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Title: Climate change and biodiversity in Australia: A systematic modelling approach to nationwide species distributions

Abstract

Climate change is a driving force of changes to biodiversity worldwide and presents considerable management challenges for the resource-constrained environmental management sector. Effective management of biodiversity requires information about what species are present, how species respond to environmental conditions and which species are likely to be able to persist in the presence of ongoing change. Species distribution models are commonly used to predict future suitable habitat for particular species and areas of interest but a consistent nationwide approach is needed to understand how climate change will affect Australia's biodiversity. Here we describe a modelling approach that uses a consistent workflow and expert vetting to create current and future species distributions for 1872 terrestrial and freshwater vertebrate species. We used two emission scenarios, 18 General Circulation Models and seven time points into the future to explore how individual species distributions and taxa richness in Australia are predicted to change due to climate change. The maps are publicly available online and stakeholders can download them for post hoc analyses to assist in both regional and national management and protection of biodiversity assets and conservation planning for the future.

Keywords: climate change; natural resource management; Maxent; conservation planning; science-management partnerships

Introduction

Climate change is one of the most significant threats facing the world's already declining biodiversity (Bellard et al. 2016). Effective policies for mitigating this threat require detailed knowledge about where species currently are and where they are likely to be under various future scenarios of change (Schuetz et al. 2015). Advances in species distribution modelling have provided Australia's scientific community with this knowledge for a small number of species (e.g., tropical savanna birds [Reside et al. 2012], butterflies [Beaumont and Hughes 2002], plants [Fordham et al. 2012]) and specific regions (e.g., Australian Wet Tropics [Williams et al. 2003], southwest Australia [Stewart et al. 2018], Victoria [Liu et al. 2013]). Despite the range of species modelled, these studies lack a consistent modelling approach with differences in the choice of modelling method (Elith and Graham 2009), the selection of predictor variables, and the future climate scenarios modelled (Beaumont et al. 2008). To best understand the effect of climate change on Australia's biodiversity, a consistent modelling approach is needed for as large a number of species as possible.

Information on the impact of climate change on biodiversity is actively being sought by national, state and regional governments and organisations for strategic planning (Hilbert et al. 2007). Australia's 56 regional bodies for Natural Resource Management (NRM) are responsible for regional resource management planning under the National Landcare Program (Australian Government 2018a). The NRM bodies are funded through national grant schemes and other sources and responsible for identifying and setting local priorities for investment in strategic on-ground projects that engage local communities. In 2012, in line with the regional NRM Planning for Climate Change program (Australian Government, 2018b), NRMs were required to include region-specific climate change adaptation strategies for relevant resource sectors, including biodiversity, into their updated management plans to identify threats, prioritise actions and monitor outcomes. Engagement with the Queensland Government's

Department of Environment and Heritage Protection (EHP) and the NRM bodies in the Monsoonal North cluster identified a gap between the number of species currently modelled for Australia and the number desired by these organisations to make more informed conservation decisions.

This study endeavours to resolve the deficiency in available nationwide species distributions. First, we aim to apply what we have learned about species distribution models over the years to inform a systematic method for modelling the distribution of as many Australian vertebrate species as possible from available occurrence records. We then develop an online resource where stakeholders and the general public will have access to the resulting maps. Despite the consensus regarding the potential impacts of climate change on biodiversity among researchers, there remains a lack of acceptance and acknowledgment of these effects by the general public. The large number of species modelled here and the accessibility of the visible results aims to change this perspective.

