climate change; optimization analysis could prove useful (Possingham *et al.* 2012).

Of the terrestrial monitoring, the Atlas of Australian birds offers by far the best value for money. While it is not designed for the monitoring of threatened taxa, most of which need specialist techniques, it is highly effective at tracking large scale trends that are also likely to affect threatened taxa, as well as highlighting areas of concern among more common species. One problem is that the Atlas of Australian Birds, for which over three quarters of the records for the current modelling were derived, is not freely accessible. Sustained public investment in the Atlas of Australian Birds would appear to be highly desirable to ensure the best data are available for assessing the impacts of climate change in a timely manner.

Future costs are dominated by refugia management and captive breeding. Both may be under-estimates of the true cost of managing climate change effects but cannot be better estimated until impacts have started to emerge. Significantly, they are concentrated in a fairly small proportion of the landscape and are unlikely to compete with commercial interests in any major way. Overall adaptation to climate change for Australian birds ought to be affordable in an economy the size of Australia’s given our legal and international obligations to conserve biodiversity.

5. GAPS AND FUTURE RESEARCH DIRECTIONS

5.1 Knowledge gaps and research directions

Key knowledge gaps and further directions for research have already been discussed in the *Research Activities and Methods* section. Probably the key concept is that appraisals such as this study constitute only a preliminary assessment, and indeed consider only one aspect of conservation priorities – threats to taxa which may lead to extinction or the threat thereof. More detailed projections of population change and their management implications is required for a subset of Australian bird taxa identified by this and other studies, and by future monitoring. These assessments will likely involve finer-scale species distribution models which incorporate factors other than climate, along with the most recent available General Circulation Models. They will also – and perhaps even more importantly – involve taxon demographics, interactions with key elements of habitat and other species, and the role of stressors additional to climate change. Depending on the availability of information and the resources to appraise it, these may vary from heuristic models to detailed demographic-bioclimatic models. Examples of the latter include those for an Australian forest bird (Harris *et al.* 2012), an Australian tropical waterbird (Traill *et al.* 2009), an endangered Australian reptile (Fordham *et al.* 2012) and a beach-nesting bird in Florida (Chu-Agor *et al.* 2012).

Detailed modelling of individual taxa will, where appropriate, involve identification of taxon-specific refugia. Supplementary to this, generic appraisal of refugia at regional scales, and the management necessary to optimise their value for a range of biodiversity, is also a key area for further research.

Basic ecological research may seem hard to justify in a time of challenge and tight priorities. However, we emphasize the value of autecology, comparative ecology of the related and co-existing species, and of ecosystem ecology with an emphasis on stressors and tipping points, as particularly important – indeed essential – background for the successful management of threatened taxa. Detailed recommendations on the Glossy Black-Cockatoo, for instance, were only possible because of intensive research carried out over several decades. Such knowledge is lacking for most taxa, and the response of managers has often been to manage the landscape and hope for the best. While this will work for many taxa, some will fall through the cracks, as evidenced by the recent loss of the Christmas Island Pipistrelle *Pipistrellus murrayi* (Martin *et al.* 2012).

The loss of significant numbers of a threatened goose (Shaughnessy and Haberley 1994; Halse *et al.* 1995) and of a threatened cockatoo (Saunders *et al.* 2011) following heat waves illustrates the potential for extreme climate events to threatened taxon survival. Currently such sensitivities are not predictable and we were unable to include any measure in our assessment of sensitivity. All species and most subspecies have come through a period of warmer climate 120,000 years ago, but the net rate of speciation slowed substantially during the even warmer Eocene (Jetz *et al.* 2012) suggesting that temperatures higher than a few degrees may cause substantial bird extinctions. Increasingly, we are able to identify the genes responsible for adaptations and fitness and understand what will be likely to happen to them under different management scenarios. An important area of work will be to relate this new knowledge to the probability that particular taxa will be sensitive to climatic stressors such as excessive heat, and then provide the means by which such stressors can be mitigated.

5.2 Skills gaps

The litany of uncertainties about the predictions points to a range of skills gaps that will need to be filled through the iterative process of preparing for climate change. Of highest priority will be to increase the regional predictive skills of models so that there is greater certainty about which parts of the landscape need to be secured and managed for climate change adaptation. Currently, broadscale mapping allows some projections to identify taxa that are likely to be exposed, but the breadth between the 10th and 90th percentile for different climate models illustrates the extent of our uncertainty about how climate will change at a local level. The climate models will undoubtedly improve, enabling re-evaluation and clarification of priorities for climate change adaptation action. We envisage that an exercise similar to the current project could usefully be conducted every decade to track both changes in the birds and their distributions and advances in modelling and potential adaptation responses.

