National Environmental Research Program

TROPICAL ECOSYSTEMS hub

Final Report

Species resilience: the key to understanding biodiversity in the rainforests of the Australian Wet Tropics

Stephen E. Williams, Brett R. Scheffers, Jeremy VanDerWal, Nadiah Roslan, Alex Anderson, Collin Storlie, Rebecca Brunner, Justin Welbergen and Scott Parsons

Australian Government
Department of the Environment

Reef & Rainforest RESEARCH CENTRE

Species resilience: the key to understanding biodiversity in the rainforests of the Australian Wet Tropics

Stephen E. Williams[1] , Brett R. Scheffers[1], Jeremy VanDerWal[1,2], Nadiah Roslan[1], Alex Anderson[1], Collin Storlie[1], Rebecca Brunner, Justin Welbergen and Scott Parsons[1]

[1] Centre for Tropical Biodiversity & Climate Change, College of Marine and Environmental Sciences, James Cook University, Townsville QLD 4811

[2] e-Research Centre, James Cook Unniversity.

Australian Government

Department of the Environment

Supported by the Australian Government's National Environmental Research Program

Project 3.1 Rainforest Biodiversity

This report should be cited as:

Williams, S. E., Brett R. Scheffers[1], Jeremy VanDerWal[1,2], Nadiah Roslan[1], Alex Anderson[1] and Scott Parsons[1] (2014) *Species resilience: the key to understanding biodiversity in the rainforests of the Australian Wet Tropics.* Report to the National Environmental Research Program. Reef and Rainforest Research Centre Limited, Cairns (37pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's National Environmental Research Program (NERP) Tropical Ecosystems (TE) Hub.

The Tropical Ecosystems Hub is part of the Australian Government's Commonwealth National Environmental Research Program. The NERP TE Hub is administered in North Queensland by the Reef and Rainforest Research Centre Limited (RRRC). The NERP Tropical Ecosystem Hub addresses issues of concern for the management, conservation and sustainable use of the World Heritage listed Great Barrier Reef (GBR) and its catchments, tropical rainforests including the Wet Tropics World Heritage Area (WTWHA), and the terrestrial and marine assets underpinning resilient communities in the Torres Strait, through the generation and transfer of world-class research and shared knowledge.

Cover photograph: *Hypsilurus boydii*, Stephen Williams.

This report is available for download from the NERP Tropical Ecosystems Hub website:

http://www.nerptropical.edu.au/research

December 2014

Contents

List of Figures

List of Tables

Acronyms Used In This Report

ALA............... Atlas of Living Australia
AWT............. Australian Wet Tropics
CTBCC........... Centre for Tropical Biodiversity and Climate Change
EHP............... Environment and Heritage Protection
JCU................ James Cook University
MTSRF........... Marine and Tropical Sciences Research Facility
NCCARF........ National Climate Change Adaptation Research Facility
NERP............. National Environmental Research Program
QLD............... Queensland
RRRC............. Reef and Rainforest Research Centre Limited
TERN............. Terrestrial Ecosystem Research Network
WTWHA........ Wet Tropics World Heritage Area
WTMA.......... Wet Tropics Management Authority

Abbreviations Used In This Report

18 k.............. Last Glacial Maxima (18 thousand years ago)

Acknowledgements

This work was carried out with financial support from the Australian Government (Department of the Environment) under the National Environmental Research Program. We are also grateful for the generous funding or in-kind support that we have received from other partnerships and organizations that have helped us achieve our goals, particularly the Earthwatch Institute and the 100+ Earthwatch volunteers that helped us collect data and endured weeks of camping and field sampling in rain and shine. This research was also supported by collaborative links to the National Climate Change Adaptation Research Facility (NCCARF), the Centre for Tropical Biodiversity and Climate Change (CTBCC) and the Terrestrial Ecosystems Research Network (TERN). We would like to thank all partnerships who have contributed to the publications, case studies and Workshops that have provided foundation to this project and for the individuals who took part and contributed ideas. We would like to thank the traditional owners of the lands across the breadth of the Wet Tropics region for allowing us to work on their land and in particular Marilyn and Peter and the Bana Yarralji rangers who made us so welcome on their country. We thank all past and present post-graduate students, volunteers and personnel for their dedicated and enthusiastic work with the project. We thank QPWS for always finding a way to provide a complicated and expansive permit for this research across the whole region.
.

Introduction

Australia's only tropical montane forest occurs in the Wet Tropics Bioregion, in North Queensland. This region is only 0.1% of Australia's land mass, but contains approximately 30% of Australia's vertebrate biodiversity and has more than 90 endemic species which occur nowhere else on the Earth (updated from Williams 2006). The flora and fauna of this system are well adapted to its unique climate conditions and as a result this region is particularly susceptible to current and future climate change (Williams et al 2010). To more thoroughly understand the possible consequences of climate change to this region we must gain more knowledge of present and future biodiversity patterns and drivers, environmental and evolutionary refugia and a greater understanding of the vulnerability and resilience of rainforest biodiversity in Australian tropical forests.

To address these primary areas of research, a combination of available knowledge, existing datasets and strategic research was used to provide a better understanding of biodiversity pattern in the region and the drivers and vulnerabilities of this biodiversity. Our aim is to provide the knowledge to inform adaptive management and policy strategies that promote the persistence of the regions unique biodiversity. This knowledge enables efficient spatial and temporal prioritisation of vulnerable species and threats to maximise the efficiency of management investment. Utilising the significant potential of the Wet Tropics as a "learning landscape", we capitalised on previous investment in biodiversity research in the region to maximise the national benefits of this research via the development of biodiversity science, analytical approaches/tools, resources, capacity and expertise at both national and international levels.

All analyses and outputs from this project were only possible because of long-term monitoring of species using standardised survey methods at established sites. The data compiled under prior funding schemes (e.g., Rainforest-CRC &MTSRF) set the stage for the analyses that were conducted under this NERP funded project. In doing so, we have accumulated one of the most comprehensive databases on tropical rainforests in the world. We tackled extensive monitoring of rainforest vertebrates from 2010-2014 to add to our previous 19 years of data from which we can model species distributions in the present and predict how they might change in the future. As you will see, even with extensive data we are just now beginning to see population level trends and we suspect another 10+ years would vastly increase the long-term understanding of the status and trends of the biodiversity assets of the region.

BOX 1: Summary of project by a major stakeholder, the Wet Tropics Management Authority (Written by Kerryn O'Connor, WTMA)

Resilience vital for vulnerable rainforest fauna

Introduction
The biodiversity of the Wet Tropics is in serious trouble. A project funded by the National Environmental Research Program has found that the region's fauna is likely already experiencing the effects of climate change. For the first time, long term, field based evidence is showing that a significant number of bird and mammal species are already in decline and on the move, seeking refuge in higher, cooler mountain environs. Regional endemics appear most at risk.

Professor Steve Williams from James Cook University has been leading the project to assess the status of the region's vertebrates, predicting future trends and vulnerabilities and identifying areas requiring priority management attention. The research is confirming the vulnerability of many rainforest species to climate change, highlighting the need for urgent action to maximise regional resilience.

Observing Change
Professor Williams and his team have been monitoring fauna in the Wet Tropics for over fifteen years and, more recently, collecting microclimate data from over thirty locations. This is the longest constant faunal survey ever conducted in the region providing an invaluable, baseline data set. Worryingly, observed changes in the abundance and distribution of bird and mammal populations during this period concur with modelled climate change predictions for the region, albeit at a much faster rate than forecast.

Many of the upland bird species surveyed have declining populations with rapid decline observed in fourteen species, six of which are regionally endemic. Birds from the warmer lowlands have also been affected with fourteen species showing increased population abundance but at higher altitudinal ranges than their previous distributions. In fact, for the bird species for which the survey data are sufficient, fifty percent are showing an upward elevational shift. This pattern appears to be repeated for the surveyed mammals, with population declines and upward distributional movements observed in a number of montane possum. Many more species show similar trends but the results for these species are not yet statistically significant.

Predicting trends
As well as documenting changes that are already occurring in the Wet Tropics, Professor Williams' project is predicting the vulnerability and resilience of individual species and landscapes under different climate change scenarios. By considering the biological traits of the species and using sophisticated spatial analyses, the research is identifying which species and areas require priority management focus, both now and into the future.

Using IPCC temperature projections, the research forecasts significant changes in the conservation status of Wet Tropics vertebrates under a 'business as usual' scenario with considerable increases in the number of extinct, critically endangered, endangered and vulnerable species expected. The modelling suggests that this can be countered by a reasonable mitigation approach which would greatly strengthen the resilience of the threatened fauna.

Improving resilience
Professor Williams' research highlights the need to improve regional resilience, particularly in those areas identified as being priority, so that species are better able to respond to existing and predicted changes. It points to a range of practical adaptation measures that can improve resilience, many of which have broader application beyond the Wet Tropics.

Spatial analyses of species vulnerability and landscape resilience has already been provided by the researchers to the Queensland Government to identify refugial areas throughout the State for potential protected area acquisition. It has also been used to identify priority restoration {link to article on Carla's research} areas in the Wet Tropics. This work informed the award winning 'Making Connections' rainforest restoration project that was undertaken by the Wet Tropics Management Authority and the local community to create strategic wildlife corridors on the Atherton Tablelands. Other measures that can enhance resilience include preventing and controlling biosecurity incursions, protecting important peripheral areas and establishing micro habitat to provide thermal refugia for vulnerable species.

Keeping the 'long' in long term
The field data underpinning this NERP project constitutes the longest constant faunal survey ever conducted in the region. It provides an invaluable, baseline data set with which to understand and plan for environmental change into the future.

With the NERP project coming to conclusion, it demonstrates the important role that long term monitoring can play in safeguarding biodiversity into the future.

Mapping of biodiversity values and trends in time

Monitoring

A comprehensive review of regional literature followed by extensive stakeholder consultation identified long-term monitoring data as the most important knowledge gap in the region (Welbergen et al. 2011). Maintaining and significantly improving a regional-scale, long-term environmental monitoring program is essential in order to track status and trends of biodiversity in the wet tropical regions of Australia. Such a program provides biodiversity and environmental data that has a demonstrated value to a wide range of users including the research community, regional/state/national management agencies and conservation policy development, and national / international bioinformatic infrastructure initiatives (e.g. ALA, TERN). Data collected and maintained over the four-year period (2010-2014) serve as the foundation for all data outputs described below with flow-on inputs to many of the other published projects across Australia (e.g., Warren et al. 2013) and globally (Scheffers et al 2013). These data serve as the basis for this report including:

Regional microclimate sensor network at more than 30 sites established under MTSRF and maintained under NERP that are strategically placed across elevational and latitudinal gradients in the region. Microclimate stations have been updated with newer data logging technologies (i.e., hygrobuttons) to continue standardised established microclimate site monitoring. Standardised weather stations were also established in new sites in gaps in environmental coverage. These stations were also used to identify climatic refugia. Data: temperature (air, soil, microhabitats) and humidity.

Standardised vertebrate surveys across all long-term sites (>30) including: 2-3 complete surveys per year for three years with 6 replicated sampling points within each site and including standardised surveys of: birds, reptiles, spotlighting (mammals and other nocturnal fauna) and microhylid frogs, with other taxonomic groups added because of specific student projects (e.g., ground and canopy ants). These surveys follow well-established and extensively published methodologies within the CTBCC (e.g. Williams et al. *Ecology* 2010).

Table 1: Summary of biodiversity suveys conducted under NERP Rainforest Biodiversity Project 3.1 from 2011 to 2014.

Long-term Monitoring Sites (across altitudinal gradient >30 in total)	**No. Bird Surveys**	**No. Reptile Surveys**	**No. Spotlight Surveys (nocturnal mammals)**	**No. Other standardised surveys (microhylid frog, invertebrate, thermal profiles etc.)**
Spec Uplands Lamb Range Atherton Uplands Daintree Lowlands Carbine Uplands Windsor Uplands Finnegan Uplands	> 900	> 800	> 400	> 400

Power analyses performed in 2012 suggested that in order to detect biologically significant trends (ca. 10% increase or decrease) in species abundance over a ten year period, sites needed to be sampled at least twice a year. On average, this project visited 4 long-term monitoring sites per year and conducted over 100 spotlight and 200 standardised bird, reptile and microhylid frog surveys per year. Through positive collaboration with Earthwatch Australia, this project completed surveys in excess of the 2 per year as outlined in the Project Schedule.

Our data is searchable online and meta-data is made available on main data portals including JCU eResearch, Tropical Data Hub, Research Data Australia and eAtlas. In addition to this, our data continues to be provided to TERN, National Parks, Australian Wildlife Conservancy and Bana Yarralji Rangers on an annual basis.

It is only through long-term monitoring that the findings presented in this report are possible. Our monitoring program has been funded by four different primary sources however by maintaining our methodology over the 20 year period, we now have data that drives results right up to an International level.Our long-term rainforest biodiversity monitoring is a solid demonstration as to how how well this kind of research can advance and gain results for stakeholders as long as vision is maintained and research is completed in a way where the knowledge can be exported successfully.

Increased understanding of biodiversity pattern and process in Australian rainforests

An understanding of the drivers of biodiversity in the region is crucial to predicting impacts from a variety of threats and ensuring effective conservation planning and management that aims to maintain a resilient landscape. We used data collected across our standardised sites from 2010-2014 and in combination with our existing vertebrate and invertebrate data to examine the organisation of biodiversity in the region.

We mapped almost all rainforest vertebrates and identified key locations and taxa where we have long-term count data and/or high frequency of repeat count surveys over time periods that have encompassed important environmental change. We summarize in this report our findings of biodiversity patterns observed across the region and how these patterns are changing due to current climate change.

Observing Change

Species on the move

Our analysis on the status and trends of Wet Tropics vertebrates used measurements of species abundance from the monitoring program to test for species that have undergone significant changes in local abundance at the specific monitoring sites. In these analyses we tested for significant changes in abundance within our field data and our analyses compares trends in abundance over time and at different elevations. Our results are revealing:
Several ringtail possum species have declined at the lower elevational limits of their ranges - Lemuroid Ringtail Possums (*Hemibelideus lemuroides*) and Herbert River Ringtail (*Pseudochirulus herbertensis*) whereas abundance of Daintree Ringtails (*Pseudochirulus cinereus*) and Greeen Ringtail (*Pseudochirops archeri*) have significantly increased at the upper limits of their elevational ranges. Of 56 bird species with sufficient abundance data for statistical analysis, 28 species show significant shifts upwards in elevation.
These results are consistent with modelled predictions of upwards shifts in population abundance that we published more than 10 years ago (Williams et al. 2003) and are in accordance with expectations under a warming climate and knowledge of the physiological tolerances of these species to maximum temperatures.