Methods

Modelling method

Numerous methods exist to predict species occurrence based on environmental conditions, ranging from relatively simple bioclimatic envelopes to more complex machine learning methods (Franklin 2010). We selected Maxent (Phillips et al. 2006), a machine-learning technique, because it is one of the most commonly used, widely recognised methods to model species distributions with presence-only species records (Elith et al. 2011), and has proven effective for many species and regions (Elith et al. 2006). Secondary decisions that affect distribution model outputs include the selection of background data that replaces absence data in other modelling techniques (VanDerWal et al. 2009), the selection of predictor variables

(Harris et al. 2013), and the threshold chosen to convert projected habitat suitability values into presence-absence (Jimenez-Valverde and Lobo 2007). Using advice gleaned from the literature (Phillips and Dudik 2008, Elith et al. 2011, Merow et al. 2013) and consultation with stakeholders as described above to discuss these secondary decisions, we developed a rigorous workflow and applied it to Australian vertebrates.

Taxa modelled and species occurrence records

Species distribution models were created for eight taxa: four terrestrial vertebrate groups (amphibians, birds, mammals, and reptiles) and four freshwater-associated groups (fish, crayfish, turtles, stream frogs). Amphibian and reptile species that were strongly related to freshwater networks were modelled with the freshwater species.

Species occurrence records were sourced from the Australian Atlas of Living Australia (ALA 2012), the Queensland Museum, and CSIRO. Due to the limited number and geographically-biased nature of the available freshwater taxa' distribution records, we supplemented the above occurrence records with data from the University of Canberra Turtle Tissue Database (Institute for Applied Ecology, University of Canberra), the Fish Atlas of Northern Australia (TropWATER, JCU), and published literature.

All occurrence records went through a rigorous cleaning process prior to modelling. Records were discarded if the location information was incomplete or if the current location was a clear outlier. Records older than 1950 were also excluded. Only species with at least species-level taxonomic identification were included. For the freshwater taxa, species were excluded from the analysis if they occurred in less than five of the 1.4 million catchments defined in the Australian Hydrological Geospatial Fabric product of the Bureau of Meteorology (BOM 2011).

Species distribution modelling

Terrestrial taxa

Species distribution models were generated for the four terrestrial taxa using Maxent (Phillips et al. 2006). For each species, cleaned occurrence records were standardised to 0.01 degrees resolution so that only unique geolocations were used. To reduce sampling biases in the observation records, taxon-specific background data were generated for each taxonomic group (Phillips et al. 2009). A subset of the Worldclim (2012) variables that have been shown to influence terrestrial Australian species (Reside et al. 2013) were downscaled to 0.01 degrees resolution and used as predictors of species distributions. Climatic variables were annual mean temperature, temperature seasonality, maximum temperature of warmest month, minimum temperature of coldest month, annual precipitation, precipitation seasonality, precipitation of wettest quarter, and precipitation of driest quarter.

Maxent was run with a 10-fold cross validation and projected onto a current baseline of climate data, defined as the years between 1976 and 2005. To convert habitat suitability predictions into presence-absence maps, threshold values were chosen based on previous work highlighting their applicability to Australian species (Reside et al. 2013). Maxent's "equate entropy of thresholded and original distributions" (EETOD) was used for all birds, unless the minimum training presence area was greater than 80%, in which case the EETOD was halved to be more inclusive, based on extensive expert judgement as part of a previous project (Garnett et al. 2013). For the remaining terrestrial taxa, three Maxent-provided threshold values were assessed: equal training sensitivity and specificity; balance training omission, predicted area, and threshold value; and EETOD. The resulting binary presence-absence maps were then vetted by experts to identify which of the four threshold values produced a mapped distribution most similar to the species current empirical distribution. Model performance was evaluated using the area under the receiver operating characteristic curve (AUC) statistic. Any model with an AUC < 0.7 was inspected to determine if the model should be excluded from further analysis (Lobo et al. 2007). If the low AUC score could be attributed to the widespread distribution of that species (Reside et al. 2011), and the model was an appropriate approximation of the species' known range, then the model was retained.

