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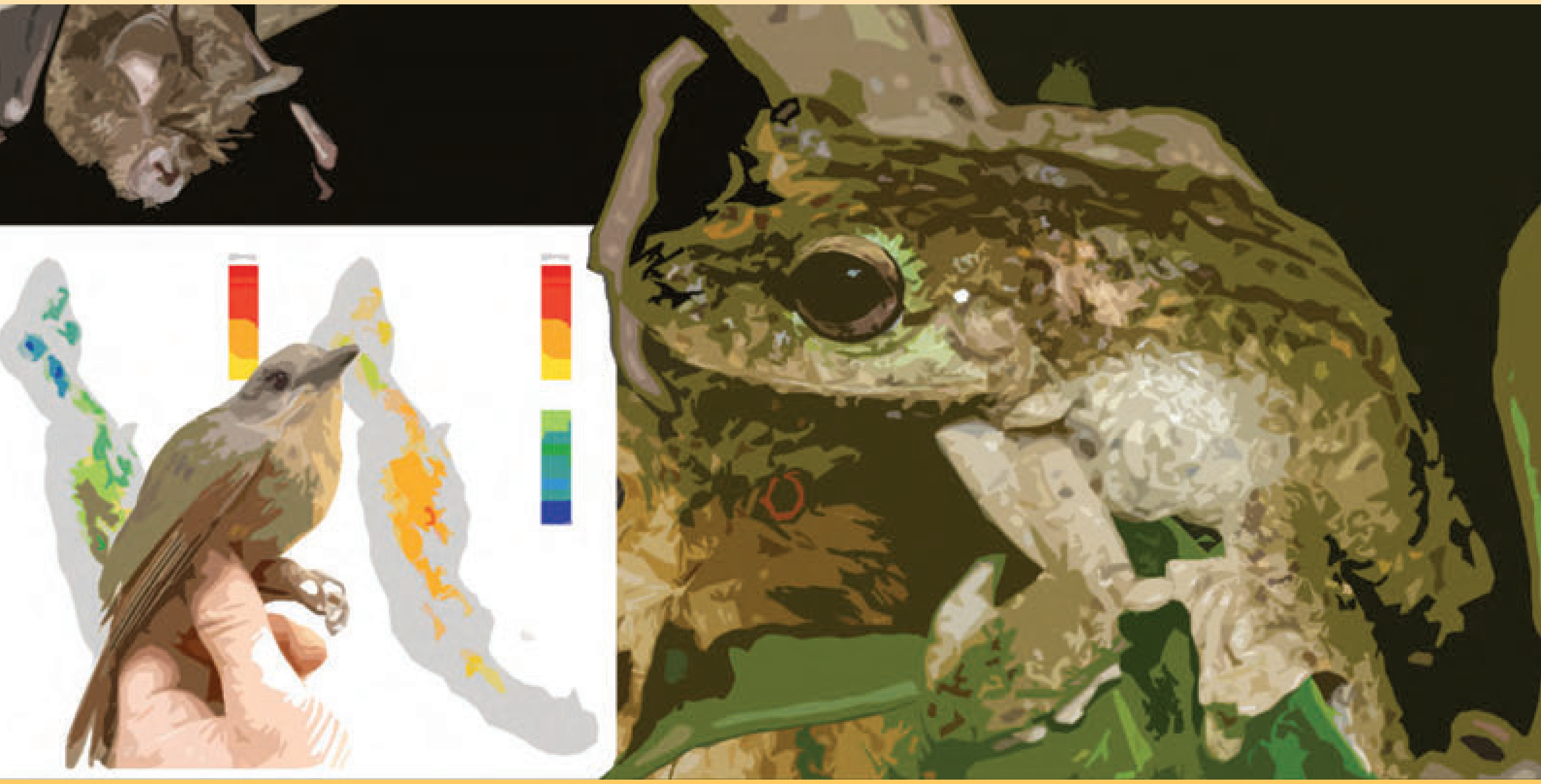
TROPICAL ECOSYSTEMS hub

Final Report

Climate change and the impacts of extreme events on Australia's Wet Tropics biodiversity



Justin Welbergen, Jessica Meade, Collin Storlie, Jeremy VanDerWal, Anastasia Dalziell, Lauren Hodgson, Johan Larson, Andrew Krockenberger and Steve Williams

Australian Government
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Cover image: Justin Welbergen

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Contents

List of Figures

List of Tables

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Executive summary

While gradual changes in climate means will have numerous effects on a range of environmental, social, and economic sectors, emerging evidence shows that many of the environmental, social, and economic impacts of anthropogenic climate change will arise from shifts in the regimes of extreme weather and climatic events, including heat waves, fires, flooding rain, and cyclones (IPCC 2012, IPCC 2013). Such extreme events represent the way in which communities, animals and plants experience climate change (BoM-CSIRO 2006). However, despite their clear importance for our understanding of climate change impacts (and hence adaptation action), very little is known about the effects of extreme events on natural systems (IPCC 2012, Welbergen et al 2008a).

Tropical rainforests are the hotbed of the world’s biodiversity; yet, the vulnerability of tropical rainforest biota to extreme temperature events is largely unknown (Williams et al 2008). This project investigates the *exposure* and *sensitivity* of Wet Tropics biota to extreme temperature events. Integration of the information on exposure and sensitivity has enabled us to assess quantitatively the *vulnerability* of Wet Tropics biota to extreme temperature events, and map the contemporary and future impacts of these events on biodiversity in the Wet Tropics Bioregion. The focus is on the impacts of temperature extremes on the rainforest vertebrates of the Wet Tropics, but the analytical and conceptual advances gained from this project form the basis of a generalized framework for assessing the impacts of extreme weather and climate events, including droughts and wildfires, on natural systems across Australia and elsewhere.

Main outputs

- Accurate, high resolution maps of the exposure to temperature extremes as experienced by Wet Tropics vertebrates in in-situ
- Accurate estimates of the resilience, thermal behavioural plasticity, and thermotolerance of Wet Tropics vertebrates to temperature extremes
- Maps of the areas where biodiversity is most vulnerable to temperature extremes at present and in the future (‘*thermal hotspots*')
- Maps of the areas where biodiversity is least vulnerable to temperature extremes at present and in the future (‘*thermal refugia*')
- Rankings of species particularly at risk from extreme events
- Generalised analytical toolkit for assessing vulnerability of biodiversity to extreme events in Australia and elsewhere

Benefits to end users

It is widely recognised that knowledge of the relative vulnerability of biodiversity to extreme events is crucial for sound conservation action in the face of climate change (Hughes et al 2009, IPCC 2007a, IPCC 2012). This is further evidenced by the high ranking of this issue among the stated research priorities of the main end-user organisations at both the national [e.g. (e.g., Land & Water Australia 2008) and bioregional levels (TERRAIN 2010, Welbergen et al 2011 , WTMA 2010).

The value to end users of this project is that it provides spatially-explicit and species-specific foci for efficient and targeted conservation and habitat restoration management. Efficient conservation and habitat restoration management of the most vulnerable species and areas will improve the resilience and resistance of the Wet Tropics landscape to the increasingly extreme temperature events.

The tangible contributions of Project 7.3 are in the hundreds of high-resolution maps (submitted to e-Atlas) as well as the very large temperature datasets and associated scripts available through e-Research/Centre for Tropical Biodiversity and Climate Change (CTBCC). These provide the basic information and tools that we hope will be of benefit to research providers with a stake in climate change adaptation research in the Wet Tropics. While the focus of Project 7.3 was on the impact of temperature extremes on vertebrate biodiversity, our modelling scripts are flexible and easily tailored to suit examinations of any subset of species in any area, against any environmental or physiological threshold. Thus, collectively also they provide a generalised analytical toolkit for assessing organismal vulnerability to extreme events in the Wet Tropics and beyond.

General Introduction

Impacts of climate change on biodiversity

It is now widely accepted that climate change is probably the most significant threat to global biodiversity and human well-being (Hughes 2000, Parmesan & Yohe 2003, Pounds et al 2006, Root et al 2003, Warren et al 2013). Over the past 100 years, the global average temperature has increased by approximately 0.74 ± 0.18 (mean ± SE) and is projected to continue to rise at a rapid rate (IPCC 2007b). Current conservative projections are for a 'best-estimate' increase in global average temperatures of 1.7 to 4.0 °C by the end of this century (IPCC 2007b). In Australia the frequency of extremely warm days and nights has generally increased while that of extremely cool days and nights has decreased (Nicholls & Collins 2006). The inevitable anthropogenic changes in the world's climate are significant for natural systems as they affect population abundance, species distributions and invasions, potentially resulting in significant levels of extinction among the world's biota (Humphries et al 2002, Parmesan & Yohe 2003, Root et al 2003, Thomas et al 2004, Warren et al 2013). Indeed, changes in Australian species and ecosystems consistent with recent changes in temperature, rainfall and sea level have already been detected (Dunlop & Brown 2008), and significant impacts are projected to occur in the Wet Tropics bioregion this century (Hilbert 2001, Hilbert et al 2001, Hilbert & Williams 2003, Shoo et al 2005a, Shoo et al 2005b, Williams et al 2003, Williams & Hilbert 2006).

Tropical regions are the hotbed of the world's biodiversity. Here, in addition to the global rise in temperature, changes in rainfall patterns are predicted, with rainfall becoming more variable, longer dry spells and increased frequency or intensity of disturbance events such as flooding rains and cyclones (Easterling et al 2000, Johnson & Murray 2004, Palmer & Raisanen 2002). Additionally, a rise in the average altitude of the orographic cloud layer is expected (Pounds et al 1999), which will likely exacerbate the effects of longer and more variable dry seasons due to a reduction in cloud capture by the canopy in mountain rainforests (Still et al 1999). There is a common, though incorrect, perception that the impacts of climate change will be worse in temperate regions than in the tropics. However, tropical biota may already be living closer to their maximum thermal tolerances so that even small temperature changes could have disproportionally large impacts, and the potential impacts of anthropogenic climate change on tropical systems is of special concern (Deutsch et al 2008, Huey et al 2009, Tewksbury et al 2008).

Australia's Wet Tropics bioregion is the world's best understood tropical system (Stork & Turton 2008). In the Wet Tropics the average maximum temperature has increased by 0.8°C (0.14°C per decade) since 1950 and is projected to increase by between 0.5 and 1.4°C by 2030 and between 1.0 and 4.2 °C by 2070 (Suppiah et al 2007). Mountain systems such as those found in the Wet Tropics Bioregion represent hotspots of biodiversity and endemism due to the compression of climatic zones over the elevational gradient (Körner 2002). The rainforests of the Wet Tropics are isolated habitats with no potential for rainforest endemics to shift their latitudinal and altitudinal ranges (Nix & Switzer 1991), providing the ingredients for an impending environmental catastrophe (Williams et al 2003). This is in accordance with predictive modelling of impacts on species distributions and abundance, which provides clear warnings regarding the potential for extinctions across a range of taxa in the Wet Tropics (Hilbert 2001, Hilbert et al 2001, Hilbert & Williams 2003, Shoo et al 2005a, Shoo et al 2005b, Williams et al 2003, Williams & Hilbert 2006).