Using measurements of species abundance from the monitoring program, we completed analyses of changes in total population size on approximately 100 species of vertebrates to assess which species have undergone significant changes in total population size. At least 32 species of birds and possums have undergone significant changes in population size over the last two decades. Worryingly, many of the upland endemic species have undergone significant declines and the species that have increased are predominantly lowland generalist, widespread species. Indeed, these may be the first signs of climate driven changes in species distributions and we have not come close to the 2° C increase as predicted by 2030.

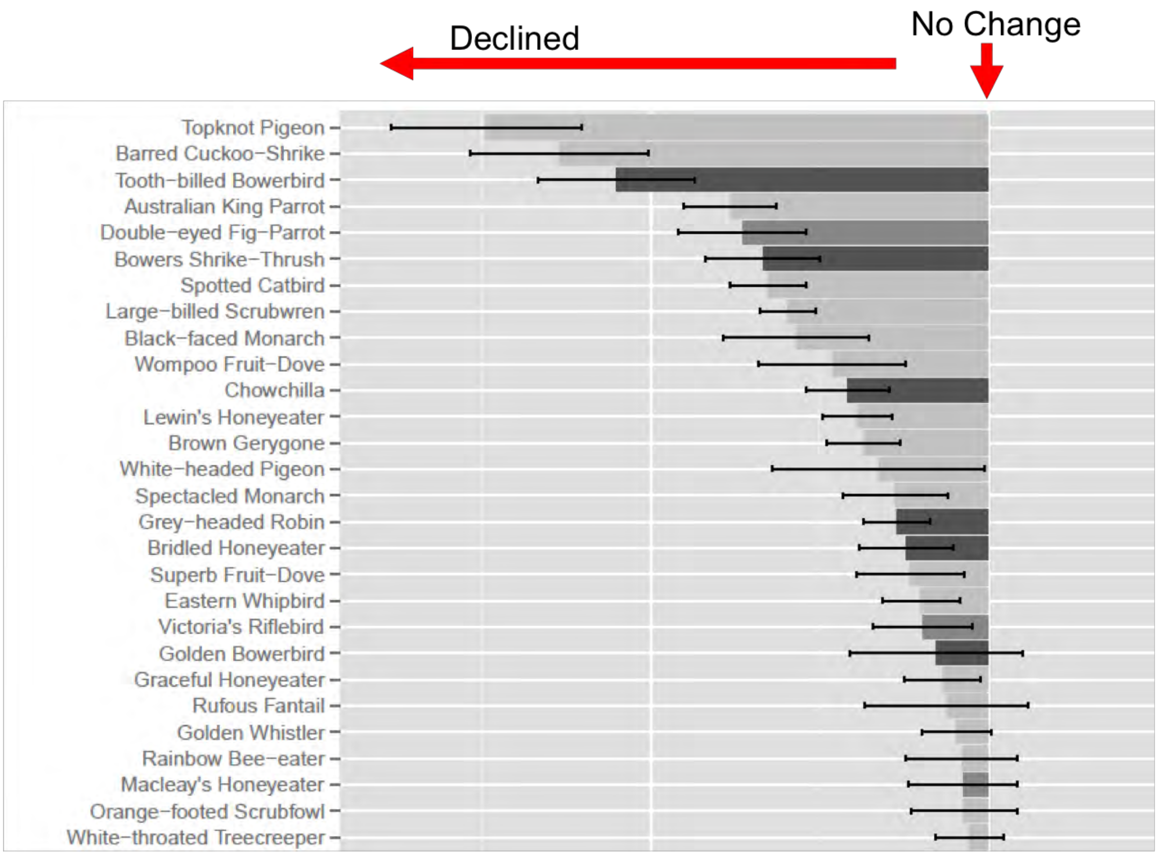


Figure 1: Bird Population Declines in the AWT. A representation of relative declines in bird populations over the last 10 years in the Australian Wet Tropical bioregion. For example, Bridled Honeyeater experienced a 30% decline in population size across the region.

Increased understanding of the relationships between rainforest ecosystems and biodiversity; implications for conservation planning, prioritisation, policy and management

Resilience-based prioritization of tropical fauna

Identifying areas with high species richness and endemism is an important first step in determining key conservation areas in the future. By using conservation prioritisation software, we can ensure that the areas of highest priority incorporate complementarity across both species and sites. This process can incorporate species attributes to fine-tune and improve decision-making. Thus, the way forward with this problem is to apply the tools of conservation planning to identify key areas that maximise species probability of survival given their biological resilience to climate change.

We used freely available and widely used software Zonation to produce a conservation prioritisation for the Australian Wet Tropics (AWT). Zonation is a widely used landscape conservation prioritisation software (Moilanen 2007 and references therein) designed to identify the areas of highest conservation priority for many species (or other biodiversity features) over a large landscape. The Zonation analysis proceeds by iteratively calculating the biological value of each planning unit in the landscape, and then removing the unit, which has the lowest biological value until all units have been removed (Moilanen 2007). The order of removal then gives a hierarchical conservation prioritisation across the landscape. Which planning unit has the lowest biological value depends on the removal rule being used, and the relative weightings placed on different preferred outcomes by the user. The iterative recalculation of all values ensures that Zonation achieves maximum complementarity in its ranking process. The basic output of Zonation is a hierarchical ranking of the landscape based on the series of biodiversity feature layers. This allows the user to immediately assess and visualise the importance of grid cells for any given fraction of the landscape. We report this basic output below as maps.

'Value' in Zonation, as with other conservation planning tools, is determined by the input layers and the weightings placed on different preferred outcomes by the user. Here we prioritised the landscape based on the "occurrence levels of biodiversity" (e.g., biodiversity weighted by priority species, endemics and range size) while accounting for species natural resilience of each species to disturbance.

Certain outflows from the NCCARF were first produced in cooperation with NERP targets. The NCCARF report by Reside et al (2013) highlights this product in detail but most importantly, for current, priority areas are not only centres of species-level biodiversity, but have also been major refugial areas under the climatic fluctuations of the last two million years. Importantly, the analysis highlights the largest tract of intact upland rainforest of the Atherton Uplands as highest priority refugia (Reside et al 2013). Under projected future distributions of biodiversity, Zonation identifies many of the same areas for current will remain as important refugia under contemporary climate change, although it is also clear that the Herberton Range in the central highlands and parts of the southern highlands become relatively more important under a median 2085 future climate.

We further built upon Reside et al (2013) and we identified areas of greatest conservation importance for 165 species in the Australian Wet Tropics based on species-level resilience to environmental change. In addition to traditionally incorporating home range and habitat suitability data (from Williams et al. 2010), we have weighted each species based on predicted values of resilience (first calculated in Isaac et al. 2009) scored from 1 (high resilience) to 8 (very low resilience). Resilience for each species was calculated based on various levels of reproductive output, climatic niche marginality, and potential for dispersal.

In short, our analyses incorporates current patterns of biodiversity and so we can identify key localities for conservation while also considering the biological resilience of the species that live there. Thus, an area may be prioritised as high priority under a 'normal' prioritisation scheme due to its biological value, however, may be downgraded in value in this area contains high proportions of species resilient to climatic change.

When species resilience scores were included in the analysis, we found that the remaining proportions of rainforest endemics and specialists were retained 1-15% more compared to runs with only home range and distribution data (Figure 1 and 2). This increase necessitates that distributions of other species must decrease. However, weighting by resilience almost exclusively reduces the remaining proportions of species that are common or widespread in areas beyond the Wet Tropics. This is an important finding, as these resilience weightings reduce any importance on species that do not require special consideration within a selected region in exchange for increased area for species that are truly vulnerable and reliant on the area in question. This highlights the importance of natural history and behavioral data in conservation planning decisions as without fine-scale details on species-specific traits, conservation planning may inappropriately prioritise land for conservation.

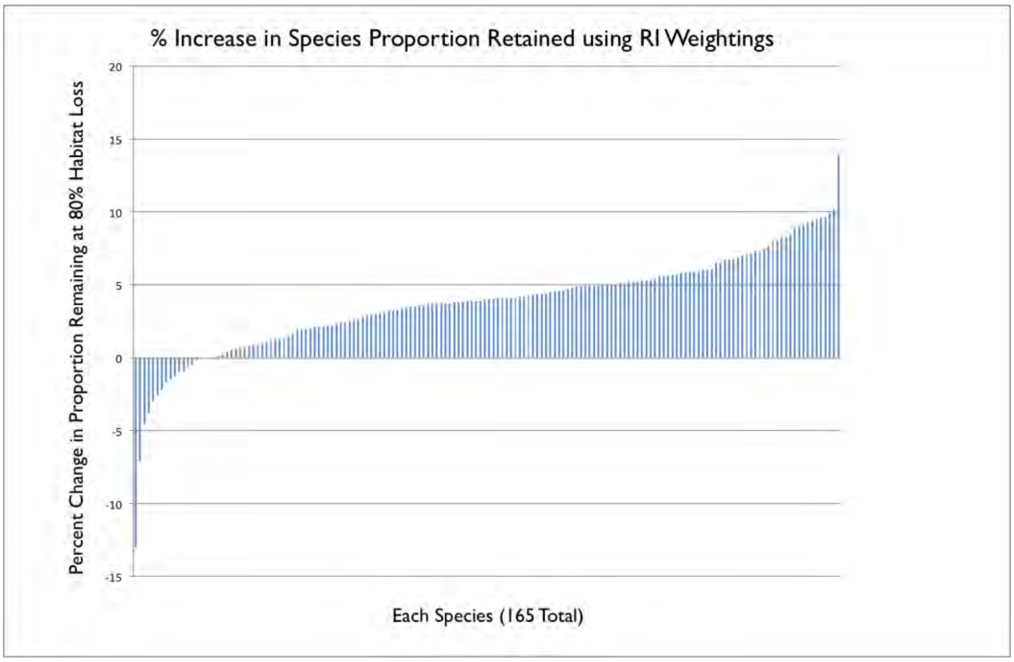


Figure 2: Conservation Prioritisation: Percentage in Species Proportion Retained using Resilience Weightings. Each bar represents one species, and it shows that overall, our conservation planning approach is preserving/retaining a higher percentage of each species' distribution when resilience is used as a weight. This, of course, comes at the expense of the distributions of some species (which lose percentages of their distribution), but those species are common and/or are not rainforest specialists. Put another way, Zonation is sacrificing the distributions of highly resilient species and retaining the distributions of low resilience species. This suggests that weighting by resilience could be a simple metric to use for conservation prioritization.

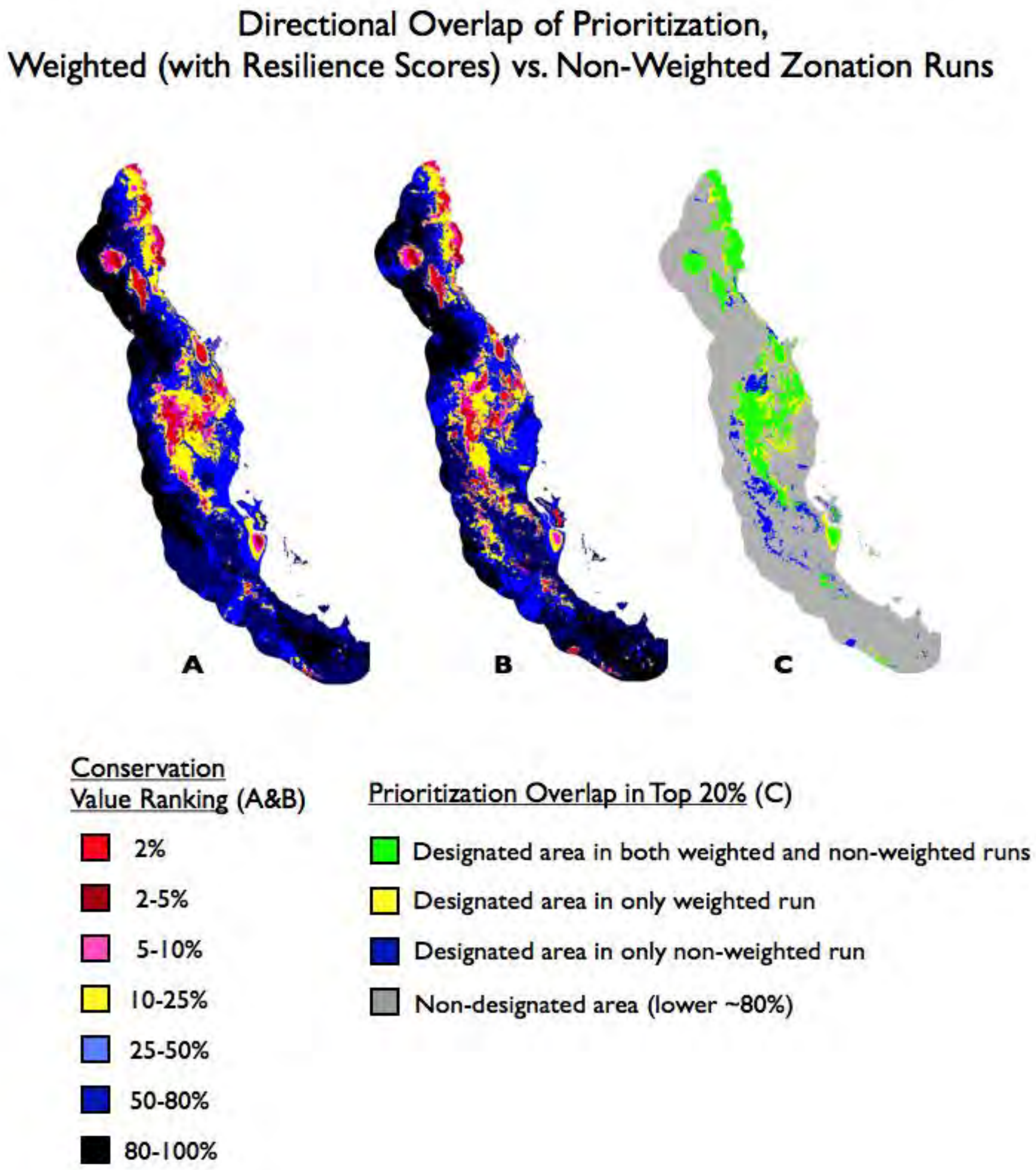


Figure 3: Prioritising Areas of Conservation Concern A) Areas of highest conservation concern for 165 species in the Australian Wet Tropics, weighted by expect resilience to environmental change (calculated in Isaac et al 2009). B) Areas of highest conservation concern for the same 165 species, without taking resilience into account. C) Zones of overlap between A and B for the highest ranked 20% of each map. Zonation runs agree in areas coloured in green, and disagree in areas coloured in yellow and blue.