Future climate projections were generated for each species in Maxent with two carbon emission scenarios (Representative Concentration Pathways, or RCPs): RCP 4.5, a moderate scenario representing an emissions peak around 2040 and RCP 8.5, a severe scenario where emissions continue to rise throughout the 21st century (Rogelj et al. 2012). For each RCP, 18 General Circulation Models (Table 1) were used to generate suitable habitat predictions for seven time points into the future: 2025, 2035, 2045, 2055, 2065, 2075 and 2085. To make the future species distribution models more realistic, we placed limitations on the distance a species could disperse from their current climatic niche. We selected an optimistic dispersal rate of 4 km per year for mammals and birds and a rates of 0.5 km per year for reptiles and amphibians (Warren et al. 2013) and used them to clip the future distributions. Finally, for each species, we calculated the 10th, 50th, and 90th percentiles of the 18 General Circulation Models suitability predictions for each 1km grid cell within Australia (i.e., the median suitability prediction and 10th and 90th percentile suitability's as confidence estimates) to produce summaries of each RCP:year combination.

Freshwater taxa

Species distribution models were generated for the freshwater-associated groups in a similar manner as described above for terrestrial species, but adapted to the freshwater stream network (James et al. 2017). In addition to the eight climate variable predictors used for the terrestrial taxa, we included three environmental attributes: the length of any dry period, the severity index associated with that dry period, and the accumulated mean annual runoff. We used the same EETOD threshold as for birds. Current distributions were made more realistic by clipping the predicted suitability areas to biogeographic provinces for fish (Unmack 2001) or Level 2 National Catchment Boundaries (BOM 2011) for crayfish, turtles, and stream frogs. For future predictions, predicted suitability distributions were restricted to sub-catchments that intersected the clipped current distribution or previous time point's restricted distribution.

Species richness

To produce species richness maps for each taxon, we summed the individual presence-absence species distribution maps together for the current time period and for each emission scenario by General Circulation Model percentile by future time points resulting in 42 distributions. For freshwater-associated taxa, turtle and stream frog distributions were included in the reptile and amphibian biodiversity maps respectively.

Regional summaries

To make the information more localised for regional managers and stakeholders, we created summaries of both species and climate at multiple scales for all Australian states and territories, NRM bodies, and the Interim Biogeographic Regionalisation for Australia (IBRA) regions (Environment Australia, 2000).

Results

The total number of modelled species was 1872: 221 mammals, 599 birds, 582 reptiles (including 25 turtles), 210 amphibians (including 38 stream frogs), 66 crayfish, and 194 fish. For each species, we produced a current distribution map and 42 future distribution maps (2 RCP's x 7 time points * 3 percentiles). The number of occurrences for all species ranged from six for one species of crayfish (*Euastacus urospinosus*) to 82282 records for the Australian magpie (*Cracticus tibicen*). The average AUC score for all species was 0.9408 with a minimum score of 0.5770 for the wedge-tailed eagle (*Aquila audax*) and a maximum score of 0.9998 for the Proserpine rock-wallaby (*Petrogale persephone*). The expertly-vetted thresholds used to classify Maxent's suitability values into presence-absence are available on request.