Wet Tropics vertebrate species seem particularly vulnerable to climate change (Hilbert et al 2004, Meyneeke 2004, Williams et al 2003), and many are now considered severely threatened (Williams et al 2003). Bioclimatic models of the spatial distribution for endemic rainforests vertebrates predict that many species will lose the majority of their core habitat under relatively small increases in temperature, resulting in an amplification of extinction rates and a significant reduction in overall biodiversity in the region (Hilbert et al 2004, Hilbert et al 2000, Isaac et al 2009, Shoo et al 2005b, Shoo & Williams 2004, Williams et al 2003). However, while changes in the long-term mean state of climate will have numerous effects on the biodiversity in the Wet Tropics, many impacts of climate change may emerge through shifts in the frequency, intensity, and duration of extreme weather and climate events (IPCC 2012, IPCC 2013).

Impacts of extreme events on biodiversity

Extreme weather and climate events, including heatwaves, flooding rain and cyclones, are the way in which animals and plants strongly experience climate change (BoM-CSIRO 2006, IPCC 2007b, IPCC 2012, IPCC 2013). The study of extreme events is a relatively new emphasis in ecology (Smith 2011), despite long-standing recognition by palaeoecologists (Klaassen et al 2012) and evolutionary biologists (Combes 2008). Therefore, at present, there is no coherent mechanistic understanding of ecological responses to extreme events, which severely restricts our ability to project their impacts (Parmesan 2006). Nevertheless, there is mounting empirical evidence for biological impacts of extreme events at all system levels - from morphology (Grant & Grant 2006), physiology (du Plessis et al 2012), behaviour (Welbergen et al 2008b), and phenology (Bokhorst et al 2011); to population dynamics (van de Pol et al 2010), species interactions (Cahill et al 2013), and the structure and function of whole ecosystems (Anderegg et al 2013, Smale & Wernberg 2013). As such, they profoundly affect the ecology and evolutionary trajectories of the world's biota (Combes 2008).

Extreme temperature events are of special concern to biodiversity conservation (Hughes et al 2009, Kapos et al 2008), both because of their direct impacts on organismal health, but also because of their effects on water demand and evaporative losses and the frequency and intensity of droughts and wildfires (e.g., IPCC 2007a). Worryingly, the frequency, duration and severity of extreme temperature events are rising faster than the means (Easterling et al 2000, Katz & Brown 1992, Schär et al 2004, Tebaldi et al 2006), therefore, they will continue to gain significance as mechanistic drivers of ecological responses to climatic change (Hughes et al 2009, Kapos et al 2008). Therefore, knowledge of the probability that species will be exposed to changes in the regimes of temperature extremes, and of species-specific differences in sensitivity to such extremes temperatures, is critical for the successful development and targeting of proactive conservation strategies that minimise the impacts of anthropogenic climate change on biodiversity (Isaac et al 2009).

Vulnerability of Wet Tropics vertebrates to extreme temperature events

The vulnerability of tropical rainforest biota to extreme temperature events is largely unknown (Williams et al 2008), but studies have recently begun addressing this issue. The few examples include studies on the potential of microhabitats to protect species against extreme heat stress under climate change (Isaac et al 2008, Shoo et al 2010). The Centre for Tropical Biodiversity and Climate Change (CTBCC) has detailed distribution and environmental data collected systematically in the bioregion over the last 19 years (Williams 2006, Williams et al 2010). The dataset is recognised as one of the world's most comprehensive ecological and environmental information sources available, and is unique for any tropical region. As such, this dataset enables first comprehensive assessment of the vulnerability of tropical biodiversity to contemporary and future impacts of extreme events.

Here we investigate the *exposure* and *sensitivity* of Wet Tropics biota to extreme temperature events. Integration of the information on exposure and sensitivity will then enable us to assess quantitatively the *vulnerability* of Wet Tropics biota to these events (Figure 1, pp 23), and map the contemporary and future impacts on biodiversity in the Wet Tropics Bioregion. The focus is on the impacts of temperature extremes on the rainforest vertebrates of the Wet Tropics, but the analytical and conceptual advances gained from this project can form the basis of a generalized framework for assessing the impacts of extreme climate and weather events, including droughts and wildfires, on natural systems across Australia and elsewhere.

PART 1 – EXPOSURE

Summary of outputs:

Objective 1a: Landscape-scale exposure. We downscaled weather data for the entire Wet Tropics bioregion from 1950-present to a 250x250m resolution (499,085 cells), generating the most detailed historical weather data set so far produced for the bioregion.

Objective 1b: Microhabitat-scale exposure. We further downscaled our daily weather data set (from objective 1a) to hourly thermal exposures within the key microhabitats in the Wet tropics (at different heights under canopy, in leaf litter, in soil, under logs). This enabled us to map the temperature in any of the microhabitats at any hour of any day of any year since 1950.

Objective 1c: 'Exposure' as experienced by organisms in-situ. By integrating the outputs from objectives 1a & 1b and combining them with species occurrence data already available at the CTBCC, we were able to map at 250m and hourly resolutions, any thermal regime species have been exposed to in their respective microhabitats since 1950.

Introduction

Exposure to climatic change of a particular species depends upon the level of climatic change within a species' range, and the amount that microhabitat buffering that might reduce this exposure (Williams et al 2008). Here we first quantified landscape-scale exposure based on the relationships between broad-scale macro climate and direct measurements of organism exposure in different environments. Next, we determined microhabitat-scale exposure by combining the microhabitat preferences of Wet Tropics vertebrates with the thermal characteristics of their known preferred habitat. Finally, we combined landscape-scale and microhabitat-scale exposure to generate accurate maps of the temperatures experienced by organisms in-situ.

1a. Landscape scale exposure:

Methods

To generate accurate estimates of landscape-scale exposure we downscaled available weather data using a relatively new statistical methodology [Boosted Regression Trees (BRT)], relating empirically measured temperatures to existing spatial estimates of weather and topography. The empirical (dependent) dataset for the downscale procedure comprises 32,239 measurements of daily maximum temperature (Tmax) and daily minimum temperature (Tmin), gathered by field data loggers at 53 sites across the Wet Tropics during the period June 2004 – June 2009. A set of ten topographic, weather, and environmental spatial layers were assembled and entered as the independent variables for the modelling procedure. These included 5-km resolution estimates of daily Tmax and daily Tmin from the Australian Water Availability Project (AWAP).

The independent topographic variables were slope; aspect; elevation; latitude; distance to coast; and distance to stream. Other environmental surfaces in the independent dataset include Foliage Projected Cover (FPC) and insolation (hours of direct sunlight).

Two separate BRT models (one for daily Tmin and one for daily Tmax) were created with the above dataset in the statistical software package R, and spatial estimates of Tmax and Tmin were created for every day between January 1st 1950 and November 25th 2011. We then used simple linear regression to validate the precision and accuracy of the broad-scale and BRT climate predictions. In both cases, predictions were regressed against empirically measured weather; accuracy was assessed by departure from expected regression coefficient values (slope of 1, y-intercept of 0) and precision was assessed using the adjusted R^2 measure of fit. Our statistically downscaled estimates of daily Tmax have proven to be both far more accurate and precise than the 5-km resolution daily AWAP surfaces upon which they are based (Storlie et al 2013).

Results

We have downscaled the available weather data for the entire Wet Tropics Bioregion from 1950-present from a 5x5km to a 250x250m resolution (499,085 cells), producing the most accurate and precise historical weather data set ever produced for the bioregion. Having downscaled the available weather data for the entire Wet Tropics bioregion from 1950-present, we can now interrogate our dataset for any quantitative property of extreme temperature regimes in the bioregion and then project this spatially for any time between 1950-current at a very high spatial resolution. Our statistically downscaled estimates of daily Tmax have proven to be both far more accurate and precise than the 5-km resolution daily AWAP surfaces upon which they are based (Storlie et al 2014, Storlie et al 2013).

As examples of what we have achieved we have included maps of the following quantitative properties of extreme temperature regimes at a 250x250m resolution: 1) the absolute maximum daily Tmax; 2) the 95th percentile of daily Tmax; and 3) the mean length of consecutive days above the 90th percentile recorded in the bioregion (see Figure 2, pp 24).

In addition, we have included maps that show how such quantitative properties of extreme temperature regimes have changed since 1950 in the bioregion, including the change in Tmax since 1950 (Figure 3, pp 25); the change in the annual number of hot days (Figure 4, pp 26); and the change in the duration of hot spells (Figure 5, pp 27).

1b. Microhabitat-scale exposure

Methods

We further downscaled our accurate daily weather data set to hourly thermal exposures within the main microhabitats in the Wet tropics (at different heights under canopy, in leaf litter, in soil). This enabled us to produce extremely specific estimates of temperature at specific times and locations (e.g., the temperature in the canopy at 12:00 pm August 17th 1953; Figure 6, pp

28), thus quantifying the thermal buffering experienced by key representative Wet Tropics animal species in their preferred microhabitats.

Empirical temperature data were gathered at ~30 sites across the Wet Tropics from November 2006 – Present; multiple distinct microclimates (e.g. soil, leaf litter, surface, under log, ambient air, and 7 canopy heights) were monitored at these sites.

Next, we fit curves to standardised empirical temperature and time values, which describe the daily thermal regime of a distinct microclimate. To do this we standardised empirical temperatures against daily max and min temp to scale between 0 and 1. Empirical times were standardised against sunrise and sunset times to account for the effect of topographic features on the daily thermal regime. Parameters estimated during this procedure were then used to back-solve for normalised temperature of that microclimate during a given normalised time. Un-standardising the resultant temperature value requires an estimate of max and min temperature in that distinct microclimate.

To obtain hourly estimates of microclimate temperatures, we used linear regression to establish a predictive relationship between spatial estimates of daily max and min temperature (objective 1a) and empirically measured maximum and minimum temperatures. Daily estimates of max and min temperature in a given microclimate were then used to un-standardise temperature, yielding an hourly estimate of temperature for every day of the year spatially at 250m resolution across the entire Wet Tropics.

Thus, the outputs include historical temperature estimates for the main microhabitats at 499,085 cells within the Wet Tropics over the last 62 years, representing a vast dataset of historical microhabitat temperatures, which is currently held by the CTBCC.

Results

Having downscaled our accurate daily weather data set (from objective 1a) to hourly thermal exposures within the key microhabitats in the Wet tropics means that we were able to accurately estimate and map key microclimates at any given location within the Wet Tropics, at any given time and on any given day within the last 62 years. For example, at 12:00 pm on August 17th, 1953, the temperature at 19m into the canopy was 21.8 degrees Celsius in Mossman Gorge (-16.468832 degrees South, 145.326447 degrees East (see Figure 6, pp 28, panel C).