Figure 3 identifies those areas of the greatest conservation importance in the region and maximizes the efficieny of spatial prioritization for management and policy by taking into account the natural resilience of each species. The final high resolution maps are available on request and will be lodged with WTMA. These results form the basis for a more detailed analysis of current and future priority areas to improve connectivity, landscape resilience and biodiversity retention in the region.

Decision Frameworks for Managers and Policy Makers under a Changing Climate

This project has built upon several key outputs from the previous MTSRF project and a linked NCCARF project on climate refugia to produce some significant outcomes in natural ecosystems management and policy. At the very beginning of the NERP program we put out a report that summarized the regional priorities based on a large meeting of stakeholders (Welbergen et al. 2012). The priorities set out in that report was influential in determining the specific aims of this project and more generally the other rainforest projects within the TE-NERP hub.
We published a decision framework to assist managers and policy makers to prioritise decisions around climate change adaptation (Shoo et al. 2013) that directly built upon an earlier framework on assessing species vulnerability (Williams et al. 2008) and climate refugia (Shoo et al. 2011).

This body of work directly lead to a number of significant projects and outcomes including:

- A national scale analysis of terrestrial climate refugia under the NCCARF program lead by Williams (Reside et al. 2013, Reside et al. 2014)
- A national scale analysis of freshwater refugia under the NCCARF program lead by VanDerWal (REFS??)
- A paper on assisted colonisation to conserve biodiversity (Byrne et al. 2013)
- The establishment of a new conservation area at Mt Baldy
- The instigation of an award winning restoration project in a collaboration with the Wet Tropics Management Authority, the “Making Connections” project
- The “Landscape Resilience” project by the Queensland Government to use climate resilience as a primary information source to evaluate the acquisition of new national parks in Queensland (see below).

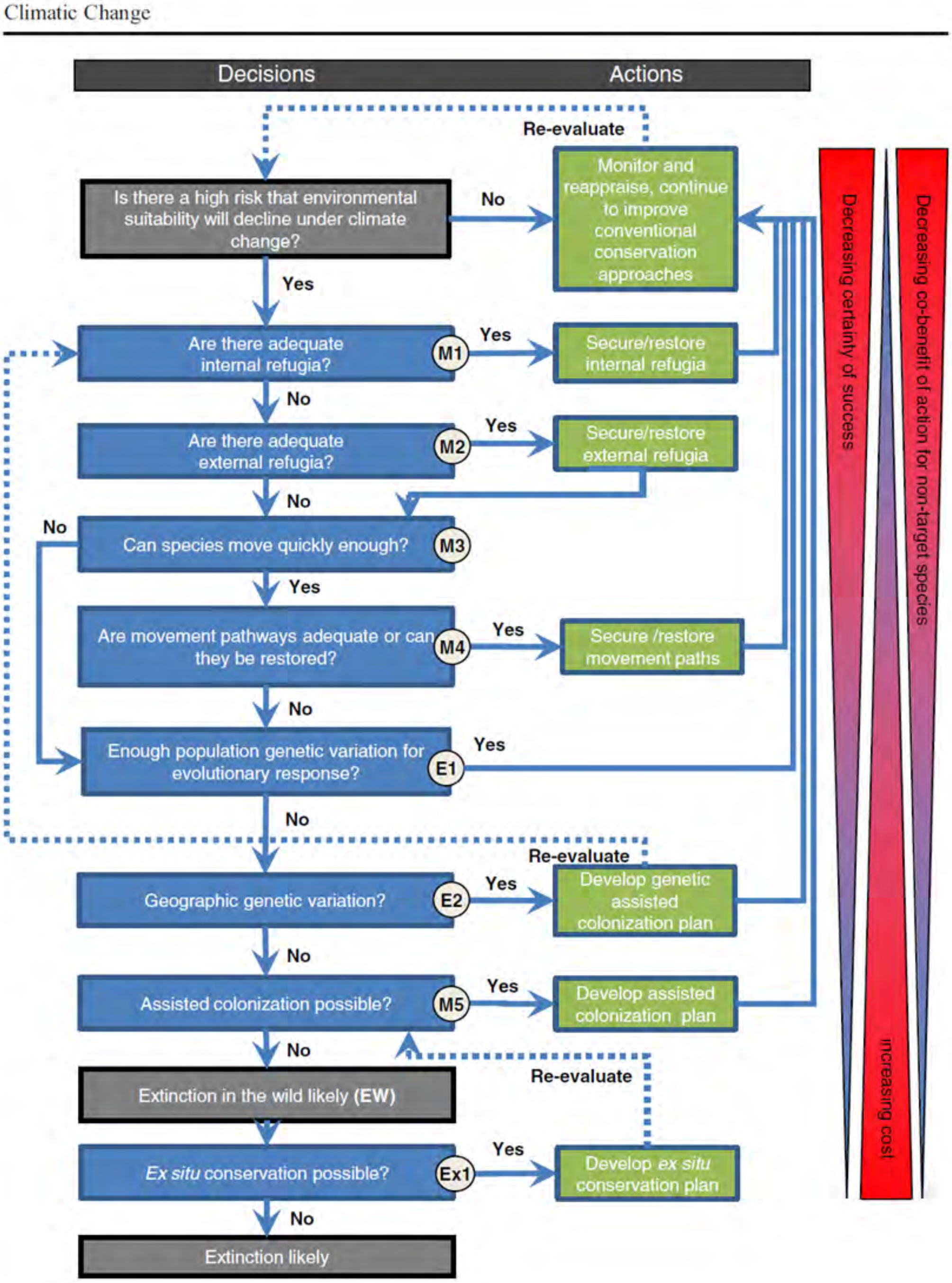


Figure 4: Decision framework for management actions focused on ameliorating impacts of climate change. Shoo *et al* 2013.

Understanding and Improving Landscape Resilience

The "Making Connection" Project

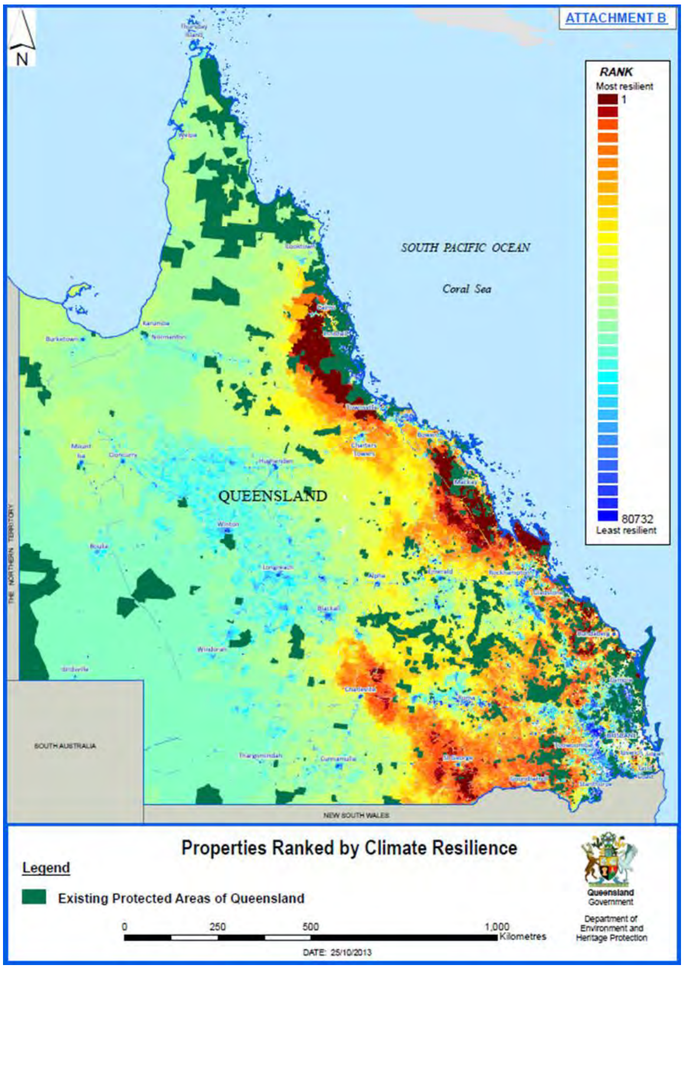
Analysis of landscape resilience and prioritisation of areas to give the best biodiversity outcomes for rehabilitation resulted in an award winning WTMA / community reforestation project funded by Caring for Country program, aimed at restoring habitat and connectivity in the upland rainforests of the Wet Tropics (for more details see **http://www.wettropics.gov.au/cfoc).**

The "Landscape Resilience" Program

The Landscape Resilience project was a collaboration with the Queensland Department of Environment that directly used research conducted within NCCARF and this project to inform the prioritisation of national parks acquisition in Queensland. The analysis aimed to maximise biodiversity retention based on future resilience to climatic change. The outcome of this research has been the allocation of approximately $17M and has acquired more than 5 new national parks and a number of conservation agreements in 2014 and a number more are still in the negotiation phase for purchase.

This project utilised a combination of species distribution modelling, future climatic resilience across the landscape and refugia analysis and combined these data with remnant vegetation, potential to increase landscape connectivity with existing conservation areas and potential to add important regional ecosystems to the existing protected area network (see Figure below).

Figure 5: Queensland climate resilience based on biodiversity



Dealing with an Uncertain, but Extreme Future

Extreme weather events, such as unusually hot or dry conditions, can cause death by exceeding physiological limits, and so cause loss of population. Survival will depend on whether or not susceptible organisms can find refuges that buffer extreme conditions. Microhabitats offer different microclimates to those found within the wider ecosystem, but do these microhabitats effectively buffer extreme climate events relative to the physiological requirements of the animals that frequent them? In Scheffers et al (2014), we collected temperature data from four common microhabitats (soil, tree holes, epiphytes, and vegetation) located from the ground to canopy in primary rainforests in the Philippines. Ambient temperatures were monitored from outside of each microhabitat and from the upper forest canopy, which represent our macrohabitat controls. We measured the critical thermal maxima (CTmax) of frog and lizard species, which are thermally sensitive and inhabit our microhabitats. Microhabitats reduced mean temperature by 1–2 °C and reduced the duration of extreme temperature exposure by 14–31 times. Microhabitat temperatures were below the CTmax of inhabitant frogs and lizards, whereas macrohabitats consistently contained lethal temperatures. Microhabitat temperatures increased by 0.11–0.66 °C for every 1 °C increase in macrohabitat temperature, and this nonuniformity in temperature change influenced our forecasts of vulnerability for animal communities under climate change. Assuming uniform increases of 6 °C, microhabitats decreased the vulnerability of communities by up to 32-fold, whereas under nonuniform increases of 0.66 to 3.96 °C, microhabitats decreased the vulnerability of communities by up to 108-fold. Microhabitats have extraordinary potential to buffer climate and likely reduce mortality during extreme climate events. These results suggest that predicted changes in distribution due to mortality and habitat shifts that are derived from macro- climatic samples and that assume uniform changes in microclimates relative to macroclimates may be overly pessimistic. Nevertheless, even nonuniform temperature increases within buffered microhabitats would still threaten frogs and lizards.

Understanding ecosystem processes in the Australian Wet Tropics

Decomposition, nutrient cycling and climate change in Australian tropical rainforests.

Parsons, Scott Anthony. Decomposition, nutrient cycling and climate change in Australian tropical rainforests. PhD thesis, James Cook University.

Knowledge of the mechanisms that dictate the composition and dynamics of ecosystems is essential for understanding the natural world. It is important to consolidate our understanding of ecosystem processes due to the need to understand and adapt to global anthropogenic climate change. The processes of decomposition and nutrient cycling that occur on the soil surface in forested environments both sustain ecosystems and have a substantial influence on the biosphere at many scales. This encapsulates the processes of plant litterfall, litter decomposition and nutrient release. Litter decomposition and nutrient cycling, although controlled by climate, vegetation and soil communities, are highly spatially and temporally variable. Our lack of understanding of these processes limits our ability to understand and adapt to climate change. The Australian Wet Tropics bioregion of north Queensland is an interesting natural environment in which to investigate the drivers and controls on litter decomposition and nutrient cycling. The region contains a range of tropical rainforest types on a variety of soils and is subject to varied climatic conditions. The risks of adverse effects from climate change are also high for this region, potentially leading to substantial losses of biodiversity and rare plant communities.

Decomposition and nutrient cycling were studied in this region at 21 locations (from near sea level to around 1300 m elevation), covering most of the climate range and soil conditions of the region. The aim was to understand the patterns and controls on these processes and how these controls may deviate from their current states under climate change scenarios. The approach determined spatial and temporal patterns in: leaf litter decomposition rates and nutrient dynamics in leaf litter using the litterbag technique for ~ 420 days; litterfall nutrients and chemical quality (i.e. chemical potential to decompose) of litterfall; litterfall rates and seasonality (in-conjunction with another PhD student); the amount of litter on the soil surface (litter standing crop, LSC) and the seasonality and turnover/duration of litter on the soil surface. Models explaining litter dynamics were then applied to climate change predictions specific to the region to determine the sensitivity of litter processes to climate.

Plant litter chemical quality is a highly significant driver of decomposition and nutrient cycling processes; however, standard methods for determining litter quality indices are often arduous and limited in their ability to explain ecological phenomena. Near infrared spectrometry (NIRS) has the potential to extend standard methods for chemical quantification. NIRS was used here to quantify the concentrations of nutrients, carbon fractions (total carbon and lignocellulose portions) and plant secondary compounds in litterfall, and leaf litter that underwent decomposition. NIRS also accurately predicted litter decomposition rates based on their initial NIR spectral composition (i.e. organic chemical composition) to determine litter decomposability, and was successfully used to model chemical changes in the material during decomposition.
The first exponential decomposition rate constants of in situ leaf litter (litter characteristic of each site) ranged from 0.33 y^{-1} (upland microphyll fern forest on granite) to 2.15 (complex mesophyll vine forest on basalt). Decomposition rates were explained well by climate, soil and litter quality, for litter collected in situ: average leaf wetness in the dry season (LWDS, moisture condensation) and the initial P content of the leaves ($r^2 = 0.78$, $p < 0.001$, $n = 17$), or LWDS and initial C ($r^2 = 0.75$, $p < 0.001$, $n = 17$); control treatment (a standard leaf litter, no litter quality

effect): rainfall seasonality (% dry season days with 0 mm rainfall), soil P, and mean annual temperature ($r^2 = 0.78$, $p < 0.001$, $n = 12$). Nutrients were not mineralised for periods of more than 12 months. Increased temperatures and moisture (especially in the dry season) improved lignocellulose and C mineralisation.