There is also uncertainty arising because of the historically low level of investment in monitoring. While the Atlas of Australian Birds provides some benchmarks, the hiatus between them has meant that the baseline for even the more common Australian taxa has been punctuated by gaps. While Atlas recording has continued after the most recent period of intense recording (1998-2002), there would be great merit in increasing the area and intensity of coverage, particularly in the more remote parts of the country where exposure to climate change is likely to be greatest. In a country as variable as Australia, detecting climate signals will be difficult without strong baselines. That said, there are increasingly sophisticated modelling approaches that make it possible to take advantage of patchy data to understand shifts in bird distributions (VanDerWal *et al.* 2013).

5.3 Funding gaps

Apart from an on-going chronic shortage of funding for the threatened species management, the need for which will likely greatly increase with climate change, major funding gaps are in the areas of monitoring and modelling.

Mention is made above of the potential benefits for substantial sustained investment in the Atlas of Australian Bids as a means of creating a national biodiversity baseline. While technical programs will monitor many elements of biodiversity at a general level, the strengths of the Atlas are its low cost, wide coverage, capacity to respond flexibly to areas of need, and its buy-in from the general public for whom an attachment to the natural world is a necessary prerequisite for public investment in biodiversity conservation.

The same sentiment underlies the suggestion that substantial funds need to be invested in modelling, particularly at the local scale. While it is often technically feasible to design landscapes top-down, take up by local decision-makers about land planning is going to be far greater if they have participated in the modelling process, can understand its underlying assumptions, have a chance to challenge the constituent data and create the research questions, and have ownership of the final outputs. Such local involvement requires substantial upfront investment but the return on investment, and local leverage of support, will be far greater than the delivery of local models by modellers who are unfamiliar with the area and local decision-makers.

Future funding requirements for refugia management and captive breeding could be substantial, and will reflect philosophies and economic conditions at the time. However, anticipation of future costs can allow planning. For captive breeding, substantial savings can undoubtedly be made by involving the private sector. However, legal and policy restrictions that reflect a suspicion of aviculture and its impact on the conservation of wild birds, currently inhibit such collaboration. The need for a substantial funding commitment to captive breeding may open up constructive dialogue with aviculturists so that costs can be shared between the public and private sectors.

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APPENDIX 1. CLIMATE SCENARIOS AND BIOCLIMATIC VARIABLES

Appendix 1.1: Representative Concentration Pathways used in analysis.

RCP	Short Description	Detailed Description
RCP3PD	Low RCP with Peak & Decline (2005-2500)	The RCP 3-PD is developed by the IMAGE modelling team of the Netherlands Environmental Assessment Agency. The emission pathway is representative for scenarios in the literature leading to very low greenhouse gas concentration levels. It is a so-called peak scenario its radiative forcing level first reaches a value around 3.1 W/m2 mid-century returning to 2.6 W/m2 by 2100. In order to reach such radiative forcing levels greenhouse gas emissions (and indirectly emissions of air pollutants) Are reduced substantially over time. The final RCP is based on the publication by Van Vuuren et al. (2007).
RCP45	Medium-Low RCP with stabilisation from 2150 onwards (2005-2500)	The RCP 4.5 is developed by the MiniCAM modeling team at the Pacific Northwest National Laboratory’s Joint Global Change Research Institute (JGCRI). It is a stabilization scenario where total radiative forcing is stabilized before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions. The scenario drivers and technology options are detailed in Clarke et al. (2007). Additional detail on the simulation of land use and terrestrial carbon emissions is given by Wise et al (2009).
RCP6	Medium-High RCP with stabilisation from 2150 onwards (2005-2500)	The RCP 6.0 is developed by the AIM modelling team at the National Institute for Environmental Studies (NIES) Japan. It is a stabilization scenario where total radiative forcing is stabilized after 2100 without overshoot by employment of a range of technologies and strategies for reducing greenhouse gas emissions. The details of the scenario are described in Fujino et al. (2006) And Hijioka et al. (2008).
RCP85	High RCP	The RCP 8.5 is developed by the MESSAGE modelling team and the IIASA Integrated Assessment Framework at the International Institute for Applies Systems Analysis (IIASA) Austria. The RCP 8.5 is characterized by increasing greenhouse gas emissions over time representative for scenarios in the literature leading to high greenhouse gas concentration levels. The underlying scenario drivers and resulting development path are based on the A2r scenario detailed in Riahi et al. (2007).