1c. Exposure as experienced by organisms in-situ

Methods

By combining the outputs from objective 1b with known points of occurrence for a species, we can determine any thermal regime a species has been exposed to in their respective microhabitats since 1950. We have set up effective linkages between this dataset and our CTBCC's main vertebrates dataset (details in (e.g. Williams et al 2010), which includes thousands of occurrence records and the preferred microhabitats of nearly every vertebrate species known to occupy the Wet Tropics. This means that we can now generate, within minutes, maps of any historical microhabitat-specific thermal regime for any species for which we have occurrence records.

This capability is essential for PART 3 (below) where we estimate the current and future vulnerability of specific taxa to extreme temperature events.

Results

From the outputs of objectives 1a and b we can now link thermal sensitivity and microhabitat-specific thermal exposure, and test empirically the role of thermal sensitivity in limiting species distribution. For example, from previous work (Krockenberger et al 2012) we already know that green ringtail possums (*Pseudochirops archeri*) are unable to cope when exposed to temperatures above 30 degrees for more than 5 hours per day for more than 4 consecutive days. We also know that the species lives high up in the canopy. Using this information we have mapped the frequency of this particular thermal regime occurring in the species' preferred microhabitat. Known occurrence points for the species were then overlaid on these maps which revealed that less than 1% of occurrences (n=125) had been exposed to this critical thermal regime within the last 60 years (Figure 7, pp 29), suggesting that, as expected, the distribution of the green ringtail possum is (at least in part) limited by this critical thermal regime. This type of analysis has never been achieved before for any species.

PART 2 - SENSITIVITY

Summary of outputs:

Objective 2a: Species resilience. We developed a new, quantitative index of resilience for the vertebrates of the Wet Tropics. Previous indexes of resilience have always been based on subjective combinations of species traits, whereas our index is the first quantitative measure of resilience that has been objectively validated. The top 20 least-resilient species is provided in the report (Table 1, pp 63).

Objective 2b: Behavioural plasticity. We quantified 'thermal behavioural plasticity' of the Wet Tropics vertebrates as the maximum difference between the thermal exposures in the microhabitats that a species is known to inhabit, representing the ('adaptive') capacity of individuals to reduce their thermal exposure by moving into the microhabitat that is most thermally favourable and available to them.

Objective 2c: **Thermotolerance**. We have experimentally determined the thermotolerance of 53 Wet Tropics mammals and birds. Extensive review of the literature revealed an additional 49 species of mammals, birds, reptiles and frogs for which information on thermal tolerance limits is available. This means that we have quantitative information of the absolute thermotolerance of 102 of 202 Wet Tropics vertebrates.

Introduction

Species' sensitivity to climatic change is mediated by resilience and adaptive capacity (Williams et al. 2008). 'Resilience' to climate change is the ability of a species or population to recover after an environmental insult. Traits predicted to increase resilience include high productivity, fast life history and short life span (McKinney 1997). Dispersal ability is also predicted to affect population recovery time after a perturbation (Fjerdingstad et al 2007). 'Adaptive capacity' is the ability to adapt to changing conditions. This capacity to adapt to change can be through evolutionary adaptation (e.g. Bradshaw & Holzapfel 2006), but is more likely to occur via physiological and/or behavioural plasticity (Williams et al. 2008), which is what we consider here. This is because plasticity acts over a shorter timescale (within a generation) and can include shifts in microhabitat use, changes in temporal activity, shifts in distribution, and contraction to refuges (e.g. Hughes 2000; Parmesan 2006).

2a. Resilience

Methods

Many studies have established indexes of resilience that can modify population responses to climate change (e.g. Isaac et al., 2009 and references therein); however, these indexes have never been externally validated. Instead, they have invariably been based on the informed reasoning that certain species-specific traits (e.g., reproductive rate, dispersal capacity, population density) affect a population's ability to recover quickly from collapse. But how do we know that an index based on (some combination of) such traits does in fact represent what it aims to represent?

Our approach does not suffer from this subjectivity because it is based on the novel idea that due to extinction filtering, less resilient species will be less likely to occur in areas where habitat has changed frequently in the past. Therefore, habitat stability could potentially act as an index of resilience, and can be validated by testing it against traits that are conventionally thought to affect a population's ability to recover quickly from collapse.

For our measure of habitat stability we use the dynamic predictions of the stability of rainforest during the last 18,000 years in the Wet Tropics ('high dispersal dynamic model' from Graham et al. 2010). Current work at CTBCC shows that this habitat stability layer is closely correlated with the spatial patterns of species and endemic richness in the region (Figure 8, pp 30), which strongly supports the idea that past habitat changes have led to extinction filtering throughout the Wet Tropics bioregion.

To examine how habitat stability relates to known traits that affect a species' ability to survive and recover from an environmental insult, we followed two approaches: an assemblage-level approach and a species' level approach:

For the assemblage level approach we ran a series of boosted regression trees that included for each of 499,085 cells that make up the Wet Tropics bioregion, the average value for each of 30 species-specific traits that we had information on (data from Williams et al 2010) independent variables and habitat stability as the dependent variable. This allowed us to determine which species-specific traits were most closely associated with the spatial distribution of rainforest habitat stability.

For the species-level approach we first extracted from the habitat stability layer the average habitat stability that each of the 202 rainforest vertebrates present in the CTBCC database inhabits. Next we ran a multiple regression with the average habitat stability for each species as the dependent variable, and vegetation specialisation and ENFA marginality as dependent variables to determine their relative contributions to habitat stability.

The resulting average species habitat stabilities were scaled from 0 (most stable) to 1 (least stable). In a previous CTBCC publication (Isaac et al 2009) established a non-validated resilience index for 160 Wet Tropics vertebrates based on climatic niche breadth, reproductive output, and dispersal capacity. We tested whether our new index of resilience was correlated with Isaac's resilience index to further demonstrate the validity of our approach.

Results

Our best assemblage-level model almost perfectly explained the spatial distribution of habitat stability from the species traits (97% of variance explained; Figure 9, pp 31).

In this model, vegetation specialisation, ENFA marginality, and local abundance (log scale) together explained more than 58% of the total variance, with the remaining variables explaining less than 10% of the variance each (Figure 10, pp 32).

In the species-level approach, a multiple regression with vegetation specialisation, ENFA marginality, and local abundance (log scale) as dependent variables, explained 68.3% of the variance in the average habitat stability for each species; and, with all three dependent variables showing significant and independent effects (all $P < 0.02$). Thus, the species-level analysis is consistent with the assemblage-level approach, showing that species that live in more stable habitats have significantly narrower niches and higher local abundance. Narrow niches and high local abundance are K-selected traits, characteristics of species found in stable environments; therefore, our findings are in accordance with r/K-selection theory (MacArthur and Wilson 2001),

Examining this further, we found that vegetation specialisation, ENFA marginality, and local abundance were highly significantly correlated with reproductive rate and dispersal capacity (all $P < 0.001$), and in turn, reproductive rate and dispersal capacity were significantly negatively related to average habitat stability (both $P < 0.001$), together explaining 25% of the variation between the average habitat stabilities of the Wet Tropics vertebrates. Reproductive rate and dispersal capacity are the three critical parameters for determining population growth rate, and hence a population's ability to recover from an environmental insult, and for that reason are commonly incorporated in indexes of resilience (Isaac et al 2009).

Taken together, therefore, these analyses demonstrate that habitat stability can be used as a valid proxy of species resilience (Figure 11, pp 33).

Next, we scaled the average species habitat stabilities from 0 (most stable) to 1 (least stable) so that the scaled values can be used as our new, validated index resilience. Isaac et al (2009) previously established a non-validated resilience index for 160 Wet Tropics vertebrates based on climatic niche breadth, reproductive output, and dispersal capacity. We found that our new index of resilience was strongly correlated with Isaac's resilience index (Figure 12, pp 34), further increasing our confidence that our new resilience index is valid (Figure 11, pp 33).

Ranking of the species by our new resilience index resulted in a remarkably intuitive top 20 of least resilience species (Table 1, pp 63). The top 20 is dominated by species with low dispersal ability, low reproductive rates and/or narrow niches, and contains a high proportion of threatened species.

At this point it is important to note that resilience does not equal vulnerability, and that therefore our resilience ranking cannot be taken as a ranking of species most vulnerable to extreme temperature events, although they can certainly be expected to be strongly related. Resilience is part of sensitivity, as are 'thermal behavioural plasticity' (objective 2b, below) and 'thermal tolerance (objective 2c, below). Only by combining sensitivity (objectives 2a-c) and exposure (objectives 1a-c) can we arrive at quantitative estimates of current and future vulnerability (PART 3).

2b. Thermal behavioural plasticity

Methods

During an extreme heat events, individuals will likely select the most thermally favourable microhabitat available to them (e.g., a skink might reside in leaf-litter but in the event of a temperature extreme it will retire to under a cooler log). Such 'thermal behavioural plasticity' in response to changes in the thermal environment can thus increase the capacity of individuals to cope with ('adapt to') changes in extreme heat events.

For objective 1b we had already downscaled the daily weather data set from objective 1a to create hourly thermal exposure estimates for 10 key microhabitats in the Wet tropics (i.e. in soil, under a log, ambient air, and in the canopy at 4, 7, 10, 13, 16, 19, and 22 meters), enabling us to map the temperature in any of the microhabitats at any hour of any day of any year since 1950. This dataset formed the basis of our quantification of thermal behavioural plasticity.

To quantify the thermal behavioural plasticity of the species we began by extracting from the outputs of objective 1b for each species all the daily maximum temperatures that it could have been exposed to (e.g. see Figure 13, pp 35). We did this by clipping the dataset by a species' known range, and by the microhabitats that the species is known to inhabit (as recorded in CTBCC's vertebrate database (Williams et al 2010).

Thermal behavioural plasticity could then be calculated for any species as the difference between the n^{th} percentile exposure temperature of the least and most thermally favourable microhabitat. This difference represents the reduction in realised thermal exposure that results when, during a hot day (i.e. > n^{th} temperature percentile), individuals move into the microhabitat that is most thermally favourable and available to them.

Results

We calculated the thermal behavioural plasticities of the Wet Tropics vertebrate species to the 90^{th}, 95^{th}, and the 99^{th} percentile of maximum daily temperatures occurring in the species' microhabitats (e.g. see Figure 14, pp 36; and Table 2, pp 64); however, our methodology enables us to readily quantify (and plot) the thermal behavioural plasticities of the species to any summary temperature metric, including those pertaining to highly specific regimes of extreme temperature events.