Litterfall leaf litter quality (24 months worth of sampling from 40 study plots at 20 sites) was driven by the combination of soil fertility (nutrient contents), climate (phenolics and C) and species/disturbance (lignocellulose components). Trends in litter quality indicated a negative feedback on soil and nutrient cycling processes in more stressed environments characterised by higher rainfall seasonality and lower soil fertility. Also, short term climate changes were determinants of litter chemical quality, with NIRS predicted decomposability lower, and total phenolic contents higher, in the dry season.

Two year average litterfall rates ranged from 4.89 to 11.29 t ha^{-1} y^{-1} ($n = 40$ plots). No environmental variable could explain litterfall rates but calculations were hindered by the secondary status of the vegetation, particularly resulting from damage caused by Cyclone Larry at many sites in March 2006. Seasonality of litterfall (vector algebra index) was linearly related to mean annual temperature and soil nitrogen. The temperature effect was partially explained by dry season moisture, however the trend was for higher seasonality in the wetter/cooler uplands ($n = 29$). LSC was determined in the field by a volumetric method developed especially for this study. LSC values ranged from 3.70 t ha^{-1} to 10.94 t ha^{-1} ($n = 36$ plots), and were explained by litter quality (NIRS decomposability) and the composition of litterfall, along with soil Na, mean annual temperature and leaf litter C content. LSC turnover quotients ranged from 0.57 to 2.81, and were controlled by similar variables to mean annual LSC. Seasonality in LSC was linearly related to soil Na. Local variability was high for mean annual LSC, with around 35% of the full regional variation contained within single 1 km transects. Climate change scenarios suggest temperature increases and decreases in dry season rainfall, with associated uncertainty, and dependent on emission scenario (mean for the full range of SRES, WRE450 and WRE550). The predicted changes in climate related to increases in the climate decomposition index (potential for climate driven decomposition, determined from min/max temperatures and monthly rainfall totals/seasonality) of +5.2 to +20.5% from current conditions (average from 40 study plots). Predicted changes in leaf decomposition rate and leaf lignin mineralisation rate (from control litterbag study), and full litter layer turnover rate were determined at 10 year time steps until 2080. For 2080 relative to present day, leaf decay rate showed large uncertainty: -7.46 to +8.15%; lignin mineralisation increased: -0.32 to +3.39%; and litter turnover increased: +5.9 to +24.2. The uncertainty in the leaf decay models were driven by uncertainty in the changes in dry season rainfall. The data suggests increasing decomposition rates from current conditions for poorer (chemical) quality material, such as whole litter standing crop and leaf lignin, compared to less recalcitrant material such as leaf litter. The magnitude of change is predicted to be greater at upland sites than lowland sites due to the non-linear relationship between temperature and the climate decomposition index, and on poorer nutrient soils due to the increasing effect of temperature on the decomposition of low chemical quality litter.

The extent and direction of change in these forests will depend not only on the direct effects of temperature and dry season rainfall and subsequent alterations in soil level litter processes, but also changes in primary productivity, including the timing and seasonality of litter inputs, and climate-driven succession of vegetation and plant traits such as litter chemical quality. These changes in the landscape feed back to global biogeochemical cycles in complex ways. Increases in litter decay, as mostly predicted to occur from this work, may act to further accelerate global warming. However, the direction of climate change driven changes in primary productivity, vegetation communities and plant litter quality, are essential in determining outcomes.

Climate Change Vulnerability and Adaptation

Population changes will largely depend on the physiological sensitivity of species as well as their exposure to climate. This serves as the backdrop to our monitoring program and is a critical consideration for making accurate and sensible predictions about how species might respond to future climate change. To this end, the relative resilience of a species based on the specific biological traits of each species is a key component to further our understanding of the drivers of changes in species abundance, distributions and biodiversity pattern and to create robust predictions about future vulnerability.
We explored how species resilience interacted with past climate to form current species distributions. In doing so, we confirmed that climate change has had a strong interaction with species-level resilience and this interaction largely formed where we see species in the AWT today.

Using the past to predict the future

We investigated the applicability of population modelling (i.e. species distribution modelling) to improve understanding of the drivers of biodiversity in the wet tropics. Broadly, understanding the drivers of biodiversity is a primary goal of the Centre for Tropical Biodiversity and Climate Change. The Wet Tropics Bioregion of North Queensland is one of the best studied tropical regions in the world, and recent modelling work undertaken in the centre has brought unique insights into past, present and future drivers of biodiversity for this tropical region, with broad implications for understanding biodiversity and ecology in general.
In this report, we show how species distribution modeling can be used to predict future climate change impacts on the wet tropics vertebrates. Coinciding with this, the species distribution models produced therein have been used to further disentangle the drivers of biodiversity in the Australian wet tropics and vulnerability to climate change effects. By understanding potential mechanisms behind current biological patterns, we may garner additional support for predicting patterns in the future.

All species have an inherent resilience (or vulnerability) to extinction, based on life history traits and the species' general ecology. Previous work in the Centre of Tropical Biodiversity and Climate Change by Isaac et al. 2009 explored in detail the resilience of all of the species of vertebrates in the Wet Tropics. Resilience in this way is defined by the reproductive output (indicated by clutch or litter size), climatic niche marginality, and potential for long distance dispersal. Isaac et al. used this information to rank all of the Australian Wet Tropics vertebrate species with sufficient data (163 species) by their potential to recover from environmental disturbance (Isaac et al. 2009). Here, we assessed the distribution of species' resilience to change, by looking at the relationship between historical habitat stability in the region and the species' resilience score. We did this because understanding of patterns of biodiversity should be considered in light of both contemporary and historical influences (Moritz et al. 2000; Araújo et al. 2008; Hoskin et al. 2011; Sandel et al. 2011). We hypothesized in this, that there would be a spatial relationship between species resilience and habitat stability, potentially showing areas where extinction had "filtered" species from an area. Understanding of this distribution is essential as it enables us to better comprehend the species that are potentially more vulnerable to extinction under future climate change and where these species are located/centred in the Wet Tropics.

The index of historical habitat stability was determined using the methods of Graham et al. (2010) over a grid surface of 500k evenly distributed points over the whole Australian Wet Tropics. Historical habitat stability can be as important, and in endemic low-dispersal taxa even more important (Graham, Moritz & Williams 2006; Sandel et al. 2011) than current habitat area in explaining spatial patterns of species richness. This method takes into account historical climatic stability and habitat refugia, and species endemism, to summarise habitat stability into a single index (1 = static/highly stable habitat, 0 = dynamic/unstable habitat) (Figure 6a). We see that the most stable habitats through time are those currently containing rainforest in the region (mountain ranges and the central "wetter" subregions) and that historically stable habitats make up the majority of the region (Figure 6a).

Spatial distribution of species richness was determined from long term regional scale monitoring of biodiversity (data collected herein) and spatial modelling of distributions with Maxent software (analyses conducted herein)(Figure 6b). A total of 202 rainforest vertebrate species from four broad taxonomic groups (frogs, reptiles, birds, mammals) were used for this purpose. Spatial patterns in vertebrate endemism (70 endemic species) were then determined from the full list of species for the region and the species assemblage for each point location (Figure 6c). These maps, and the distribution line plots with habitat stability in Figure 6c, show that the areas with the highest biodiversity and endemism are the most historically stable habitats. Thus, these areas have generally been refugia through time.

We then mapped the species resilience scores in the region (i.e. species resilience is shown as the mean resilience per grid cell and mapped). Areas of high historical climate stability are also dominated by species of low resilience e.g. to past climatic change (Figure 6c). This suggests that areas of low historical habitat stability have filtered out low resilient species, leaving a community assemblage dominated by species with high resilience (in this case, generally on rainforest margins and outside of rainforest in the Wet Tropics).

Our hypothesis suggests that the distribution of resilience across species should be determined by historical extinction filtering, that is, in areas of low stability it should be skewed towards having more species with higher resilience and in high stability areas there should be a more normal distribution of species with a range of resilience levels. To show the distribution of resilience values in terms of habitat we calculated the relative skewness (from a normal distribution) in species resilience for each point location in the region. We did this as it was possible that average resilience scores do not indicate the distribution of resilience for community assemblages, (i.e. due to being taken from the mean per grid cell/pixel) and could have been derived by the presence of equal parts low and high resilient species or little to no variation around mean resilience. That is, in order to determine whether historical extinctions are a non-random phenomenon and in the direction we would predict, we assessed the skew (from a normal distribution) of resilience for species assemblages across the Australian wet tropics. Indeed, resilience skew indicated that extinction filtering was non-random and areas of low habitat stability had a community assemblage with a resilience distribution that was highly skewed towards high resilience, whereas areas of high habitat stability had a more normal distribution of resilience scores (Figure 6d). This suggests that species with low, medium, and high resilience persisted in areas of high habitat stability, however the low stability areas were dominated by high resilience species, clarifying the historical filtering hypothesis.

This has important implications for future climate change, as we show that areas with high biodiversity and rare species are from highly stable habitats (historically). However, their low resilience leads them to be highly vulnerable to change, and extinction. This is especially true if predicted climate change is more severe than historical climate fluctuations (e.g., see Mora et al. 2013 and Beaumont et al. 2011). If projected climate depart from recent and historical variability, biotic communities will undoubtedly pass through yet another extinction filter event. These results provide merit to our future predictions of population trends. If past climate change can strongly influence species distributions, as seen in the strong spatial signature of environmental stability and species patterns, then future climate change will undoubtedly has similar affects on species distributions.

We validated these measures of resilience by successfully predicting the spatial patterns of localisedextinction in the past caused by paleo-climatic changes. Basically, areas of high historical climate stability have a range of species of variable resilience. However, unstable areas are dominated by highly resilient species. Resilience is an appropriate and novel indicator of future vulnerability to climate change because it accounts for a suite of species biological traits such as reproductive output, climatic niche and dispersal capabilities. Areas of low historical habitat stability have filtered out low resilient species leaving a community assemblage dominated by species with high resilience. Consequently, low resilient species are found solely in refugia areas of high habitat stability across the AWT.

We are using a combination of observed measurements of species distributions and abundances over the 20 years of Williams' dataset for the Wet Tropics, combined with spatial modelling and measures of ecological resilience to further our understanding of the status and trends of biodiversity in the region. We have successfully validated many of these results by testing them against changes in climate over paleo-climatic changes, thereby providing more confidence in utilising the data and models in future predictions. These analytical techniques are proving extremely useful in furthering our understanding of what drives biodiversity pattern in the region (see below).

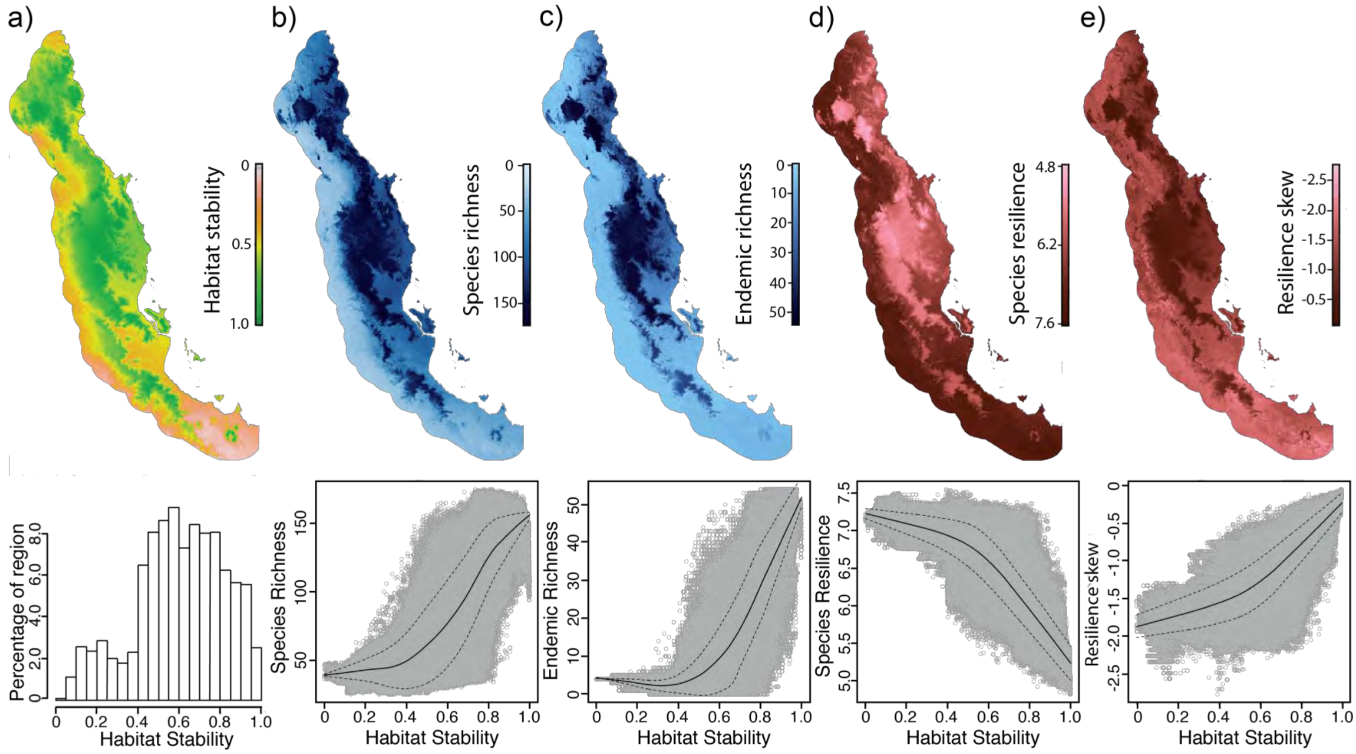


Figure 6: Spatial patterns of vertebrate species in the Australian wet tropical region. Maps show spatial patterns in: (a) Habitat stability, (b) species richness, (c) endemic richness, (d) mean species resilience, and (e) mean species resilience skew from a normal distribution. Also shown is the frequency of stable habitats in the region, and the relationship of the richness and resilience variables with habitat stability. Points in the scatter plots come from spatial modelling using 500k base points covering the region (lines show best fit from non-linear regression around 95% CI). Resilience analysis was based on all species with valid distribution models and sufficient biological trait data (N=163).