Accessing Results

All of the individual species maps, richness maps, and summary reports produced in this study are online and publicly available for viewing and download (JCU 2018; http://climas.hpc.jcu.edu.au/). Stakeholders interested in a single species are able to download its projected current and future distributions to visualise any changes in suitable habitat. For example, the southern cassowary (*Casuarius casuarius*) is a range-restricted species occurring in the Australian Wet Tropics region of Queensland with current suitable habitat ranging from just north of Townsville up to Cooktown with an isolated area around the Iron Range in the far north-east of Australia (Figure 1). In the future, its suitable habitat is projected to continuously contract around its central habitat in the Atherton Tablelands. Stakeholders can also display two distribution maps side by side, e.g., to compare the difference between the low and high emission scenarios for a particular species. The common wallaroo (*Macropus robustus*), for example, is currently common throughout all of Australia. Like the cassowary, however, its future climate space is projected to decrease and it will lose much of its suitable habitat by 2055 depending on the emission scenario (Figure 2). The importance of incorporating multiple General Circulation Model projections can be seen by the variation among the 10th, 50th, and 90th percentile maps. Interested parties are able to view the richness of each of the six taxa nationwide to be able to identify areas of high biodiversity. Current fish richness in Australia is highest (60 species) on the east coast of Cape York and the mean number of fish across the country is five species (Figure3a). At the lower emission scenario, the maximum number of species in one location drops to 57 but some fish species are projected to gain suitable habitat, particularly in northern Australia, increasing mean fish richness to six species (Figure 3b). Projected maximum and mean fish richness for the high emission scenario were 54 and five species respectively. The user can choose to download the individual map they are viewing as a geoTIFF, or download the complete set of the individual species distributions maps for that particular species or biodiversity group (i.e., current and future distributions) as a zip file. Users are also able to create reports for specific years and regions of interest. The report is dynamically generated based on the user's selections and uses custom-built document assembly software for scientific reporting, *Prosemaker*, to facilitate readability (Baird 2013). The reports are customisable by region and year, and may include a climate summary, a biodiversity review, appendices with species lists detailing which species are lost or retained in the region based on future predictions, or any combination thereof.

Application of Results

The results of this study can be used for a variety of post hoc analyses for conservation planning purposes. Combining species distributions with future land use maps can indicate which areas are most likely to be threatened in the future by grazing, agriculture, mining, and urbanisation, as well as which areas have high potential for carbon storage (Reside et al. 2017a). Overlaying the species distributions with protected areas can identify which areas are most efficient for protecting the most amount of species into the future (Reside et al. 2017b), or for a particular species of interest. A case-study of the use of the results from this modelling approach is that of Queensland's Environmental and Heritage Protection Department's Landscape Conservation Unit (VanDerWal et al. 2015). This group used the current and future distribution of species to highlight areas that were resilient to climate change resilient across Queensland (Figure 4). They then used the resulting map to inform additions to its protected area network.

Conclusion

Bringing comprehensive, evidence-based modelling of species distributions to on-ground planning initiatives is essential for achieving the best possible outcomes for biodiversity under climate change (Walsh et al. 2015). This study followed a systematic workflow of acquiring species occurrence records from disparate sources, expertly vetting them to ensure their accuracy, downscaling multiple future climate scenarios into a comprehensive set of predicted climate change futures, incorporating the uncertainty across emissions trajectories and General Circulation Models and providing spatially-based products at national and regional scales that can be used to inform decision makers. Although simpler methods to map the distribution of individual species exist that can be performed by planners themselves (e.g. Atlas of Living Australia's modelling platform), they cannot easily be used to map the entire suite of species present in a particular region, with fine spatial resolution and multiple future scenarios; these require scientific expertise and advanced computing resources that stakeholders are not likely to have. This study ensures the consistency of results across species and enables government organisations and NRM bodies, as well as the general public, to see the potential impacts of climate change on biodiversity nationwide. Armed with this information, conservation managers can identify particularly vulnerable taxa at multiple scales and develop timely and well-targeted strategies to protect Australian biodiversity.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Table 1. List of 18 General Circulation Models used for future climate scenarios.