*source: https://tntcat.iiasa.ac.at:8743/RcpDb/dsd?Action=htmlpage&page=welcome#descript

Appendix 1.2: Eighteen Global Climate Models used in analysis.

Abb.	Global Climate Model	Group	URL for further info
cccma-cgcm31	Coupled Global Climate Model (CGCM3)	Canadian Centre for Climate Modelling and Analysis (CCCma)	http://www.ipcc-data.org/ar4/model-CCCMA-CGCM3_1-T47-change.html
ccsr-miroc32hi	MIROC3.2 (hires)	CCSR/NIES/FRCGC - Japan CCSR = Center for Climate System Research - University of Tokyo NIES = National Institute for Environmental Studies FRCGC = Frontier Research Center for Global Chance - Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (The University of Tokyo is a National University Corporation and NIES and JAMSTEC are Independent Administrative Institutions)	http://www-pcmdi.llnl.gov/ipcc/model_documentation/MIROC3.2_hires.pdf
ccsr-miroc32med	MIROC3.2 (medres)	CCSR/NIES/FRCGC - Japan CCSR = Center for Climate System Research - University of Tokyo NIES = National Institute for Environmental Studies FRCGC = Frontier Research Center for Global Chance - Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (The University of Tokyo is a National University Corporation and NIES and JAMSTEC are Independent Administrative Institutions)	http://www-pcmdi.llnl.gov/ipcc/model_documentation/MIROC3.2_hires.pdf
cnrm-cm3	CNRM-CM3	Centre National de Recherches Meteorologiques - Meteo France - France	http://www.ipcc-data.org/ar4/model-CNRM-CM3-change.html

Abb.	Global Climate Model	Group	URL for further info
csiro-mk30	CSIRO Mark 3.0	The CSIRO Mk3.5 Climate Model The Centre for Australian Weather and Climate Research	http://www.ipcc-data.org/ar4/model-CSIRO-MK3-change.html
gfdl-cm20	CM2.0 - AOGCM	Geophysical Fluid Dynamics Laboratory - NOAA	http://www.ipcc-data.org/ar4/model-GFDL-CM2-change.html
gfdl-cm21	CM2.1 - AOGCM	Geophysical Fluid Dynamics Laboratory - NOAA	http://www.ipcc-data.org/ar4/model-GFDL-CM2_1-change.html
giss-modeleh	GISS ModelE-H and GISS ModelE-R (which differ only in ocean component)	Goddard Institute for Space Studies (GISS) - NASA - USA	http://www.ipcc-data.org/ar4/model-NASA-GISS-EH-change.html
giss-modeler	GISS ModelE-H and GISS ModelE-R (which differ only in ocean component)	Goddard Institute for Space Studies (GISS) - NASA - USA	http://www.ipcc-data.org/ar4/model-NASA-GISS-ER-change.html
iap-fgoals10g	FGOALS1.0_g	LASG - Institute of Atmospheric Physics - Chinese Academy of Sciences - P.O. Box 9804 - Beijing 100029 - P.R. China	http://www.ipcc-data.org/ar4/model-LASG-FGOALS-G1_0-change.html
inm-cm30	INMCM3.0	Institute of Numerical Mathematics - Russian Academy of Science - Russia.	http://www.ipcc-data.org/ar4/model-INM-CM3-change.html

Abb.	Global Climate Model	Group	URL for further info
ipsl-cm4	IPSL-CM4	Institut Pierre Simon Laplace (IPSL) - France	http://www.ipcc-data.org/ar4/model-IPSL-CM4-change.html
mpi-echam5	ECHAM5/MPI-OM	Max Planck Institute for Meteorology - Germany	http://www.ipcc-data.org/ar4/model-MPIM-ECHAM5-change.html
mri-cgcm232a	MRI-CGCM2.3.2	Meteorological Research Institute - Japan Meteorological Agency - Japan	http://www.ipcc-data.org/ar4/model-MRI-CGCM2_3_2-change.html
ncar-ccsm30	Community Climate System Model - version 3.0 (CCSM3)	National Center for Atmospheric Research (NCAR) -	http://www.ipcc-data.org/ar4/model-NCAR-CCSM3-change.html
ncar-pcm1	Parallel Climate Model (PCM)	National Center for Atmospheric Research (NCAR) - NSF (a primary sponsor) - DOE (a primary sponsor) - NASA - and NOAA	http://www.ipcc-data.org/ar4/model-NCAR-PCM-change.html
ukmo-hadcm3	HadCM3	Hadley Centre for Climate Prediction and Research - Met Office - United Kingdom	http://www.ipcc-data.org/ar4/model-UKMO-HADCM3-change.html
ukmo-hadgem1	Hadley Centre Global Environmental Model - version 1 (HadGEM1)	Hadley Centre for Climate Prediction and Research - Met Office United Kingdom	http://www.ipcc-data.org/ar4/model-UKMO-HADGEM1-change.html