Understanding Microhabitat Buffering to Global Climate Change

A primary goal of our research it to understand how complex habitats mediate local and landscape climate. Previous research under MTSRF highlighted the importance of habitat and microhabitat buffering, particularly of temperature extremes (Williams et al 2008; Shoo et al. 2010, Shoo et al. 2012). Several subprojects have continued to increase our understanding of habitat buffering and the potential links to understanding species vulnerability including a PhD project using our datasets on biodiversity and microclimate measurments (Collin Storlie) and microhabitat analyses conducted by Brett Scheffers.

Vegetated habitats contain a variety of fine-scale features that can ameliorate temperate extremes. These buffered microhabitats may be used by species to evade extreme weather and novel climates in the future. Yet, the magnitude and extent of this buffering on a global scale remains unknown. Across all tropical continents and using 36 published studies, we assessed temperature buffering from within microhabitats across various habitat strata and structures (e.g., soil, logs, epiphytes, and tree holes) and compared them to non-buffered macro-scale ambient temperatures (the thermal control). Microhabitats buffered temperature by 3.9 °C and reduced maximum temperatures by 3.5 °C. Buffering was most pronounced in tropical lowlands where temperatures were most variable. With the expected increase in extreme weather events, microhabitats should provide species with a local layer of protection that is not captured by traditional climate assessments, which are typically derived from macro-scale temperatures (e.g., satellites). Our data illustrate the need for a next generation of predictive models, which accounts for species' ability to move within microhabitats to exploit favorable buffered microclimates. (Scheffers et al in press Biology Letters).

One such modelling approach to assess the influence of local microhabitat on species distributions was undertaken by Storlie et al (2013). To assess a species' vulnerability to climate change, we commonly use mapped environmental data that are coarsely resolved in time and space. Coarsely resolved temperature data are typically inaccurate at predicting temperatures in microhabitats used by an organism and may also exhibit spatial bias in topographically complex areas. One consequence of these inaccuracies is that layers created from coarse data (e.g., Satellites) may predict thermal regimes at a site that exceed species' known thermal limits. In this study, we use statistical downscaling to account for environmental factors and develop high-resolution estimates of daily maximum temperatures for a 36 000 km^2 study area over a 38-year period. We then demonstrate that this statistical downscaling provides temperature estimates that consistently place focal species within their fundamental thermal niche, whereas coarsely resolved layers do not. Our results highlight the need for incorporation of fine-scale weather data into species' vulnerability analyses and demonstrate that a statistical downscaling approach can yield biologically relevant estimates of thermal regimes (Storlie et al. 2013, Biology Letters).

Storlie, Collin James (2014) Balancing the Costs and Benefits of Increasing Information in Ecological Models. PhD thesis, James Cook University.

Ecology transitioned from observational studies to experimental studies and hypothesis testing, and is now transitioning back again; this reversal is largely due to technological advances in data collection, storage and computation that have enabled mining disparate sources of data to explore broad ecological relationships and theories. While mining these disparate sources of data has facilitated whole new fields of ecology and better understanding of ecological processes, there is a tendency to assume advanced analytics with complex data yields better results or better understanding; this is not always the case. As models and analysis become more complex so do the underlying assumptions, but the increased complexity may not be necessary. Herein, this thesis explores the value of mining disparate data sources, and of increasing model and data complexity, for exploring species-environment relationships (SERs) in ecology.

The spatially explicit models underlying exploration of the SERs typically rely on linking attributes of a species to coarsely interpolated and temporally aggregated information such as 'climate'. Climate is typically a 30 or 50 year average (as opposed to 'weather', which is more temporally discrete, e.g. daily maximum temperature), and spatially explicit estimates of climate and weather are typically interpolated between known locations based on latitude, longitude and elevation. Such climate and weather estimates represent spatial data which are naïve to the importance of key factors (e.g. topography and vegetation) that structure thermal regimes at fine scales. Further, such climate and weather surfaces may be biased in a non-random fashion as a result of estimating the environment at fine scale without reference to certain biotic and abiotic factors. Hence, gridded climate and weather data are often poor predictors of the true environmental conditions to which species are exposed – but how much does this matter in exploring spatiotemporal patterns in species distribution and abundance, and how these SERs may change?

Species tend to experience the environment at very local scales of time and space, thus a major flaw in spatially explicit ecological studies may be temporally aggregated, inaccurate, or spatially biased environmental data. SERs based on spatial environmental layers with any of the above problems will be biased, potentially leading to false inference of how the species interacts with the abiotic environment, and how this in-turn structures the species distribution. Herein, I focus on improving the accuracy of spatial weather and climate layers and proceed to quantify the value and need to improve these estimates using several algorithms of increasing complexity to estimate SERs. I demonstrate increased concordance of model outcomes with ecological niche theory when using accurate spatial data and increased utility for exploring new relationships.

Underlying the entire thesis is a statistical downscaling of broad-scale weather layers for the Wet Tropics Bioregion in north east Queensland. I statistically downscale 30 years of existing spatial weather estimates against empirical weather data and spatial layers of topography and vegetation to produce highly accurate spatial layers of daily weather. The downscaled weather layers are more accurate with respect to empirically measured temperature, particularly for maximum temperature, when compared to current best-practice weather layers. Current best-practice climate layers are least accurate in heavily forested upland regions, frequently over-predicting empirical mean maximum temperature by as much as 7 degrees. This thesis examines the value of the extra effort, complexity and assumptions required to produce these data with respect to SERs.

Correlative Species Distribution Models (SDMs) combined with spatial layers of climate and species' localities represent a frequently utilised and rapid method for imputing relationships between a species and its environment, as well as generating spatial estimates of species distributions. However, an SDM is only as accurate as the inputs upon which it is based – garbage in, garbage out. Using current best-practice climate data and my improved climate data, I proceed to demonstrate the effect of inaccurately quantified spatial data on SDM outcomes for a group of seven rainforest skinks. Generally, the distributions of the focal species are not visibly different (at a coarse scale) but the predictions generated using the improved climate layers are more fragmented and contain less core distributional area.

To assess a species' vulnerability to climate change, we commonly use mapped environmental data that are coarsely resolved in time and space. Coarsely-resolved temperature data are typically inaccurate at predicting temperatures in microhabitats used by an organism and may also exhibit spatial bias in topographically complex areas. As a result, simple correlations between where a species occurs and mapped environmental data may predict thermal regimes at a site that exceed species' known thermal limits. In this study, I use statistical downscaling to account for environmental and behavioural factors to develop high-resolution estimates of daily maximum temperatures for the preferred diurnal shelter of a group of rainforest frogs (Family: Microhylidae). I then demonstrate that this statistical downscaling provides temperature estimates that consistently place focal species within their fundamental thermal niche, whereas coarsely resolved layers do not. These results highlight the need for incorporation of fine-scale weather data into species vulnerability analyses, and demonstrate that statistical downscaling approaches are valuable for yielding biologically relevant estimates of thermal regimes.

Methods to predict spatially explicit patterns of species abundance are numerous in form. The most accurate techniques account for variable detection rates, so that we can separate detection from our estimate of abundance. While elegant, these detection models require large presence-absence datasets, derived from repeated surveys across temporal and geographic gradients. In many cases, however, the data are simply not available for these statistical approaches. In these cases, detection-invariant models, which do not require repeated survey effort, represent an alternative. Importantly, if detection rates are unaffected by the predictor variables, then these detection-invariant approaches may yield just as useful a measure of abundance as the more data-intensive models. Thus, by avoiding the use of predictor variables that likely affect detectability, some of the pitfalls of detection-invariant methods can be avoided. To test this, I model the abundance patterns of a group of rainforest skinks using two techniques: occupancy modelling, which accounts for variable detection rate, and a commonly-used presence-only approach (MaxEnt) which does not. I verify the veracity of model outputs against a large dataset of surveys for skink abundance at 200 plus sites across 10 years of time. I find that variable detection models and detection invariant models correlate well with carrying capacity across a number of sites, although variable detection models consistently predict abundance with greater accuracy. This result indicates that detection-invariant models, such as MaxEnt, are not as good as variable detection models but in the absence of repeat survey data, they can come close to the accuracy of a variable detection model. As such, they are still useful for the majority of cases when we require rapid assessment of species abundance patterns in the absence of more robust datasets.

Spatial layers of the weather have applications beyond SDMs and in this section I leverage information from the statistical downscaling of weather maps to demonstrate the effects of vegetation clearance on thermal regimes. The impacts of deforestation are typically measured in terms of habitat: hectares lost, altered habitat fragmentation or connectivity. However, altered habitat extent is just one component of change stemming from vegetation clearance. Climatic conditions too are regulated by vegetation and so are liable to change as well. Vegetation buffers habitats from extreme climate and weather conditions, which are predicted to increase in frequency under global warming scenarios. Despite this, we know surprisingly little about the indirect legacy of deforestation on accelerating the loss of extant climates (and dependent species) projected to 'disappear' under climate change. Here I describe the legacy of deforestation on climatic availability in the Australian Wet Tropics by integrating spatial information on vegetation and weather to quantify 30 years of weather patterns under two alternative scenarios of vegetation extent: prior to European Settlement (*circa* 1750) and current (1976-2005). I find that deforestation has on average increased region-wide maximum temperatures by 0.67 °C with larger increases in localised areas subjected to more extensive deforestation (0.86-0.90 °C). I also show that these modest climate shifts can be underpinned by dramatic reductions in the available area of particular thermal regimes including important cool environments projected to become increasingly scarce under climate change. Moreover, I demonstrate that thermal environments are more fragmented and less connected as a result of deforestation. Finally, I consider the potential for targeted reinstatement of vegetation to reduce range losses and buy time for adaptation to further climate change.

As data sources describing the environment and species localities proliferate, we are left asking what value these data lend to ecological analyses. Observational studies and statistical methods have developed to accommodate ever larger datasets, often assuming that more data will produce better results. The results of this thesis demonstrate that simpler models, with less restrictive datasets and assumptions can utilise large pools of data to form accurate predictions.

However, the utility of data sources still needs to be address before they are applied. My research shows that inaccurate or spatially biased environmental data can lead to false inference of SERs, altered patterns of predicted spatial distribution, and a lack of concordance with ecological theory. However, in the process of tailoring these spatial data to suit a variety of ecological analyses, I have further improved our understanding of the interplay between vegetation and the environment. Overall, these results indicate spatially biased climate and weather layers can be corrected with statistical downscaling techniques which explicitly consider abiotic and biotic factors that influence local processes. Downscaled layers meet both statistical (predicting empirical temperatures) and biological (concordance with species thermal limits) criterions of accuracy. Further, downscaling allows for an explicit understanding of how vegetation influences exposure, and the role of forest clearing in shifting thermal regimes.

A Review of Approaches for Assessing Species Vulnerability to Climate Change

In December 2013, a workshop was held by IUCN Climate Change Specialist group to develop and build novel methods of climate modeling. We provide a summary from Pacifici et al (in press, Nature Climate Change). The effects of climate change are increasingly well documented, and a large number of methods have been developed to assess species' vulnerability to the climatic changes that have occurred to date, as well as the potential impacts of further climate change in the coming decades. To minimize global biodiversity losses, conservationists need to identify and conserve the species that are likely to be most vulnerable to climate-change impacts. In this review, we summarize different currencies used for assessing species' climate change vulnerability. We describe three main approaches used to derive these currencies (correlative, mechanistic and trait-based), together with three combined approaches and their associated data requirements, spatial and temporal scales and modeling methods. We identify strengths and weaknesses of the approaches and highlight the sources of uncertainty inherent in each approach that limit projection reliability. Finally, considering the above, we provide guidance for conservation practitioners for selecting the most appropriate climate change vulnerability assessment approach(es) for their adaptation planning needs. We emphasize that a significant and urgent focus on a globally coherent effort to test modeling approaches against observed changes is essential to advance this field.

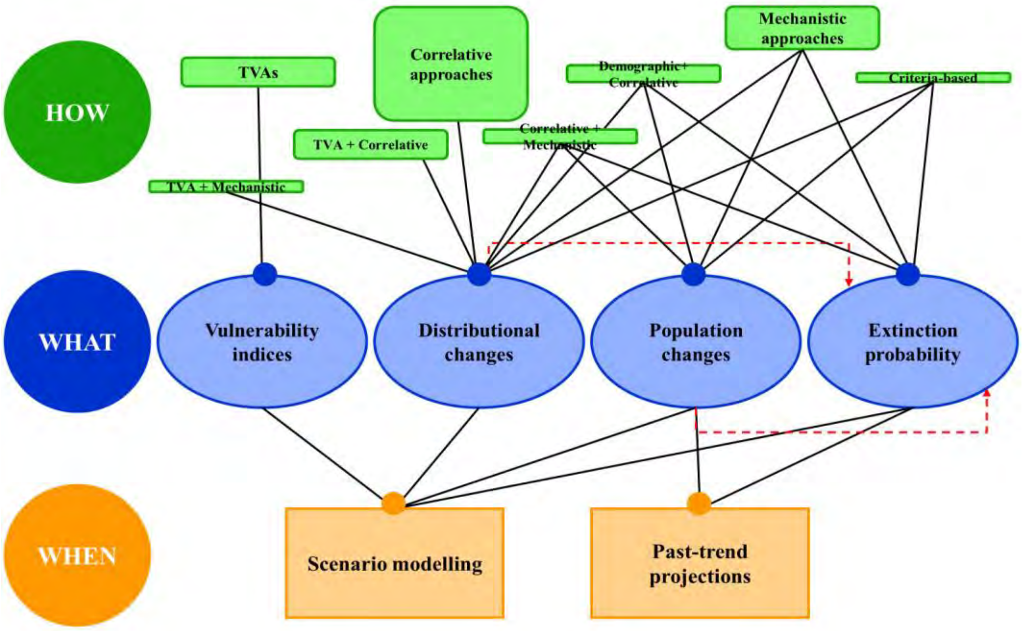


Figure 7: How to Approach Climate change Vulnerability Assessments. Climate change vulnerability assessments identified based on the kind of approach applied (HOW section), the metrics utilized (WHAT section), and the methods used to project data into the future (WHAT section). The 'Extinction probability' metric can be estimated through the use of Mechanistic approaches or combined approaches (i.e. Correlative + Mechanistic, Demographic + Correlative, Criteria-based; black arrows), as well as by calculating distributional or population changes (red dashed arrows) (from Pacifici et al. 2014, ***Nature Climate Change***).