Agency	Model Name
Canadian Centre for Climate Modelling and Analysis (CCCma), Canada	Coupled Global Climate Model (CGCM3)
Centre for Climate System Research, University of Toyko, Japan	Model for Interdisciplinary Research on Climate, version 3.2 - High resolution
Centre for Climate System Research, University of Toyko, Japan	Model for Interdisciplinary Research on Climate, version 3.2 - Medium resolution
Centre National de Recherches Meteorologiques, Meteo France, France	CNRM-CM3
Commonwealth Scientific and Industrial Research Organisation, Australia	CSIRO Mark 3.0
Geophysical Fluid Dynamics Laboratory, NOAA, USA	CM2.0 - AOGCM
Geophysical Fluid Dynamics Laboratory, NOAA, USA	CM2.1 - AOGCM
Goddard Institute for Space Studies, NASA, USA	GISS ModelE-H
Goddard Institute for Space Studies, NASA, USA	GISS ModelE-R
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciemces, P.R. China	FGOALS1.0_g
Institute of Numerical Mathematics, Russian Academy of Science, Russia	INMCM3.0
Institut Pierre Simon Laplace (IPSL), France	IPSL-CM4
Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM
Meteorological Research Institute, Japan Meteorological Agency, Japan	MRI-CGCM2.3.2
National Center for Atmospheric Research, USA	Community Climate System Model, version 3.0 (CCSM3)
National Center for Atmospheric Research, National Science Foundation, Department Of Energy, NASA, and NOAA, USA	Parallel Climate Model (PCM)

Hadley Centre for Climate Prediction and Research, Met Office, United Kingdom	HadCM3
Hadley Centre for Climate Prediction and Research, Met Office, United Kingdom	Hadley Centre Global Environmental Model, version 1 (HadGEM1)

Figure captions

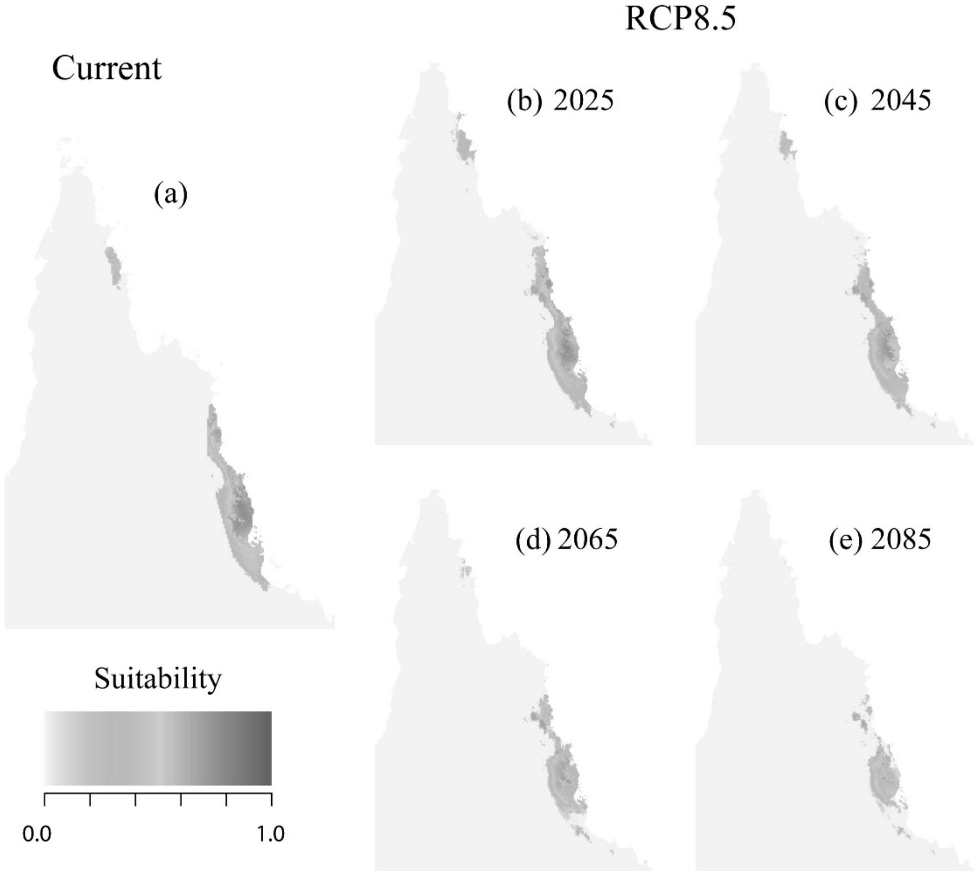
Figure 1. Current (a) and future median (50^{th} percentile) future habitat suitability distributions (b-e) for the southern cassowary (*Casuarius casuarius*) based on RCP 8.5.