This analytical capacity is essential for incorporating both relative thermal thresholds (based on the distribution of temperatures found within the species' range) and absolute thermal thresholds (based on the actual thermotolerance of species; objective 2c) into our vulnerability assessments (PART 3).

2c. Thermal tolerance

Methods

We conducted an extensive review of the literature on thermo-physiology of Wet Tropics vertebrates and identified 49 species for which thermal tolerance data are available. From our review it is clear that in the last three decades, thermal tolerance has been assessed in a range of vertebrate fauna occurring in the Wet Tropics, particularly ectotherms such as skinks, snakes and especially frogs. However, significant gaps remained in endotherms, both in mammals and in birds.

To address these gaps, we designed a relatively benign thermo-physiology experiment on a sample of 100 individuals from 53 species of mammal and bird. Our sample was designed to maximise phylogenetic spread, so that, when combined with those species that have already been assessed, it was representative for the vertebrate fauna of the Wet Tropics as a whole [i.e. because thermal tolerance is phylogenetically constrained among diverse sets of taxa (Blomberg et al. 2003; Chown et al. 2002)].

For our experiment, a focal individual was caught and held in situ in a portable metabolic chamber regulated to achieve specific conditions of temperature and humidity [Our Centre for Tropical Biodiversity and Climate Change has extensive experience using the chamber and associated methodology (Krockenberger et al 2012)].

We used the onset of panting as our marker of thermal stress, which is the measure of least-impact and is broadly applicable across mammals and birds. Our aim was to determine the relative thermal tolerance of species along a continuum, so this sub-critical measure serves well. To determine onset of panting, ventilation rate was monitored continuously while the chamber temperature increased from ambient at *c.* 0.5 ºC/minute to a maximum temperature no higher than what Wet Tropic's animals experience in the wild (as determined from objective 1c). The experiments were terminated as soon as ventilation rate no longer increased.

Results

Our thermo-physiology experiment provided information on the relationships between ambient temperature, body temperature and the onset of panting for the following 53 species of mammal and bird: **Mammals (12)**: Northern brown bandicoot, *Isoodon macrourus*; Fawn Footed Melomys, *Melomys cervinipes*; Eastern bentwing bat, *Miniopterus schreibersii*; Large-footed myotis, *Myotis adversus*; Long Nosed Bandicoot, *Perameles nasuta*; Black flying fox, *Pteropus alecto*; Spectacled Flying fox, *Pteropus conspicillatus*; Grey-headed flying fox, *Pteropus poliocephalus*; Little red flying fox, *Pteropus scapulatus*; Cane Field Rat, *Rattus sordidus*; Common Brushtail Possum, *Trichosurus vulpecula*; White tailed rat, *Uromys caudimaculatus*; **Birds (41)**: Mountain thornbill, *Acanthiza katherina*; Eastern spinebill, *Acanthorhynchus tenuirostris*; Spotted catbird, *Ailuroedus melanotis*; Golden bowerbird, *Amblyornis newtonianus*; Metalic starling, *Aplornis metallica*; Azure kingfisher, *Ceyx azureus*; Little bronze cuckoo, *Chalcites minutillus*; Bower's shrike-thrush, *Colluricincla boweri*; White-throated treecreeper, *Cormobates leucophaea*; Black butcherbird, *Cracticus quoyi*; Spangled drongo, *Dicrurus bracteatus*; Peaceful dove, *Geopelia striata*; Brown gerygone, *Gerygone mouki*; Grey-headed robin, *Heteromyias cinereifrons*; Varied triller, *Lalage leucomela*; Bridled honeyeater, *Lichenostomus frenatus*; Brown honeyeater, *Lichmera indistincta*; Lewin's honeyeater, *Meliphaga lewinii*; Graceful honeyeater, *Meliphaga gracilis*; Lewin's honeyeater, *Meliphaga lewinii*; Yellow spotted honeyeater, *Meliphaga notate*; Dusky honeyeater, *Myzomela obscura*; Olive-backed sunbird, *Nectarinia jugularis*; Red-browed firetail, *Neochmia temporalis*; Fernwren, *Oreoscopus gutturalis*; Chowchilla, *Orthonyx spaldingii*; Golden whistler, *Pachycephala pectoralis*; Helmeted friarbird, *Philemon bucceroides*; White-cheecked honeyeater, *Phylidonyris niger*; White-cheecked honeyeater, *Phylidonyris niger*; Eastern whipbird, *Psophodes olivaceus*; Satin bowerbird, *Ptilonorhynchus violaceus*; Victoria's riflebird, *Ptiloris victoriae*; Grey fantail, *Rhipidura albiscapa*; Rufus fantail, *Rhipidura rufifrons*; Toothbilled bowerbird, *Scenopooetes dentirostris;* Yellow-throated scrubwren, *Sericornis citreogularis*; Large-billed scrubwren, *Sericornis magnirostris*; Spectacled monarch, *Symposiachrus trivirgatus*; Scaly-breasted lorikeet, *Trichoglossus chlorolepidotus*; Macleay's Honeyeater, *Xanthotis macleayanus.*

Our exhaustive literature survey identified quantitative information on the thermal tolerance of an additional 8 species of mammals; 4 birds; 20 reptiles; and 17 frogs. Thus we now have quantitative data on the thermal tolerance of 102 of all 202 Wet Tropics vertebrates. The full publication of these results is currently in preparation.

An important shortcoming of these thermotolerance data is that they are not comparable across endotherms and ectotherms because they have fundamentally different responses to heat stress and have therefore been examined using different thermophysiological approaches. However, the data are comparable within these groups, and our approach is especially useful for defining the current and future vulnerability of species to specific thermal thresholds (see Part 3 below).

PART 3 -VULNERABILITY

Summary of outputs:

Objective 3a: Current vulnerability. We combined our information on exposure (Part 1) and sensitivity (Part 2) and produced maps of the areas where biodiversity is most and least vulnerable to temperature extremes (thermal 'hotspots' and 'refugia'). In addition, we used the termophysiological data from objective 2c to define areas where specific species are currently most likely to suffer from heat stress.

Objective 3b: Future vulnerability. We projected the outputs from objective 3a into the future using the latest state-of-the-art temperature projections for the Wet Tropics bioregion (4 RCPs, 18 GCMs; 8 time steps between 2015 and 2085; 250m resolution; VanDerWal et al, *unpublished*). Thus we created maps of the areas where biodiversity is most and least vulnerable to temperature extremes in the future (future thermal 'hotspots' and 'refugia'), and defined the areas where specific species are most likely to suffer from future heat stress.

Introduction

Species or system vulnerability can be viewed as a function of species' exposure and sensitivity to changes in local climate (Storlie et al 2014, Williams et al 2008). Here we use a general framework, adapted from Williams & Shoo et al (2008), for assessing the vulnerability of Wet Tropics vertebrates to extreme temperature events under climate change (Figure 1, pp 23). In this framework vulnerability is a function of the species' exposure (Part 1) and sensitivity (Part 2) to the impacts of changes in the extremes.

By combining information on the historical exposure with information on sensitivity we can generate quantitative estimates of the *current* vulnerability of Wet Tropics vertebrates to extreme events (objective 3a). By combining information on the projected future changes in exposure with the information on sensitivity we can generate quantitative estimates of the *future* vulnerability of Wet Tropics vertebrates to extreme events under climate change (objective 3b).

The quantitative estimates of the vulnerability of Wet Tropics vertebrates to extreme events can be made spatially-explicit, enabling effective prioritization of *areas* where species are most vulnerable. For example, we can define areas in the Wet Tropics landscape where species are most (thermal hotspots) and least (thermal refugia) vulnerable to (changes in the regimes of) extreme heat events. As a complementary approach, the quantitative estimates of the vulnerability of Wet Tropics vertebrates to extreme events can be made species-specific, enabling effective prioritization of most vulnerable species.

3a. Current thermal hotspots and refugia

Methods

We began by identifying the areas in the Wet Tropic's landscape where pre-defined assemblages of Wet Tropics vertebrates are currently most (thermal hotspots) and least (thermal refugia) vulnerable to extreme heat events. Following that we used the termophysiological data from objective 2c to define areas where specific species are currently most likely to suffer from heat stress.

Current thermal hotspots: We identified the areas in the Wet Tropic's landscape where vertebrates are currently most vulnerable to temperature extremes (current 'thermal hotspots') by building on the outputs from Part 1 (exposure) and Part (sensitivity).

To do this we first constructed maps of the Wet Tropics depicting the number of 'exposed' species. Using the outputs from Part 1 (objectives 1a-c), we extracted for each of the 202 vertebrate species in our database the daily temperatures of the microhabitats available to that species (as previously determined by us at 250x250m pixel resolution). Next, we selected for each time slice the minimum microhabitat temperature available at each pixel, for each species. We took these minimum values because we assumed that during an extreme heat event individuals will select the most thermally favourable microhabitat among those that they are known to use (see objective 2b). We then plotted for each species, all pixels with values that exceeded the 95th percentile of these minimum microhabitat temperatures (i.e., here a species is considered 'exposed' when it experiences temperatures exceeding the 95th percentile of the 1950-present temperature distribution in its coolest microhabitat). Finally, we overlaid this for all species creating maps to highlight the numbers of species that have experienced temperatures exceeding the 95th percentile of the 1950-present temperature distribution in their coolest local microhabitat (i.e. the maps of the Wet Tropics depicting the number of 'exposed' species in each 250x250m pixel).

We then mapped the average resilience of the species in the exposed areas. We did this by plotting the mean in the local distribution of resilience values (as quantified under objective 2a) for all areas where species were 'exposed' to temperatures exceeding the 95th percentile of their minimum microhabitat temperatures.

Finally, we created maps of 'current thermal hotspot' depicting the areas where the greatest (and smallest) number of species with the lowest (and highest) average resilience experience heat stress. We did this by weighting, at each 250x250m pixel, the number of species that experienced temperatures exceeding the 95th percentile of the 1950-present temperature distribution in their coolest local microhabitat by the mean in the local distribution of resilience values. These 'current thermal hotspots' thus identified represent those areas in the landscape where, on a hot day, the greatest proportion of least resilient vertebrate species is expected to be exposed to extreme heat.

We created equivalent maps for endemic and non-endemic vertebrates, as well as for the major taxonomic groups (birds, mammals, reptiles, amphibians), for the bottom 25% of the least resilient species, and for the species Red listed as 'Near Threatened' (NT) or worse.

Current thermal refugia: Following a similar approach as for the current thermal hotspots objective 3a, we also identified the areas in the Wet Tropics' landscape where the vertebrate biodiversity is currently least vulnerable to temperature extremes (current 'thermal refugia').