Arboreality: A New Metric for Understanding Species Resilience to Climate Change

We used a two-fold approach assessing resilience and its affects on current species distributions. We used the above approach (seen in Figure 4) from Isaac et al (2009) which collates biological traits of species such as longevity, breeding biology and ecological specialisation produced indices of resilience for each species. Secondly, we devised an entirely novel metric of species resilience called arboreality (Scheffers et al 2013). Arboreality focuses on characteristics of tree living—physiological, morphological, and ecological adaptations that allows species to live above ground and in trees. The benefit of tree living is that species that are capable of exploiting the vertical structure gradient provided by trees have a third axis of optimum climate and niches available to them that ground-dwelling species are not able to exploit. This provides an extra layer of protection under climate change.

In our research we examined 'arboreality' as a potential driver of geographic patterns of biodiversity and a significant mediator of the extinction proneness of species to past, present and future environmental instability.

We introduced the 'arboreality hypothesis' (Scheffers et al 2013), which presented the first empirical evidence showing that the vertical distribution of species within forest strata changed across elevation. Specifically, the 'arboreality hypothesis' states that the ability of a species to exploit above ground habitats within trees (habitat plasticity) expands the niche options available to a given individual. Arboreal species should therefore have improved fitness via the ability to exploit optimal microclimates anywhere from the ground to the canopy. This flexibility allows for greater geographic range size than entirely ground-dwelling species due to the ability to survive in marginal areas by exploiting variable microhabitats, and consequently a greater resilience to both spatial and temporal variation in climatic conditions.

There are two concepts that must be first understood to answer how arboreality might affect species resilience to climate change. First, species whose internal temperatures reflect their environments, commonly called ectotherms, must find environments with temperature and moisture that maximizes their performance (Huey et al., 2012). The second premise is to understand how the vertical stratification of climate changes across elevation. Specifically, at low elevations the canopy is hot and dry, at mid elevations the canopy is warm and moist and at high elevations the canopy is cool and wet (Figure 8). Similarly, at low elevations the understory is warm and moist, at mid elevations the understory is cool and wet and at high elevations the understory is cold and very wet. Thus, the conditions in the understory at low elevations are found in the canopy at mid elevations, and the conditions in the understory at mid-elevations are found in the canopy at high elevations.

Under this premise, as the climate in the canopy transitions from hot and dry to cool and wet from low to high elevations, and as the climate in the understory transitions from warm and moist to cold and very wet from low to high elevations, animals should track optimal climates as they vertically transition across elevation (Figure 8; Huey et al., 2012). Our research filled a gap not considered before in the canopy science literature—we explored whether species that live near the ground at low elevations might live in the canopy at higher elevations.

We further tested this idea using data obtained within this project and from previous years. Arboreality not only influenced local biological patterns but shaped broad biogeographical patterns (Scheffers et al 2013). For example, we found that the lowlands were dominated by ground-dwelling species and the uplands were dominated by arboreal species. The likely reason for this is that at the lowest and highest elevations, frogs are physiologically constrained at opposing ends of the vertical climate gradient (too hot and dry in lowland canopies and too cold and wet in upland understories). This is likely due to the multidimensionality of climate that changes across elevation.

We conducted a workshop with experts in animal ecology from the Wet Tropics bioregion to derive a arboreality metric for each species in the region. We further conducted an extensive collation of existing data to create robust metrics of arboreality from data on species records (~400000 records on vertebrates) and ecological traits (from S.E. Williams' CTBCC database). We to explicitly analyse how arboreality expands species resilience to environmental instability and species range size and determines biogeographic patterns of species richness and endemism.

Our analysis suggests that arboreality allows species to live in inhospitable and instable areas. Our analyses show that across the Wet Tropics Bioregion, areas with high historical climate instability are occupied by animal communities with high levels of arboreality while areas of high historic environmental stability have a relatively normal distribution of arboreality within the assemblage (Figure 9). Arboreality likely increases animals resilience to climate instability and therefore areas of high instability have fewer regionally endemic species than areas of high stability. This relationship infers, that highly arboreal animals have larger geographic range in accordance with the predictions of the 'arboreality hypothesis' (Scheffers et al 2013).

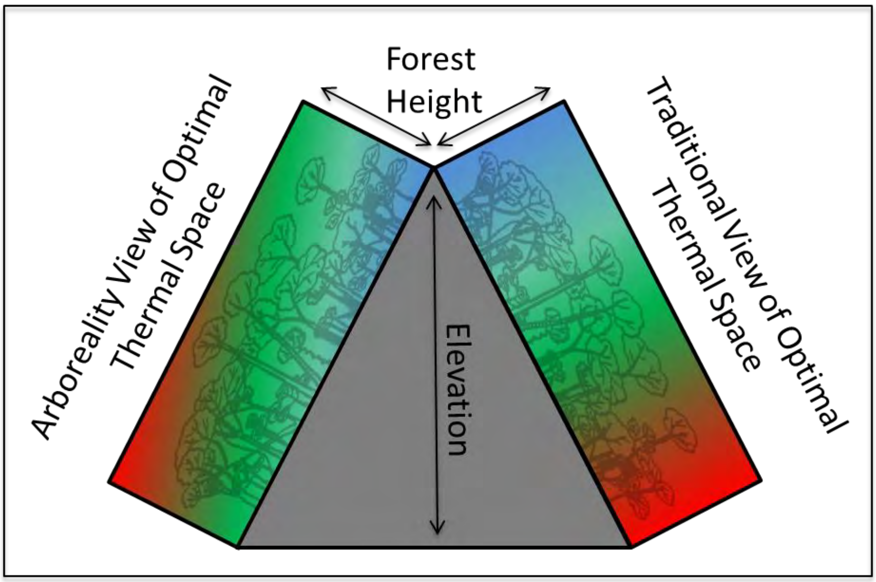


Figure 8: Arboreality. Multidimensional species distributions arise from multidimensional climate space. Climate transitions from warm on the ground and hot in the canopy in the lowlands to cold on the ground and warm in the canopy in the uplands (left panel). Arboreality treats optimal thermal space as temperature that dynamically changes when nested within other climate gradients such as elevation and latitude. This is opposed to the traditional view of optimal thermal space (right panel), which assumes temperature to be equal from ground to canopy.

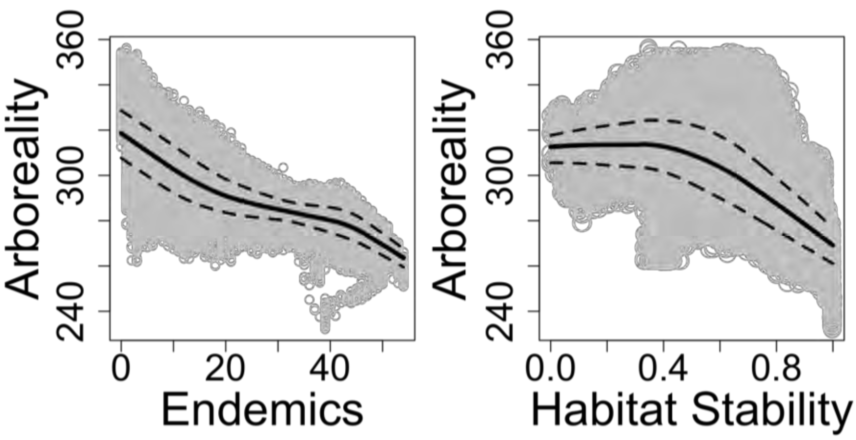


Figure 9: Arboreality of Regionally Endemic Species of the AWT. Regionally endemic species tend to be less arboreal (left). Species that are highly arboreal tend to persist in historically instable areas (right). Arboreality is currently based on expert opinion and ranked from low (min 100) to high (max 500) for 202 species across the AWT bioregion. Habitat stability indicates the climate stability across the AWT bioregion for the past 18 K years.

Predicting Future Trends in Wet Tropics Biodiversity

AR5 Climate Models and Scenarios into Biodiversity Vulnerability Analyses

We incorporated the most recent IPCC AR5 future climate scenarios in predicting future climate change impacts on biodiversity. These predictions have been undertaken for all rainforest specialist vertebrate species in the Wet Tropics region. Available data restricted the analysis to include 202 species across taxonomic groupings of birds, reptiles, amphibians and mammals. The climate change impacts on individual species and biodiversity as a whole was assessed against the latest IPCC emission scenarios (named representative concentration pathways; RCPs) for decadal time steps from present to 2085. The results of this modelling can be used to aid in defining species and areas of rainforest in North Queensland most at risk from climate change impacts, as well as understanding the ecology behind any changes.

The results largely paint a grim picture for the survival of the endemic vertebrates of the rainforests of North Queensland if global greenhouse gas emissions continue to rise rapidly. Our results show that the extent of negative impacts on species populations depends greatly on the emission scenario. We have undertaken these analyses with all scenarios in the AR5 predictions, however to show the range of impacts relative to strong anthropogenic emission/pollution and mitigation/reduction in pollution, we can focus on two emission scenarios with realistic potential of occurrence: RCP4.5 (low emissions e.g. mitigation of greenhouse gases) and RCP8.5 (high emissions e.g. continued increases in greenhouse gases this century).

The results show with the "business-as-usual" worst-case (RCP8.5) scenario, great losses in species are predicted to occur by 2085 (Table 2 and Figure 10: 59% of the 70 endemic vertebrates with > 90% of habitat loss and thus critically endangered or extinct; 79% endangered or > 70% population loss by 2085). This relates to 92% of all Wet Tropics endemic vertebrates vulnerable or worse by 2085 (Table 2). Contrastingly, mitigation of greenhouse gases (e.g. RCP4.5 scenario) will lead to substantial lessening of this impact, potentially saving many species from extinction (9% of endemic species with > 90% habitat loss, Table 2). Regardless, even with lower emissions (RCP4.5), 37% of rainforest endemics are still predicted to be in danger of extinction by 2085, with 63% vulnerable or worse (Table 2 and Figure 10).

Coupled with these predicted losses in vertebrate populations in the future, we have also shown that species distributions are likely to be greatly fragmented under these scenarios, further lowering the chances of viable populations surviving in the Wet Tropics of Queensland. The data shows that increased population fragmentation and loss of connectivity will occur together with the loss in populations, brought on by the changing climate. This means that future population distributions will be dramatically more fragmented than in contemporary landscapes (Figure 11). However the extent and the rate at which the AWT landscape changes is faster under the RCP8.5 scenario than the RCP4.5 scenario (Figure 11). Together this analysis not only clearly outlines the threats to iconic species in the future for this region, but also stresses the importance of greenhouse gas mitigation now in order to save species and rainforest habitats.

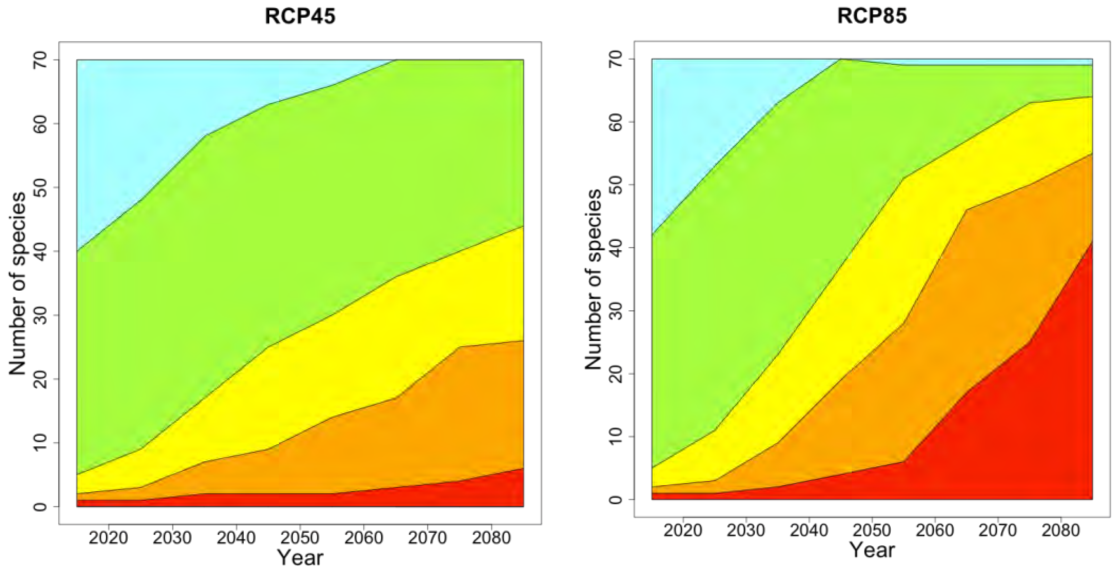


Figure 10: Projected changes in population size following exposure to a mitigation emission scenario (RCP4.5) versus a business-as-usual scenario emission scenario (RCP8.5). Colours represent IUCN population size categories: blue: increase from current; green: no change; yellow: vulnerable-50-70% population loss; orange: endangered-70-90% habitat loss; red: critically endangered-extinct-90-100% habitat loss.

Table 2: Predicted changes in endemic species abundances by 2085 under different emission scenarios for 70 endemic Wet Tropics rainforest vertebrates. Shown is the count and % of species in each category.

IUCN category	RCP4.5		RCP8.5	
Total population (% change)	#	%	#	%
Increase (+)	0	0.0	1	1.4
No change (0)	26	37.1	5	7.1
Vulnerable (50-70% loss)	18	25.7	9	12.9
Endangered (70-90% loss)	20	28.6	14	20.0
Critically endangered/Extinct (90-100% loss)	6	8.6	41	58.6
Total Threatened [V, EN, CR]	44	62.9	64	91.5

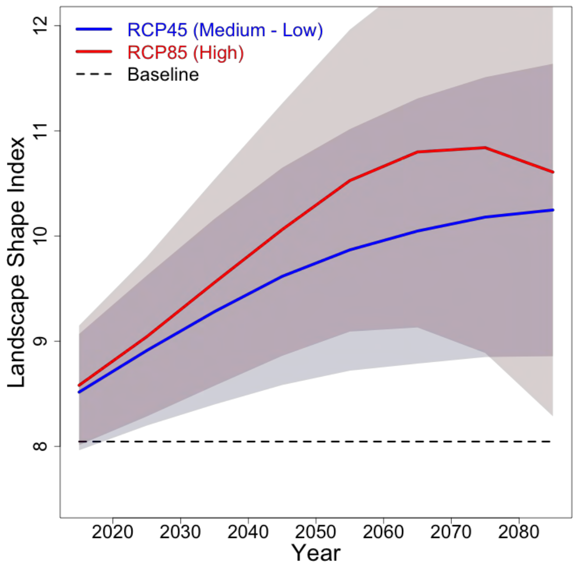


Figure 11: Change in the average level of fragmentation of populations distributions across 202 vertebrate species for two greenhouse gas emission scenarios (RCP45: medium – low emissions; RCP85: high emissions) for the Australian Wet Tropics vertebrates. Dotted lines shows the baseline (current) mean LSI for the Wet Tropics dataset. The landscape shape index represents a measure of patch aggregation or disaggregation, as LSI increases the populations become less aggregated and thus more fragmented.