Appendix 1.3: Thirty-year climate coverage

	30-year climate coverage:	
Year Represented	Start	End
Current		
1975*	1961	1990
1990	1976	2005
Future		
2015	2001	2030
2025	2011	2040
2035	2021	2050
2045	2031	2060
2055	2041	2070
2065	2051	2080
2075	2061	2090
2085	2071	2100

*used only in perenniality analysis

Appendix 1.4: Bioclimatic variables

BIO1	Annual Mean Temperature
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3	Isothermality (BIO2/BIO7) (* 100)
BIO4	Temperature Seasonality (standard deviation *100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO8	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter
BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter

APPENDIX 2. TAXA MODELLED AT A 1 KM SCALE BECAUSE THE TOPOGRAPHIC ROUGHNESS OF TERRAIN THEY OCCUPY IS LIKELY TO CAUSE STEEP CLIMATIC GRADIENTS

Brown Cuckoo-Dove (Wet Tropics)
Wompoo Fruit-Dove (Wet Tropics)
White-rumped Swiftlet (Chillagoe)
Southern Boobook (Wet Tropics)
Sooty Owl (Wet Tropics - Lesser)
Double-eyed Fig-Parrot (Wet Tropics - Red-browed)
Australian King-Parrot (Wet Tropics)
Crimson Rosella (Wet Tropics)
Superb Lyrebird (northern New South Wales)
Albert's Lyrebird
Rufous Scrub-bird
Rufous Scrub-bird (southern)
Rufous Scrub-bird (northern)
White-throated Treecreeper (Eungella)
White-throated Treecreeper (Wet Tropics)
Spotted Catbird (Wet Tropics)
Tooth-billed Bowerbird
Golden Bowerbird
Satin Bowerbird (Wet Tropics)
Pilotbird (Snowy Mountains)
Yellow-throated Scrubwren (Wet Tropics)
Fernwren
Atherton Scrubwren
Large-billed Scrubwren (Wet Tropics)
Brown Gerygone (Eungella)
Brown Gerygone (Wet Tropics)
Yellow Thornbill (Wet Tropics)
Mountain Thornbill
Spotted Pardalote (Wet Tropics)
Eastern Spinebill (Wet Tropics)
Lewin's Honeyeater (McIlwraith Range)
Yellow-spotted Honeyeater (Wet Tropics)
Graceful Honeyeater (Wet Tropics)
Bridled Honeyeater
Eungella Honeyeater
Yellow-faced Honeyeater (Wet Tropics)
Macleay's Honeyeater
Chowchilla
Chowchilla (northern)
Chowchilla (southern)
Eastern Whipbird (Wet Tropics)
Olive Whistler (northern New South Wales)
Little Shrike-thrush (Wet Tropics)
Bower's Shrike-thrush
Yellow Oriole (Wet Tropics)
Pied Currawong (Wet Tropics)
Grey Fantail (north-eastern)
Spectacled Monarch (Wet Tropics)
Pied Monarch
Pied Monarch (southern)
Pied Monarch (northern)
Yellow-breasted Boatbill (Wet Tropics)
Paradise Riflebird
Grey-headed Robin (Australian)
Horsfield's Bushlark (Wet Tropics)
Bassian Thrush (Wet Tropics)
Blue-faced Parrot-Finch (Australian)

For the following appendices see on-line attachments:

APPENDIX 3. Metrics for assessing the exposure of terrestrial and inland waters Australian bird taxa to climate change and the climate drivers of current climate space

APPENDIX 4. Exposure and sensitivity of marine birds breeding in Australia or its offshore territories

APPENDIX 5. Metrics for assessing the sensitivity of Australian bird taxa to climate change