To do this we first constructed maps of the Wet Tropics depicting the number of 'sheltered' species. We did this by first identifying the areas within a species' range where the minimum microhabitat temperature was lower than the 5^{th} percentile of minimum microhabitat temperatures experienced across the species' range. We did this only for those days that contributed to the thermal hotspots maps, so the 5^{th} percentile areas represent those locations in the landscape where individuals are most likely to find shelter from heat given that on that same day other individuals are exposed to temperatures exceeding the 95^{th} percentile of their 1950-present minimum microhabitat temperature distributions. We then overlaid this for all species to highlight the numbers of all species that are 'sheltered' where, during an extreme heat event, individuals experience minimum microhabitat temperatures that are below the 5^{th} percentile of those experienced concurrently by other individuals across the species' range (i.e. the maps of the Wet Tropics depicting the number of 'sheltered' species in each 250x250m pixel).

We then mapped the average resilience of the species in the sheltered areas. We did this by plotting the mean in the local distribution of resilience values (as quantified under objective 2a) of the species that were exposed to temperatures less than the 5^{th} percentile of their minimum microhabitat temperature distributions.

Finally, we created maps of 'current thermal refugia' depicting the areas that provide the most shelter to species currently vulnerable to extreme heat events. We did this by weighting, at each 250x250m pixel, the number of sheltered species by the mean in the local distribution of species' resilience values, thus mapping the areas where the greatest (and smallest) number of species with the lowest (and highest) average resilience is protected from heat stress. These 'current thermal refugia' thus identified represent those areas in the landscape where, on a hot day, the greatest proportion of least resilient vertebrate species is expected to find shelter from heat.

As for the thermal hotspots, we created equivalent maps of the thermal refugia for endemic and non-endemic vertebrates, and for the major taxonomic groups (birds, mammals, reptiles, amphibians, the bottom 25% least resilient species, and for species Red listed as 'Near Threatened' (NT) or worse.

Current heat stress vulnerability of individual species: We also created maps showing the current vulnerability of species to exceedance of specific predetermined thermophysiological thresholds in their coolest available microhabitat, e.g., beyond which individuals are expected to be unable to maintain thermostasis.

To do this we extracted (as above) for each of the 202 vertebrate species in our database the daily temperatures of the microhabitats available to that species. Next, we selected for each time slice the minimum microhabitat temperature available at each pixel for each species. We then produced individual maps for all species for which we had collected quantitative data on the thermal tolerance thresholds under objective 2c (45 birds; 20 mammals; 20 reptiles; 17 amphibians), showing the pixels where the maximum annual temperature in the species' coolest available microhabitat exceeded the species-specific thermal tolerance threshold (depicted as degrees above/below the threshold). We also constructed similar series of maps that, instead of on the maximum annual temperature, were based on the 90th, 95th and a 99th percentile of the annual temperature distribution, but our scripts are flexible allowing to map absolute thermal thresholds against any defined thermal regime.

Results

Current thermal hotspots:
From the current vulnerability estimates we have identified the areas in the Wet Tropics' landscape where vertebrates currently are i) most vulnerable to temperature extremes ('thermal hotspots') and ii) least vulnerable to temperature extremes ('thermal refugia'). These areas can be defined based on relative thresholds, such as based the 95th (Figure 16-24, pp 38-44) and the 5th percentile (Figure 25-33, pp 47-55) temperatures found within a species' distribution on a hot (95th percentile) day; or they can be defined based on our absolute thresholds, such as the thermophysiological limit of a focal species (Figure 34-36, pp 55-57).

3b. Future thermal hotspots and refugia

Methods

We projected our current species vulnerability estimates (see objective 3a above) into the future using the latest state-of-the-art temperature projections for the Wet Tropics bioregion (4 RCPs, 18 GCMs; 8 time steps between 2015 and 2085; 250m resolution; VanDerWal et al, unpublished) (Figure 37**,** pp 58). The mean temperature increase across the 18 GCMs was calculated for each pixel, at each time step, for each global emission scenario. These values were added to the current annual temperature for each pixel. Following the methods used to calculate current thermal hotspots and refugia, we then plotted for each species, all values that exceeded the 95th percentile of their minimum microhabitat temperatures in the baseline period (1976-2005). We then overlaid this for all species to highlight the numbers of species that are likely to experience temperatures exceeding the 95th percentile of the baseline temperature distribution in their coolest local microhabitat in the future. We repeated this process for thermal refugia.

We created equivalent maps for endemic and non-endemic vertebrates, as well as for the major taxonomic groups (birds, mammals, reptiles, amphibians), for the bottom 25% of the least resilient species, and for the species Red listed as 'Near Threatened' (NT) or worse.

Again, our scripts are flexible such that we can generate maps showing future thermal regimes against any defined thermal thresholds such as current physiological thresholds.

Results

From these *future* vulnerability estimates we have identified the areas in the Wet Tropics' landscape where vertebrates will be i) most vulnerable to temperature extremes ('thermal hotspots') and ii) least vulnerable to temperature extremes ('thermal refugia'), in the future. These areas can be defined based on relative thresholds, such as based the 95th (Figure 38, pp 59) and the 5th percentile (Figure 39, pp 60) temperatures found within a species' distribution on a hot (95th percentile) day; or they can be defined based on our absolute thresholds, such as the thermophysiological limit of a focal species (Figure 40, pp 61).

Our vulnerability estimates also allow for quantitative ranking of species most at risk from extreme temperature events under different climate change scenarios, including, for example, the top 20 species most exposed (Table 3, pp 65) and vulnerable (Table 4, pp 66) to extreme temperature events by 2085 under the worst-case emission scenario RCP 8.5.

Overall, these future vulnerability estimates represent the culmination of the most comprehensive analysis to date to combine detailed information on exposure (Part 1) and sensitivity (Part 2) to determine the vulnerability of biodiversity to extreme temperature events at present (objective 3a) and under a range of future climate change scenarios (objective 3b).

General Discussion

Changes in the regimes of extreme events (particularly temperature extremes) have already been observed, and are expected to escalate in the future due to anthropogenic climate change. They are thus likely to become increasingly important mechanistic drivers of responses to climate change (IPCC 2012, Kapos et al 2008, Katz & Brown 1992, Parmesan 2006, Parmesan et al 2000, Welbergen et al 2008b), at all levels of biological organization. However, despite the realisation that many biological impacts of extreme events will be exacerbated under climate change, we lack the quantitative predictions required to manage these impacts. This project has made the first systematic attempt at providing such quantitative estimates of impacts.

Our analyses take into account detailed information on exposure (objectives 1a-b) and sensitivity (objectives 2a-c) to arrive at the most comprehensive assessment of the vulnerability of biodiversity to extreme temperature events to date. The value to end users of these outputs is that they provide spatially-explicit and species-specific foci for efficient and targeted conservation and habitat restoration management. Efficient conservation and habitat restoration management of the most vulnerable species and areas will improve the resilience and resistance of the Wet Tropics landscape to the increasingly extreme temperature events.

Areas for conservation

The *thermal hotspots* showed a high (and encouraging) degree of spatial congruence, with disparate vertebrate groups expected to be vulnerable to extreme heat events in the same specific areas, both at present (Figure 16-24, pp 38-46) and in the future (e.g., Figure 38, pp 59). For example, birds, mammals, reptiles and amphibians, are all most vulnerable in and around the **Tully River Catchment** (Figure 19-22, pp 41-44), and this area also contains large numbers of the least resilient (Figure 23, pp 45) and Red listed species (Figure 24, pp 46). Thus, by focussing on areas such as the Tully River Catchment, species conservation and habitat restoration management can efficiently improve the prospects of these groups simultaneously.

The thermal hotspots identified her are important for habitat restoration and species' conservation because they represent:

- Areas where vulnerable species would benefit most from promotion of thermally sheltered microhabitats, such as understory and logs.
- Areas that may act as a source of relatively heat-tolerant individuals (i.e., 'locally adapted forms'), which are focal individuals for species translocations as a tool for biodiversity conservation under climate change (Hunter 2007, IPCC 2007a).

The *thermal refugia* also showed a high spatial and temporal congruence, with representatives from all major taxonomic groups likely to find shelter from heat stress in the same areas both at present (Figure 25-33, pp 47-55) and in the future (Figure 39, pp 60). For example, birds, mammals, reptiles and amphibians, are all expected to all find shelter particularly on **Mt Windsor** and the **Carbine Tablelands** (Figure 28-31, pp 50-53), and these areas also contain the highest numbers of the least resilient (Figure 32, pp 54) and Red listed species (Figure 33, pp

55). Thus, by focussing on areas such areas, species conservation and habitat management actions can efficiently improve the prospects of many vertebrates simultaneously.

The thermal refugia identified here are valuable for species conservation and habitat preservation management because they represent:

- Areas where specific (assemblages of) (vulnerable) species would currently benefit most from habitat preservation
- Areas that may act as the destinations of relatively heat-tolerant individuals translocated from thermal hotspots

Climate change refugia – areas that may facilitate the persistence of species during large-scale, long-term climatic change – are increasingly important for conservation planning (Keppel et al in press, Reside et al 2014a, Reside et al 2014b), and the thermal refugia identified here complement more coarsely-resolved efforts that seek to identify climate change refugia in Australia more generally (Reside et al 2014a) and in Wet Tropics landscape more specifically (Shoo et al 2011). However, the biological realism of these models is limited by the resolution of the environmental and biological input data (Storlie et al 2014). Our assessments are highly resolved both in terms of the environmental and biological inputs, and our scripts can be used to assess the vulnerability of specific species to changes in physiologically-defined regimes of temperature extremes (e.g., Figure 7, pp 29).

The thermal hotspots and refugia have implications for the management of the intervening landscape matrix. By promoting the connectivity (Ball & Goldingay 2008, Goosem 2003a, Goosem 2003b, Goosem & Bushnell 2005, Goosem et al 2001a, Goosem et al 2005a, Goosem et al 2005b, Goosem et al 2001b) between the thermal hotspots and refugia, this will improve both the resilience and resistance of the Wet Tropics biodiversity to increasingly extreme temperatures under climate change (Figure 41, pp 62). Connectivity will enable thermal hotspots to be replenished following local extinction from an extreme heat events with individuals from thermal refugia; and it will enable the most heat-tolerant individuals from thermal hotspots to contract to the thermal refugia a heat extremes become more frequent and intense.

Species for conservation

This project identified several species of particular concern because they have a large part of their range exposed ('exposure': Table 3), or have a high exposure and high 'sensitivity' (='vulnerability'; Table 4).

Here is the top five of each of these tables: high exposure**:** Mountain Top Nursery-Frog *Cophixalus monticola;* Mt. Elliot Leaf-tail gecko *Phyllurus amnicola*; Beautiful Nursery-Frog *Cophixalus concinnus*; Blue-throated Rainbow-skink *Carlia rhomboidalis*; Saxicoline Sunskink *Lampropholis mirabilis*; high vulnerability**:** Bartle Frere cool-skink *Techmarscincus jigurru*; Bartle Frere barsided skink *Eulamprus frerei*; Tangerine Nursery-Frog *Cophixalus neglectus*; Mountain Top Nursery-Frog *Cophixalus monticola*; Grey-bellied sunskink *Lampropholis robertsi*.