Our integration of climate models and scenarios holistically assesses population loss over the next century. We further assessed the distribution of species resilience scores by projected IUCN threat in 2085. Under RCP45 emission scenarios, climate change will threaten species with low resilience— in accordance with historical patterns of species extinction during the past Quaternary period across the Australian Wet Tropics (AWT). Under RCP85 emission scenarios, climate change will threaten species regardless of their resilience. This new analysis paints a grim and dire picture for the future status of AWT species. Importantly, our IUCN approaches further validates our future prediction of species threat and it combines our model approaches with separate criteria (i.e., IUCN) for assessments.

As mentioned in the above section "***Using the past to predict the future"***, our research suggests that extinction filtering based on biological traits occurred during the Last Glacial Maximum (LGM (18kya)) and favoured species with high resilience to climate change. Warming under RCP45 emission scenarios is predicted to be comparable to warming that occurred during the Quaternary period (i.e., deviation from mean temperature). Future warming will select for species with high resilience and this pattern is in line with past filtering events. Warming under RCP85 emission scenarios is predicted to be far more severe than that which occurred during the Quaternary period (i.e., deviation from mean temperature). Under this warming scenario, biological resilience will no longer be effective in mediating the negative impacts of warming resulting in widespread species extinctions regardless of physiological tolerances to temperature.

Conclusion – Proof and validation of climate change impacts in the rainforests of Australia

Our research has provided several lines of evidence to support the existing and ongoing impacts of a changing global climate on the biodiversity values of the wet tropical rainforests of Australia. We garner support for climate change impacts on rainforest fauna from our modeling of species abundances and in relating these trends to past climate change. We show that past climate change filtered community assemblages based on their biological traits. Unstable areas contain highly resilient species where stable areas contains species with a spectrum of resilience indicating that no filtering occurred in highly stable areas. If past climate change can impact where species occur on today's landscape, it is logical to expect that present and future climate change will do the same.

We confirm that current species populations have reduced on the 'hot' ends of their distributions and expanded on their 'cool' ends of their distribution. This was consistent for numerous mammal and bird species and shifts occurred within a very small timeframe suggesting that future warming as projected by IPCC warming scenarios will truly be catastrophic for rainforest fauna and flora.

We provide an approach in the decision making process for dealing with species decline in the Australian Wet Tropics. Specifically, the identification and preservation of refugia areas will be essential in the long-term conservation of species in the region. Microhabitats within pristine rainforests will likely serve as the first line of defense against extreme weather events—we show that these small habitats remain cool and wet during hot conditions and should provide conditions that species can survive within under short time frames. Large-scale refugia areas will, however, ultimately be required for successful long-term conservation of populations. These areas have been identified using spatially ecplicit modeling approaches that capitalize on long-term data of species distributions and climate modeling in the region. Our project shows the power of long-term data. We have detected population level trends and species shifts from current climate change. In order to fully understand the consequences of long-term climate change and in order to respond accordingly to population decline, more long-term monitoring of populations will be required. Long-term data are paramount for successfully conservation in the region.

Our future predictions from modeling abundance changes into the future are consistent with the shifts that we observed from the field. Our analyses are the most comprehensive analysis for this region to date and we predict that up to 92% of all Wet Tropics endemic vertebrates will be vulnerable or worse by 2085. However, we demonstrate that the reduction of global emmissions under a medium mitigation scenario could save the majority of the biodiversity in the wet tropics. A combination of mitigation and adaptation informed by prioritisation of species and places based on relative vulnerability is essential in order to conserve the unique biodiversity assets of the Wet Tropics World Heritage Area.

List of Outputs from NERP Rainforest Biodiversity Project 3.1

Book Entries

Williams SE, BR Scheffers and JL Isaac. 2014. 'Australian tropical rainforests', in D. Lindenmayer, S. Dovers and S. Morton (eds), *Ten Commitments Revisited: Securing Australia's Future Environment*, CSIRO Publishing, Collingwood, V.I.C., pp. 83-89

Isaac, J. & Williams, S.E. 2013. Climate change and extinctions. Cambridge Encyclopedia of Biodiversity 2nd Ed., S. Levin (ed.) Elsevier Press http://www.sciencedirect.com/science/referenceworks/9780122268656

Puschendorf R, Alford RA & Hoskin CJ. 2012. Armoured Mistfrog (Litoria lorica). In: Queensland's Threatened Species. Eds. Curtis LK, Dennis AJ, McDonald KR, Kyne PM & Debus SJS. CSIRO Publishing. p. 154–155.

Puschendorf R, Alford RA, Hoskin CJ & Cashins S. 2012. Waterfall Frog (Litoria nannotis). In: Queensland's Threatened Species. Eds. Curtis LK, Dennis AJ, McDonald KR, Kyne PM & Debus SJS. CSIRO Publishing. p. 158–159.

Reports

Reside, A.E., Ceccarelli, D.M., Isaac, J.L., Hilbert, D.W., Moran, C., Llewelyn, J., Macdonald, S., Hoskin, C.J., Pert, P. & Parsons, J. (2014) Biodiversity—Adaptation pathways and opportunities. In: Adaptation Pathways and Opportunities for the Wet Tropics NRM Cluster region (Volume 1). Eds: C. Moran, S. Turton, R. Hill. James Cook University, Cairns.

Reside, AE, VanDerWal, J, Phillips, B, Shoo, LP, Rosauer, DF, Anderson, BJ, Welbergen, J, Moritz, C, Ferrier, S, Harwood, TD, Williams, KJ, Mackey, B, Hugh, S, Williams, SE 2013 *Climate change refugia for terrestrial biodiversity: Defining areas that promote species persistence and ecosystem resilience in the face of global climate change*, National Climate Change Adaptation Research Facility, Gold Coast.

Williams Y.M. et al. Terrestrial Report Card 2013: Climate change impacts and adaptation on Australian biodiversity. 2012. National Climate Change Adaptation Research Facility, Brisbane. (http://terrestrialclimatechange.org.au/BioDiversity_Report_card.pdf)

Hughes L., R. Hobbs, A. Hopkins, J. McDonald, M. Stafford-Smith, W. Steffen & S.E. Williams. 2010. National Climate Change Adaptation Research Plan: Terrestrial Biodiversity. Australian Government, Canberra.

Other evidence of impact (Newspapers, Magazines, Newsletters, Radio, TV)

Williams, S.E. & B.R. Scheffers. 2013. As climate changes, animals move fast to escape the heat. *The Conversation*. https://theconversation.com/as-climate-changes-animals-move-fast-to-escape-the-heat-18511 (>7500 readers and over 200 comments in 3 months)

Williams - Research featured in Chandler, Jo. "Ghost of the cloud forest: Seeking the white possum." *New Scientist* issue 2980. 31 July 2014

Meetings, Conference Presentations and Invited Talks

2012

Williams contributed to a workshop in July organised by the Tropical Landscape Joint Venture (CSIRO/JCU) which focused on consultation with stakeholders on research needs and requirements for North Queensland.

Williams attended the NERP project leaders meeting in Cairns on and presented the project summary and progress to date.

2013

Williams working with Thai rangers with possible international collaboration and training on climate change monitoring similar to Wet Tropics case study in February

Anderson visited Japan Climate Change impacts Assessment group and presented Wet Tropics information in March

Anderson presented conservation planning and Wet Tropics analysis to the University of Auckland, NZ in March.

Williams worked with indigenous rangers (Bana Yarralji Bubu Inc.), in conjunction with Earthwatch as part of the next field sampling in March 2013

Williams, Roslan and Scheffers attended the NERP conference in Cairns in which Williams presented a presentation and poster showcasing the project's activities and progress to date in May 2013.

VanDerWal and Shoo consulted with WTMA over direction on conservation planning analysis on 31st Jan 2013

Williams and Alex Anderson consulted with WTMA over direction on status and trends analysis on 1st March 2013

2014

Asia-Pacific Rainforest Summit hosted by Australian Environment Minister Greg Hunt and attended by dignatories and representatives of most Asia-Pacific Nations, Sydney – Williams. Meeting resulted in a draft Asia-Pacific Rainforest Recovery Plan that is currently in process of being revised etc with input from Williams.

QLD EHP Meeting, Williams attended to discuss NCCARF generated mapping and acquisition of new national parks that were climate resilient, Brisbane.

NERP seminars at Department of Environment. Williams / VanDerWal / Scheffers presented three seminars on the results of the NERP research. Each seminar session was followed by a series of meetings with departmental staff to discuss potential for the work to be utilised by department staff, to discuss potential applications of the data and to discuss future priorities, Canberra.

ATBC Conference, Scheffers, VanDerWal and Anderson attended.

Williams and VanDerWal have had a number of meetings with senior planning staff of the Wet Tropics Management Authority to ensure the data generated in the project is easily and directly accessible by WTMA, Cairns.

VanDerWal travelled to Tasmania to collaborate with Chris Johnson around NERP projects, Hobart.

WTMA Science Advisory Committee Meetings, Williams attended, Cairns.

Workshops
2012
Tropical Landscape Workshop. Williams attended. Joint Venture (CSIRO/JCU) which focused on consultation with stakeholders on research needs and requirements for North Queensland – July

2013
IUCN Species Survival Commission Climate Change Specialist group Meeting, Williams (Chair) and Scheffers attended to discuss framework for assessing species vulnerability to climate change and the potential for IUCN "Red List" process to include a predictive assessment of future vulnerability based on a combination of species distribution modeling and species traits.

2014
Post-ATBC Workshop, "Velocity of climate change in the Tropics"; Williams/Scheffers/Roslan held Workshop and invited 17 international academics, Daintree Research Observatory.

WTMA Stakeholder Workshop. Williams helped plan regional stakeholder workshop to examine regional research priorities, outcomes from existing research and future possibilities, Cairns.

Rainforest Biodiversity Symposium, Sydney. Williams attended meeting with Federal Environment Ministers and Ministers from South-east Asian countries, Sydney.

Journal Articles

In Review

Zamora-Vilchis I.R., Esparza-Salas, C.N. Johnson, S.E. Williams, J.A. Endler and R.H. Crozier. Parasites mediate diversity and selection of host MHC genes: implications for disease impact in a warming climate. *Nature Climate Change*

Scheffers B., *et al.* (incl. S.E. Williams) Where you rear your young matters: climate change vulnerability of frogs in the Philippine global biodiversity hotspot. *Functional Ecology*

Anderson A.S., L.P. Shoo and S.E. Williams. Body size, song and detection probability: correcting for detection bias and estimating density of rare species in rainforest bird surveys. *Journal of Applied Ecology*

Anderson A.S., T. Marques, L.P. Shoo and S. E. Williams Species, weather and habitat: factors influencing detectability and density estimation of tropical rainforest birds. *PLoS 1*

In Press

Scheffers, B.R.,T.A Evans, S.E. Williams, and D. P. Edwards. *Accepted.*Microhabitats in the tropics buffer temperature in a globally coherent manner. *Biology Letters.*

Zozaya S.M. & Hoskin C.J. A significant range extension for the Magnificent Broodfrog Pseudophryne covacevichae, with comments on similarity with *P. major*, and additional data on the distribution of *Uperoleia altissima*. *Australian Zoologist.*

Published

Storlie, C.J., A. Merino-Viteri, B. Phillips, J. VanDerWal, J. Welbergen, Williams S.E. 2014. Stepping inside the niche: microclimate data are critical for accurate assessment of species' vulnerability to climate change. *The Royal Society* 10 (9) 20140576

Reside, A.E., J.A. Welbergen, B. Phillips, G.W. Wardwell-Johnson, G. Keppel, S. Ferrier, S.E. Williams, J. VanDerWal. 2014. Characteristics of climate change refugia for Australian biodiversity. *Austral Ecology* 39 (8) 887-897. DOI: 10.1111/aec.12146

Parsons, S.A., R.A. Congdon, L.P. Shoo, V. Valdez-Ramirez, S.E. Williams. 2014. Spatial Variability in Litterfall, Litter Standing Crop and Litter Quality in a Tropical Rainforest Region. *Biotropica* 46 (4) 378-386. DOI: 10.1111/btp.12113

Staunton, K., S. Robson, C. Burwell, A. Reside & S.E. Williams. 2014. Projected distributions and diversity of flightless ground beetles within the Wet Tropics and their environmental correlates. *PLoS 1* 9 (2). DOI: 10.1371/journal.pone.0088635

Weber L.C, J. VanDerWal, S. Schmidt, W.J.F. MacDonald, L.P. Shoo (2014) Patterns of rain forest plant endemism in subtropical Australia relate to stable mesic refugia and species dispersal limitations. *Global Ecology & Biogeography* 23(2) 181-190. doi:10.1111/geb.12088

Anderson, A.S., C.J. Storlie, L.P. Shoo, R. G. Pearson, S.E. Williams. 2013. Current analogues of future climate indicate the likely response of a sensitive montane tropical avifauna to a warming world. *PLoS 1* 8 (7). DOI: 10.1371/journal.pone.0069393.