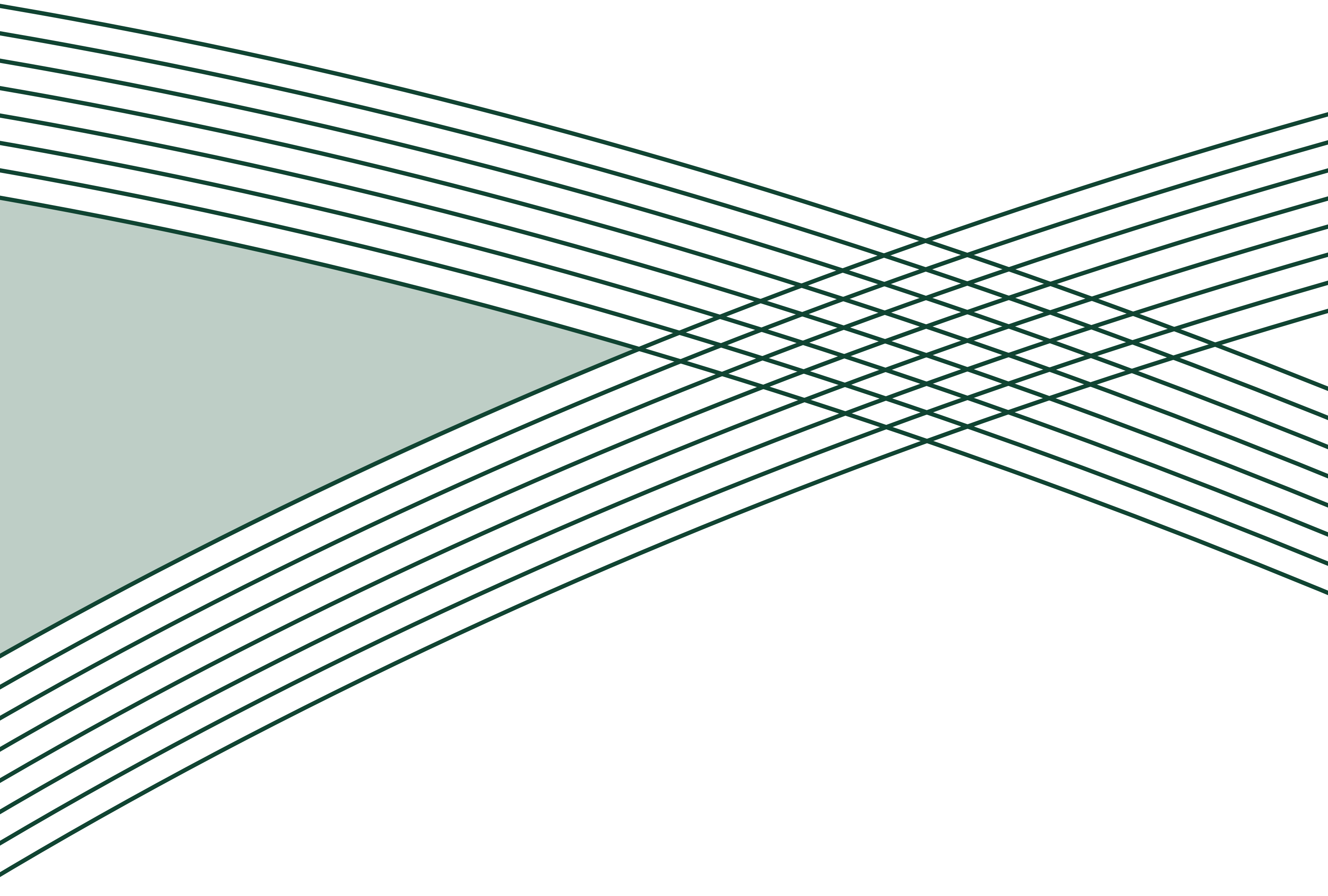
APPENDIX 6. Habitat metrics for Australian bird taxa used to characterise sensitivity to climate change

APPENDIX 7. Food and feeding metrics for Australian bird taxa used to characterise sensitivity to climate change

APPENDIX 8. Demographic, morphological and habitat specialization metrics for Australian bird taxa used to characterise sensitivity to climate change

APPENDIX 9. Rankings and risk class for sensitivity and exposure in Australian birds

APPENDIX 10. Modelled projections of exposure to climate change among Australian birds



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