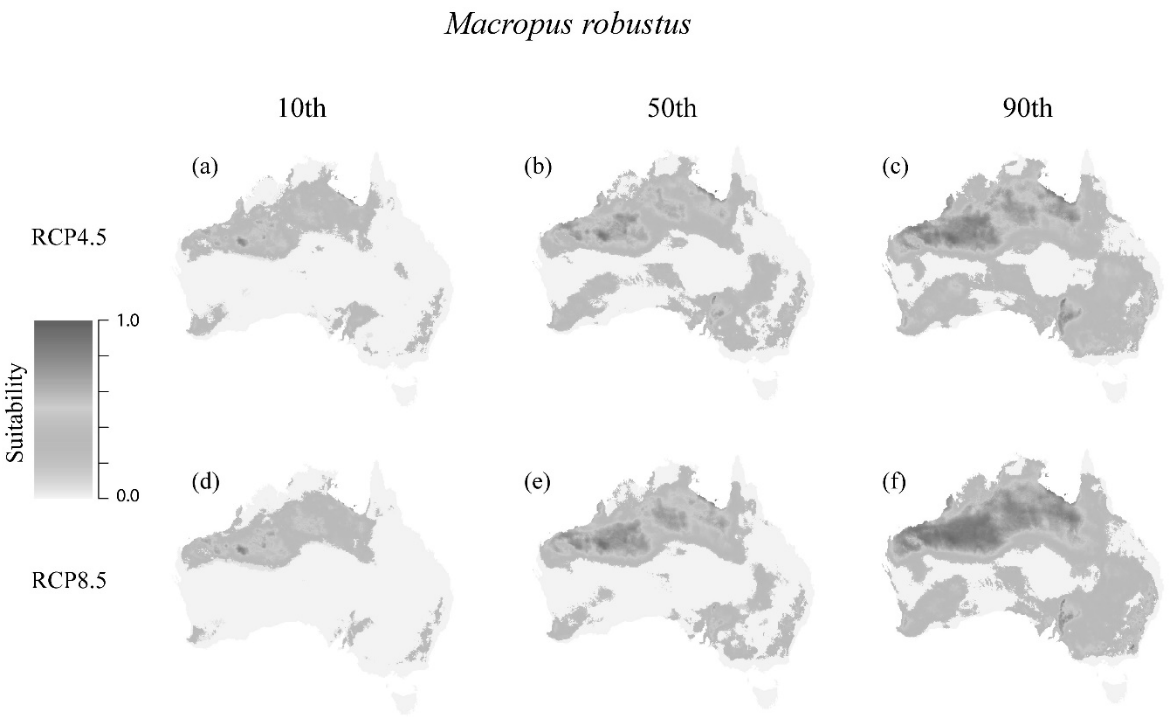
Figure 2. 10^{th}, 50^{th}, and 90^{th} percentile habitat suitability distributions for the common wallaroo (*Macropus robustus*) for the low emission scenario (RCP4.5; a-c) and the business as usual emission scenario (RCP 8.5; d-f) in the year 2055.