A common feature of all these species is that they are mountain top species with small distributions in some of the most stable areas in the Wet Tropics, species already thought to be especially vulnerable to future regional shifts in climatic means (Shoo et al 2005b, Shoo & Williams 2004, Williams et al 2003).

For some such species the future prospects seem particular dire. For example, under the worst case emission scenario, 95% percent of the range of the Mountain Top Nursery-Frog *Cophixalus monticola* is expected to be exposed to extreme heat events that currently only affect 5 percent of the species range (Table 3, #1/202). This species also has a very low resilience (Table 1, #5/202) and little opportunity to seek thermal shelter from heat events (Table 2, #2/202), all contributing to a high vulnerability of the species (Table 4, #5/202).

However, from our thermotolerance analyses, it is clear that some species that do not appear on any of our priority tables (1-4) are nevertheless already regularly exposed to heat stress (e.g., White-throated treecreeper *Cormobates leucophaeus minor*; Figure 36, pp 57). Conversely, species such as the Golden Bowerbird *Prionodura newtoniana*, that have relatively low resilience (Table 1, #17/202) and relatively high vulnerability (Table 4, #19/202), are not expected to be subjected to heat stress in large parts of its distribution even under the most pessimistic emission scenarios (Figure 40, pp 61). This highlights the limitations of using relative threshold and the importance of detailed physiological information when assessing the climate vulnerability of individual (as opposed to assemblages) of species.

Final remarks

It is widely recognised that knowledge of the vulnerability of biodiversity to extreme events is crucial for sound conservation action in the face of climate change (Hughes et al 2009, IPCC 2007a). This is further evidenced by the high ranking of this issue among the stated research priorities of the main end-user organisations at both the national (Land & Water Australia 2008) and bioregional level (TERRAIN 2010, Welbergen et al 2011 , WTMA 2010). In addition, a host of other stakeholders in the Wet Tropics bioregion, including DSEWPaC, CSRIO, JCU, the Australian Wildlife Conservancy, and the FNQ Regional Organisation of Councils expressed strong interests in research pertaining to 'extreme events vulnerability', as revealed by our '*Gap analysis of environmental research needs in the Wet Tropics*' (Welbergen et al 2011), that was conducted under the Commonwealth Environmental Research Facilities (CERF) Transition Program.

The main tangible of Project 7.3 are in the hundreds of high-resolution maps (submitted to e-Atlas) as well as the very large temperature datasets and associated scripts available through e-Research/CTBCC. These provide the basic information and tools that will be of benefit to research providers with a stake in climate change adaptation research in the Wet Tropics. While the focus of Project 7.3 was on the impact of temperature extremes on vertebrate biodiversity, our modelling scripts are flexible and easily tailored to suit examinations of any subset of species in any area, against any environmental or physiological threshold. Thus, collectively also they provide a generalised analytical toolkit for assessing organismal vulnerability to extreme events in the Wet Tropics and beyond.

Extreme events are set to escalate this century as direct manifestations of anthropogenic climate change (IPCC 2012, IPCC 2013), and therefore it is essential that we establish a coherent picture of how biodiversity will be affected by these events. To do this, we need to expand our research in this field, not only to equip conservation agencies with the necessary information for allocating their limited resources efficiently, but also to deepen our scientific understanding of biological responses to environmental change more broadly. The potential impacts of anthropogenic climate change on tropical systems is of special concern (Deutsch et al 2008, Huey et al 2009, Tewksbury et al 2008) and Australia's Wet Tropics bioregion is the world's best understood tropical system (Stork & Turton 2008). Therefore, the Wet Tropics are, and will be, key to developing our understanding of the impacts of extreme events on biodiversity, as we hope this project has shown.

Figures

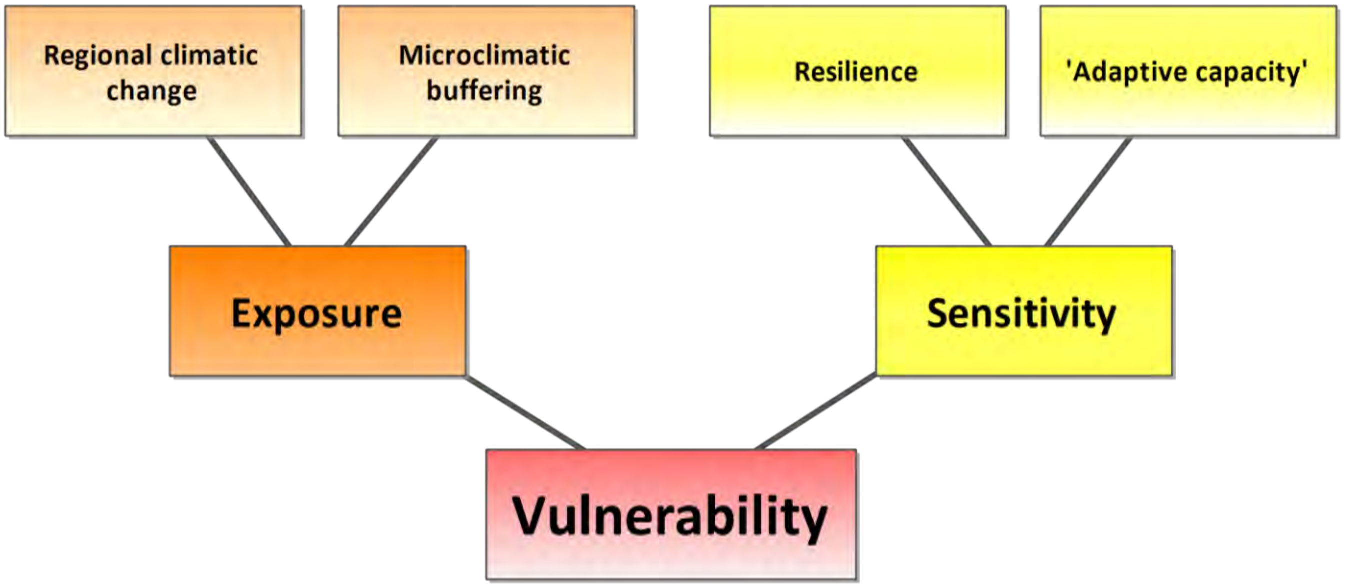

Figure 1. A general framework to assess species' vulnerability to extreme events under climate change, adapted from Williams & Shoo et al (2008). *Vulnerability* is a function of the species' exposure and sensitivity to the impacts of changes in the extremes. *Exposure* to such impacts is a function of regional changes acting at the scale of populations across their distribution, and of local buffering effects acting at the scale of individuals in their microhabitats. *Sensitivity* is a function of the *resilience* of populations to recover from the impacts, and the '*adaptive capacity*' (here 'behavioural plasticity' and 'thermotolerance') of individuals in the population to cope with the impacts.

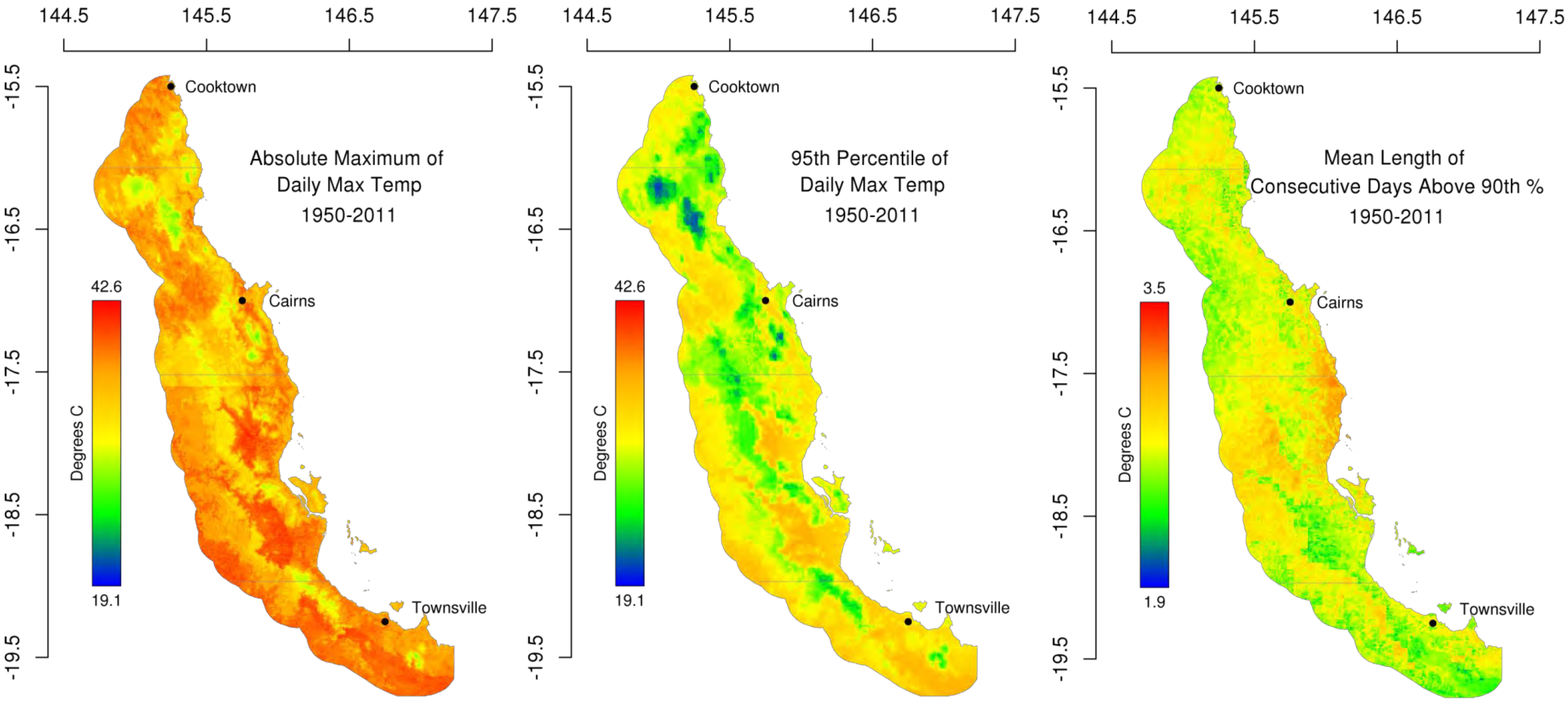

Figure 2. Spatially-explicit examples of thermal extremes' exposure in the Wet Tropics at the landscape scale. Left: The absolute maximum daily Tmax; centre: the 95th percentile of daily Tmax; right: the mean length of consecutive days above the 90th percentile.