Scheffers, BR., D.P. Edwards, A. Diesmos, Theodore A. Evans & S.E. Williams. 2013. Microhabitats reduce animal's exposure to climate extremes. *Global Change Biology* 20 (2) 495-503. DOI: 10.1111/gcb.12439

Scheffers, B.R., B. Phillips, W.F. Laurance, N.S. Sodhi, A. Diesmos, and S.E. Williams. 2013. Increased arboreality with altitude: a novel biogeographic dimension. *Proceedings of the Royal Society B Lond.* 280: 20131581

Scheffers B.R., R.M. Brunner, S.D. Ramirez, L.P. Shoo, A. Diesmos, and S.E. Williams. 2013. Thermal buffering of microhabitats is a critical factor mediating warming vulnerability of frogs in the Philippine biodiversity hotspot. *Biotropica: 45 (5), 628-635*

Zozaya, S.M., B.R. Scheffers, C.J. Hoskin, S.L. MacDonald & S.E. Williams. 2013. A significant range extension of the wet tropics skink *Eulamprus frerei*. *Memoirs of the Queensland Museum – Nature*: 56: 621-624

Garnett, S, Franklin, D, Ehmke, G, VanDerWal, J, Hodgson, L, Pavey, C, Reside, A, Welbergen, J, Butchart, S, Perkins, G, Williams, S.E. 2013. *Climate change adaptation strategies for Australian birds*, National Climate Change Adaptation Research Facility, Gold Coast, Australia. pp.109.

Warren, R., VanDerWal, J., Price, J., Welbergen, J.A, Atkinson, I., Ramirez-Villegas, J., Osborn, T.J., Jarvis, A., Shoo, L.P., Williams, S.E., Lowe, J. 2013. Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change* 7: pp 678-682

Storlie, C.J., Phillips B.L., VanDerWal J.J., Williams S.E. 2013. Improved spatial estimates of climate predict patchier species distributions. *Diversity & Distributions* DOI: 10.1111/ddi.12068

Capon, S.J., L.E. Chambers, R.Mac Nally, R.J. Naiman, P. Davies, N. Marshall, J. Pittock, M. Reid, T. Capon, M. Douglas, J. Catford, D.S. Baldwin, M. Stewardson, J. Roberts, M. Parsons, and S. E. Williams. 2013. Riparian ecosystems in the 21st Century: hotspots for climate change adaptation? *Ecosystems* DOI: 10.1007/s10021-013-9656-1

Shoo, L.P., A. A. Hoffman, S. Garnett, R.L. Pressey, Y. M. Williams, M. Taylor, L. Falconi, C.J. Yates, J.K. Scott, D. Alagador, S. E. Williams 2013. Making decisions to conserve biodiversity under climate change. *Climatic Science early online* DOI 10.1007/s10584-013-0699-2

Byrne, M., I.D. Lunt, J.J. Hellmann, N.J. Mitchell, S.T. Garnett, M.W. Hayward, T.G. Martin, E. McDonald-Madden, K.K. Zander & S.E. Williams. 2013. Using assisted colonisation to conserve biodiversity and restore ecosystem function under climate change. *Biological Conservation*. 157: 172-177

Laurance, W.F. *et al*. (incl. S.E. Williams). 2012. Averting biodiversity collapse in tropical protected areas. *Nature* 489: 290-294

Zamora-Vilchis, I., S.E. Williams & C.N. Johnson. 2012. Environmental temperature affects prevalence of blood parasites of birds on an elevation gradient: implications for disease in a warming climate. PLoS 1 7(6): e39208. doi:10.1371/journal.pone.0039208

Anderson, A.S., Reside, A., VanDerWal, J., Shoo, L.P., Pearson,R.G. S.E. Williams. 2012. Immigrants and refugees: the importance of dispersal in mediating biotic attrition under climate change. *Global Change Biology* 18: 2126-2134

Bateman, B.L., J. VanDerWal, S.E. Williams & C.N. Johnson. 2012. How much influence do biotic interactions have on predictions of shifts in species distributions under climate change? *Diversity & Distributions*. DOI: 10.1111/j.1472-4642.2012.00922.x

Bateman, B.L., J. VanDerWal, S. E. Williams and C. N. Johnson. 2012. Biotic interactions influence the projected distribution of a specialist mammal under climate change, *Diversity and Distributions* 18 (9) 861-872

Huey, R.B., M.R. Kearney, A Krockenberger, J.A.M. Holtum, M. Jess, S.E. Williams. 2012. Predicting organismal vulnerability to climate warming: incorporating the buffering roles of behaviour, physiology, and adaptation. *Philosophical Transactions of the Royal Society.* 367: 1665-1679

Moritz, C., G. Langham, M Kearney, A Krockenberger, J VanDerWal and SE Williams. 2012. Integrating phylogeography and physiology reveals divergence of thermal traits between central and peripheral lineages of tropical rainforest lizards. *Philosophical Transactions of the Royal Society.* 367: 1680-1687

Little ,J.K., L.D. Prior, G.J. Williamson, S.E. Williams, D.M.J.S. Bowman. 2012. Fire weather risk differs across rain forest - savanna boundaries in the humid tropics of north-eastern Australia. *Austral Ecology* 37: 915-925

Parsons, S.A., R.A. Congdon, I.R. Lawler, L.P. Shoo & S.E. Williams. 2012. Regional patterns and controls of leaf decomposition and nutrient dynamics in Australian tropical rainforests. *Austral Ecology* 37: 845-854

Parsons, S.A., I.R. Lawler, R.A. Congdon & S.E. Williams. 2011. Rainforest litter quality and chemical controls on leaf decomposition with near infrared spectrometry. *Journal of Plant Nutrition and Soil Science* 174: 710–720

Reside, A., J. VanDerWal, A. Kutt, I. Watson & S.E. Williams. 2011. Fire regime shifts affect bird species distributions. *Diversity & Distributions.* 18: 213-225.

Bell, R.C., J.B. MacKenzie, M.J. Hickerson, KL. Chavarría, M. Cunningham, S.E. Williams, C. Moritz. 2011. Comparative multi-locus phylogeography confirms multiple vicariance events in co-distributed rainforest frogs. *Proc. Royal Society Lond. B* 279: 991-999

Hoskin, C.J., Tonione M., MacKenzie J.B., Higgie, M., Williams S.E., VanDerWal J., & Moritz C. 2011. Persistence in peripheral refugia promotes speciation in a rainforest frog. *American Naturalist* 178: 561-578

Shoo, L.P., *et al.* (incl. S.E. Williams). 2011. Engineering a future for amphibians under climate change. *J. of Applied Ecology* 48:487-492 (IF: 4.56 ERA: A)

Laurance ,W.F., *et al.* (incl Williams S.E.) 2011. Global warming, elevational ranges and the vulnerability of tropical biota. *Biological Conservation* 144: 548-557 (ERA: A)

Shoo, L.P., C.J. Storlie, J. VanDerWal, J. Little & S.E. Williams. 2011. Targeted protection and restoration to conserve tropical biodiversity in a warming world. *Global Change Biology* 17:186-193) (IF: 5.88 ERA: A*)

Welbergen, J.A., S.E. Williams, S. Goosem. 2011. Gap analysis of environmental research needs in the Australian Wet Tropics. Marine & Tropical Science Research Facility, Australian Government.
http://www.jcu.edu.au/mtb/public/groups/everyone/documents/other/jcu_083921.pdf

Williams, S.E., J. VanDerWal, J. Isaac, L. Shoo, C. Storlie, S. Fox, E.E. Bolitho, C. Moritz, C. Hoskin & Y.M. Williams. 2010. Distributions, life history specialisation and phylogeny of the rainforest vertebrates in the Australian Wet Tropics. *Ecology* 91(8): 2493 (Access DATA via Ecological Archives http://esapubs.org/archive/ecol/E091/181/default.htm) (ERA: A*)

Williams, S.E., Shoo L., Henriod R.& Pearson R.G. 2010. Elevational gradients in species abundance, assemblage structure and energy use of rainforest birds in the Australian Wet Tropics bioregion *Austral Ecology* 35: 650-664 (ERA: A)

Shoo, L.P., C. Storlie, Y.M. Williams & S.E. Williams. 2010. Potential for mountaintop boulder fields to buffer species against extreme heat stress under climate change. *International Journal of Biometeorology* 54: 475-478 (ERA: B)

Graham, C.H., VanDerWal J., Phillips S., Moritz C., Williams S.E. 2010. Shifting refugia and species persistence: tracking spatial shifts in habitat through time. *Ecography* 33:1062-1069 (ERA: A)

Bell, R.C., M. Tonione, J. Parra, J. Mackenzie, S.E. Williams,& C. Moritz. 2010. Patterns of persistence and isolation indicate resilience to climate change in montane rainforest lizards. *Molecular Ecology* 19: 2531-2544 (IF: 5.3, ERA: A).

Supporting References

Araújo M.B., D. Nogués-Bravo, J.A.F, A.M. Diniz-Filho Haywood, P.J. Valdes, C. Rahbek (2008) Quaternary climate changes explain diversity among reptiles and amphibians. *Ecography* 31 (1) 8-15. DOI: DOI: 10.1111/j.2007.0906-7590.05318.x

Beaumont, L.J, A. Pitman, S. Perkins, A.M. Zimmermann, N.G. Yoccoz, W. Thuiller(2011) Impacts of climate change on the world's most exceptional ecoregions. *PNAS* 108 (6) DOI: 10.1073/pnas.1007217108

Graham, C.H., J. VanDerWal , B. Phillips, C. Moritz, S.E. Williams (2010). Shifting refugia and species persistence: tracking spatial shifts in habitat through time. *Ecography* 33:1062-1069

Hoskin C.J, Tonione M, Higgie, J.B. MacKenzie, S.E. Williams, J. VanDerWal , C. Moritz (2011) Persistence in peripheral refugia promotes phenotypic divergence and speciation in a rainforest frog. *The American Naturalist* 178 (5). DOI: 10.1086/662164

Huey, R.B, M.R. Kearney, A. Krockenberger, J.A.M. Holtum, M. Jess, S. E. Williams (2012) Predicting organismal vulnerability to climate warming: roles of behaviour, physiology and adaptation. *Philosophical Transactions B* 367 (1596). DOI: 10.1098/rstb.2012.0005

Isaac, J.L., J. VanDerWal, C.N. Johnson and S. E. Williams. 2009. Resistance and resilience: quantifying relative extinction risk in a diverse assemblage of Australian tropical rainforest vertebrates, *Diversity and Distributions* 15 (2) 280-288. DOI: 10.1111/j.1472-4642.2008.00531.x

Moilanen, A. 2007. Landscape Zonation, benefit functions and target-based planning: Unifying reserve selection strategies, *Elsevier* 134 (4) 571-579. DOI:10.1016/j.biocon.2006.09.008

Mora, C., A.G. Frazier, R. J. Longman, R.S. Dacks, M. M. Walton, E. J Tong, J.J. Sanchez, L. R. Kaiser, Y.O. Stender, J.M. Anderson, C. M Ambrosino, I.Fernandez-Silva, L. M. Giuseffi and T. W. Giambelluca. 2013, The projected timing of climate departure from recent variability, *Nature* 502, 183-187. DOI: 10.1038/nature12540

Parsons, S.A., R. A. Congdon, C. J. Storlie, L.P. Shoo, S. E. Williams (2012) Regional patterns and controls of leaf decomposition in Australian tropical rainforests, *Austral Ecology* 37 (7) 845-854. DOI: 10.1111/j.1442-9993.2011.02347.x

Parsons, S. A. 2010. Decomposition, nutrient cycling and climate change in Australian tropical rainforests (PhD Thesis). James Cook University, Townsville.

Reside, A.E., J. VanDerWal, B.L. Phillips, L.P. Shoo, D. Rosauer, B.J. Anderson, J.A. Welbergen, C. Moritz, S. Ferrier, T.D. Harwood, K.J. Williams, B.G. Mackey, S. Hugh, S.E. Williams (2013). Climate change refugia for terrestrial biodiversity: defining areas that promote species persistence and ecosystem resilience in the face of global climate change, National Climate Change Adaptation Research Facility, Gold Coast.

Sandel, B., L. Arge, B. Dalsgaard, R. G. Davies, J.J. Gaston, W. J. Sutherland, J. C. Svenning. 2011. The influence of Late Quaternary climate-change velocity on species endemism, *Science* 334 (6056) 660-664

Scheffers, B.R., B. Phillips, W.F. Laurance, N. S. Sodhi, A. Diesmos, S. E. Williams. 2013. Increasing arboreality with altitude: a novel biogeographic dimension. *Proceedings of the Royal Society B: Biological Sciences* 280 (1770) 20131581

Scheffers, BR., D.P. Edwards, A. Diesmos, Theodore A. Evans & S.E. Williams. 2013. Microhabitats reduce animal's exposure to climate extremes

Shoo, L. AA. Hoffmann, S.Garnett, R.L. Pressey, Y. M. Williams, M. Taylor, L. Falconi, C.J. Yates, J.K. Scott, D. Alagador & S.E. Williams. 2013. Making decisions to conserve biodiversity under climate change. *Climatic Science* 119: 239-246 DOI 10.1007/s10584-013-0699-2

Shoo, L.P., C. J. Storlie, Y.M. Williams. 2010. Potential for mountaintop boulder fields to buffer species against extreme heat stress under climate change, *International Journal of Biometeorology* 54 (4) 475-478. DOI: 10.1007/s00484-009-0286-4

Storlie, C.J., A. Merino-Viteri, B. Phillips, J. VanDerWal, J. Welbergen, Williams S.E. 2014. Stepping inside the niche: microclimate data are critical for accurate assessment of species' vulnerability to climate change. *The Royal Society* 10 (9) 20140576

Storlie, C.J., Phillips B.L., VanDerWal J.J., Williams S.E. 2013. Improved spatial estimates of climate predict patchier species distributions. *Diversity & Distributions* DOI: 10.1111/ddi.12068

Warren, R., VanDerWal, J., Price, J., Welbergen, J.A, Atkinson, I., Ramirez-Villegas, J., Osborn, T.J., Jarvis, A., Shoo, L.P., Williams, S.E., Lowe, J. 2013. Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change* 7: pp 678-682

Welbergen J.A., S.E. Williams, S. Goosem. 2011. Gap analysis of environmental research needs in the Australian Wet Tropics. Marine & Tropical Science Research Facility, Australian Government.
http://www.jcu.edu.au/mtb/public/groups/everyone/documents/other/jcu_083921.pdf

Williams, S.E. & J. Middleton. 2008. Climatic seasonality, resource bottlenecks, and abundance of rainforest birds: implications for global climate change, *Diversity and Distributions* 14 (1) 69-77

Williams, S.E., J. VanDerWal, J. Isaac, L. Shoo, C. Storlie, S. Fox, E.E. Bolitho, C. Moritz, C. Hoskin & Y.M. Williams. 2010. Distributions, life history specialisation and phylogeny of the rainforest vertebrates in the Australian Wet Tropics. *Ecology* 91(8): 2493 (Access DATA via Ecological Archives