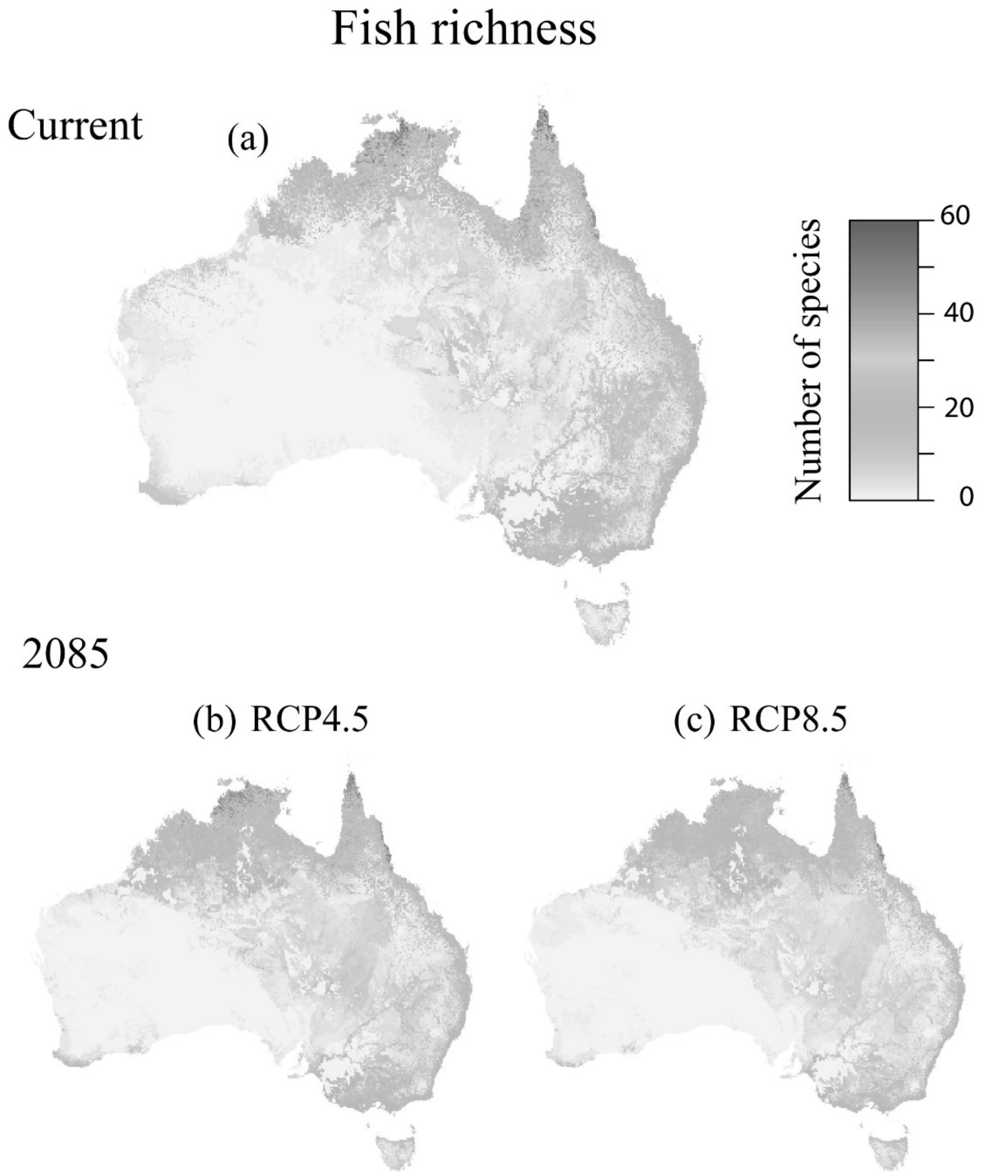
Figure 3. Current (a) and future median (50^{th} percentile) distributions (b-c) of fish richness projected for the year 2085 for two emission scenarios.