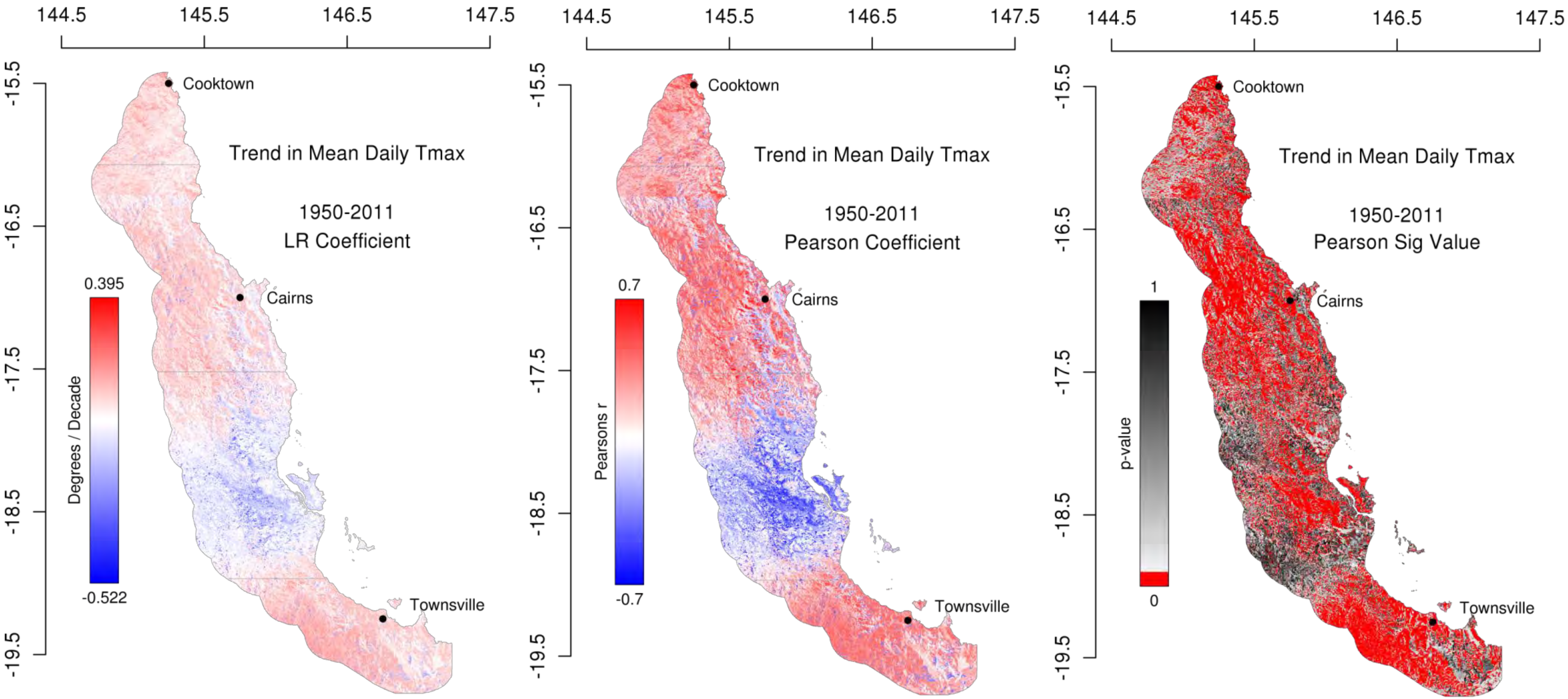

Figure 3. The change since 1950 in the mean daily Tmax in the Wet Tropics at the landscape scale. Left: the annual trends in the mean daily Tmax (in degrees C/decade); centre: the annual trends in the mean daily Tmax expressed as Pearson correlation coefficients; right: the significance of the Pearson correlation for the trends in the mean daily Tmax.

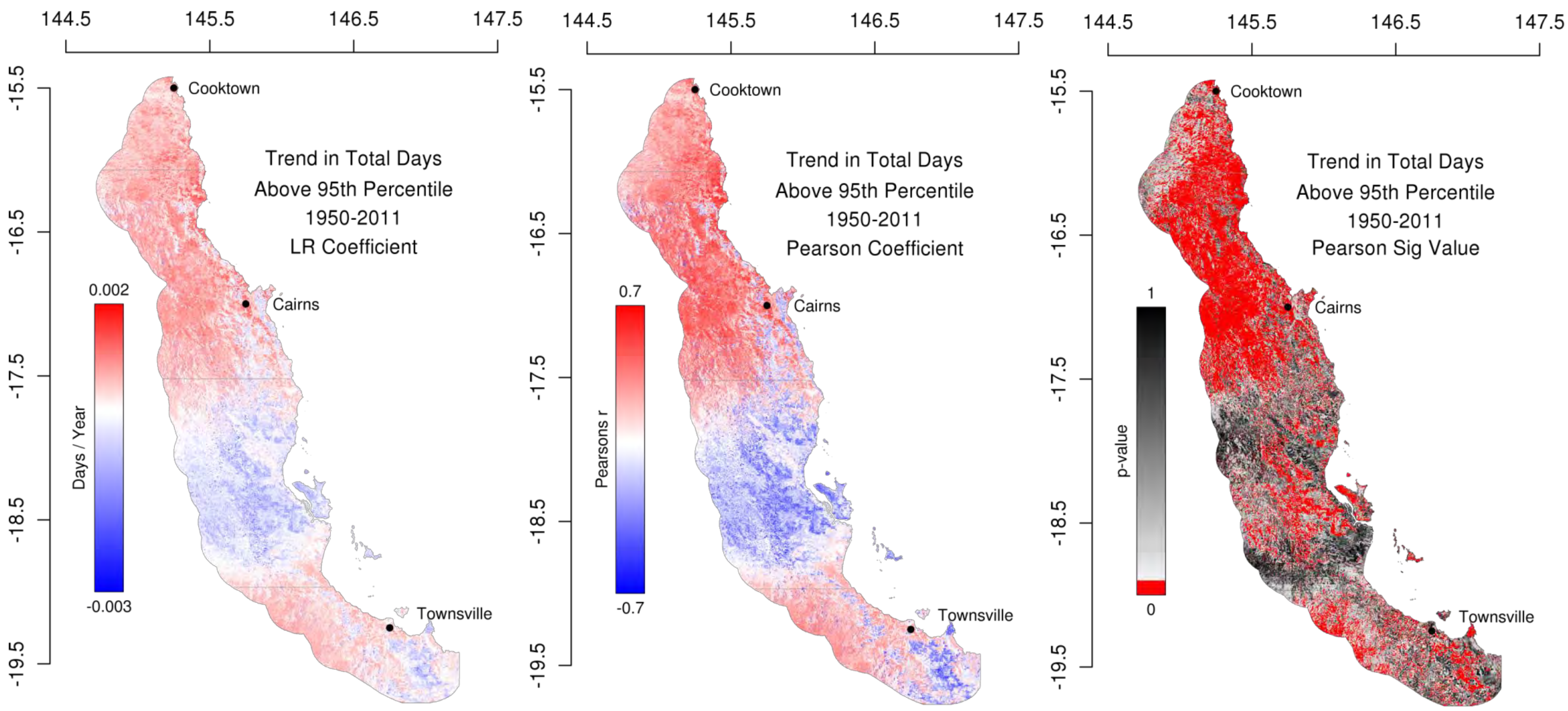

Figure 4. The change since 1950 in the annual number of hot days. Left: the annual trends in the number of days above the 95th percentile (in days/year); centre: the annual trends in the number of days above the 95th percentile expressed as Pearson correlation coefficients; right: the significance of the Pearson correlation for the annual trends in the number of days above the 95th percentile.

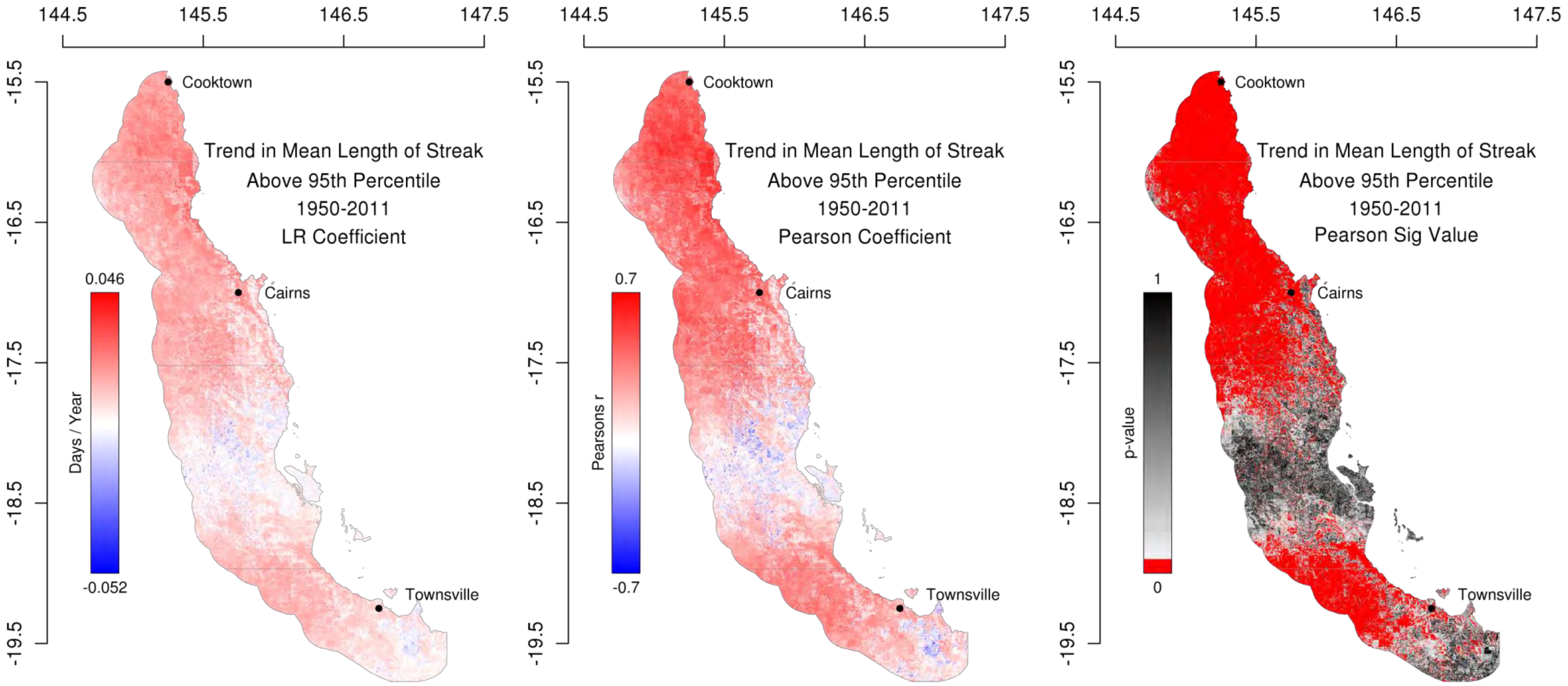

Figure 5. The change in the duration of hot spells. Left: the annual trends in the mean number of consecutive days above the 95th percentile (in days/year); centre: the trends in the mean number of consecutive days above the 95th percentile expressed as Pearson correlation coefficients; right: the significance of the Pearson correlation for the trends in the mean number of consecutive days above the 95th percentile.