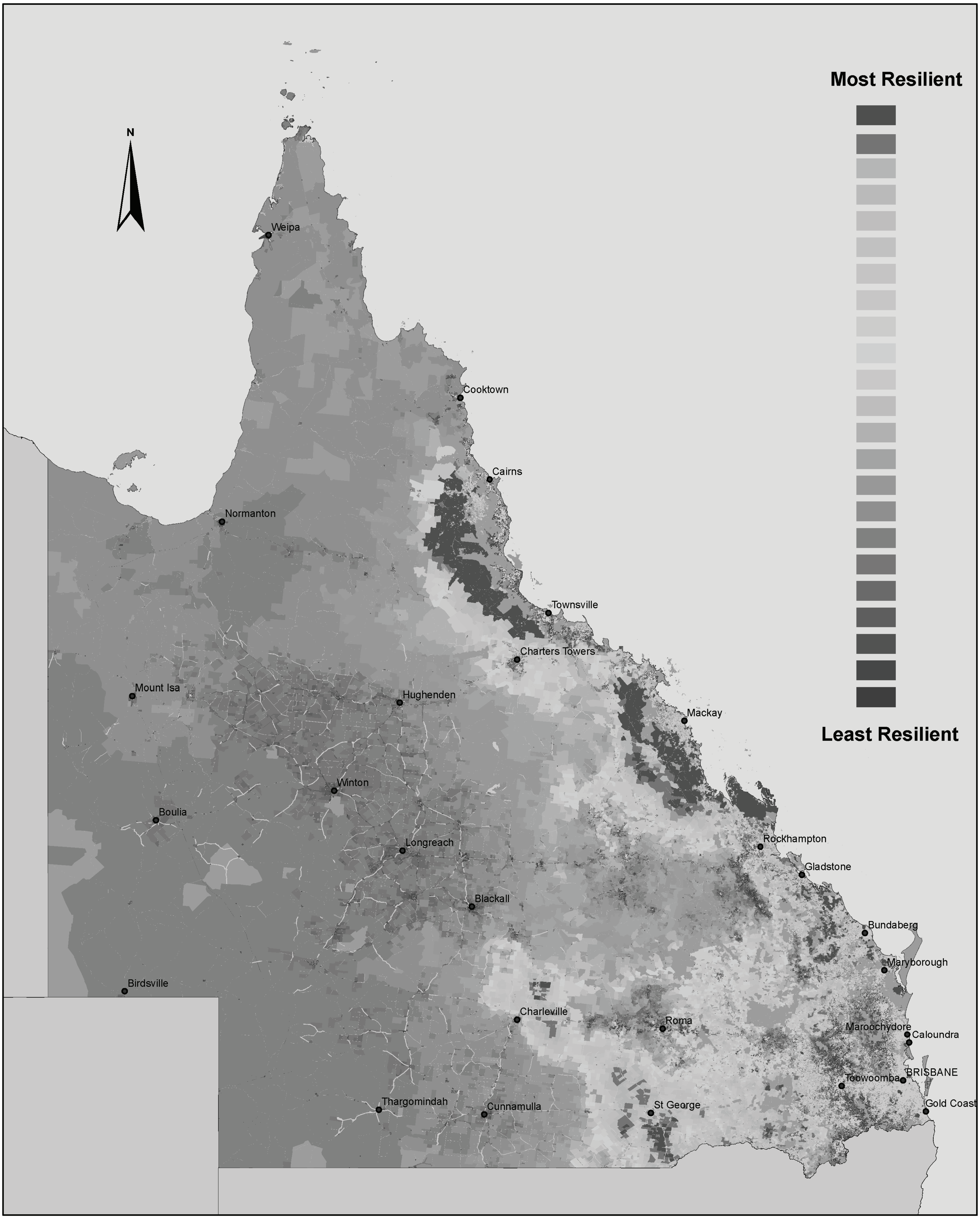
Figure 4. Queensland's properties ranked by climate resilience.

Casuarius casuarius




Macropus robustus
10th
50th
90th
(a)
(b)
(c)
RCP4.5
1.0
Suitability
0.0
(d)
(e)
(f)
RCP8.5


Fish richness
Current
(a)
Number of species
60
40
20
0
2085
(b) RCP4.5
(c) RCP8.5



Properties Ranked by Climate Resilience

Legend

Reserves of Queensland

0 50100 200
Kilometers

Queensland Government

Department of Environment and Heritage Protection