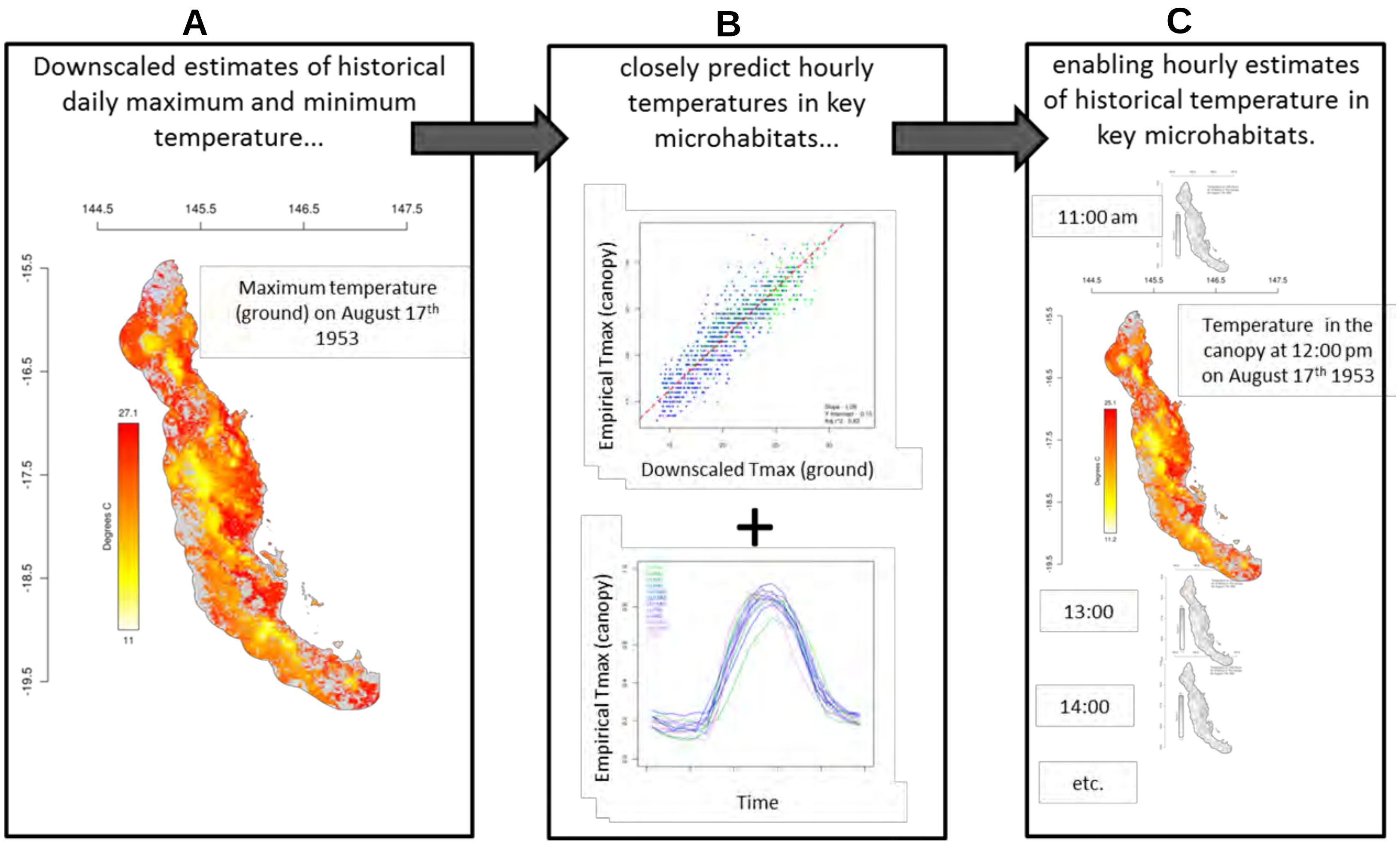

Figure 6. Schematic representation of our approach for quantifying the thermal exposure as experienced by individual organisms in their key-microhabitats (canopy, litter, soil, logs) (objective 1b). By linking our downscaled estimates of daily max and min temperature (objective 1a) to empirical microhabitat-specific hourly temperature curves (b), we can produce highly accurate estimates of hourly temperatures in the key microhabitats across the Wet Tropics, for example the temperature at 19 meters under the canopy at 12:00 pm on August 17th, 1953 (c).

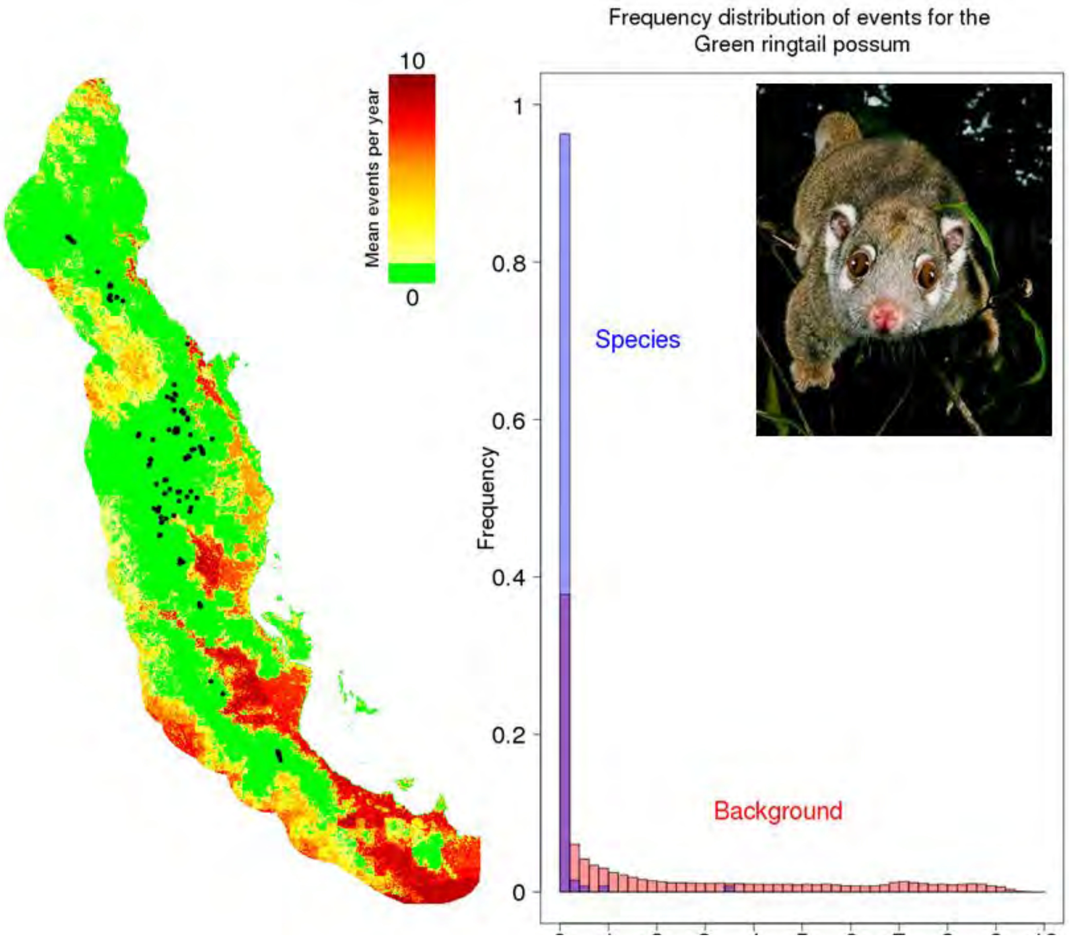

Figure 7. Left: Example of an accurate high-resolution map of the temperature extreme exposure of a key representative Wet Tropics animal species. It shows the occurrence records of the Green ringtail possum (*Psuedochrops archeri*) (black dots) overlaid on a map of the annual probability that the maximum temperature in their preferred habitat (i.e. canopy) exceeds 30 °C for more than 5 hours per day for 4 consecutive days (a critcal regime for possums Krockenberger et al 2012). Right: Plot showing that the species occurrence records fall almost exclusively in areas (cells) where the temperature in the canopy (the possum's microhabitat) does not exceed this thermal regime.

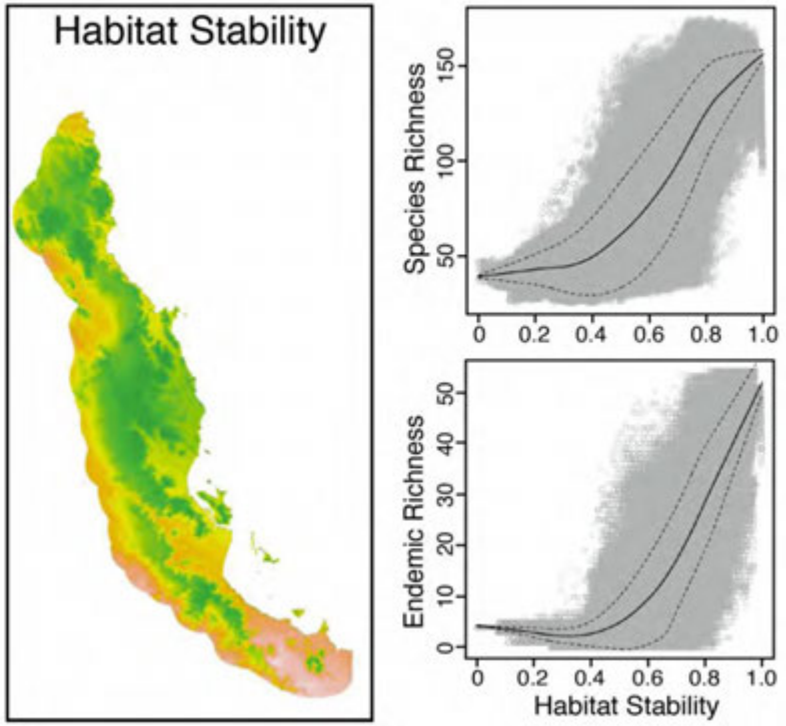

Figure 8. The stability of rainforest habitat during the last 18,000 years in the Wet Tropics bioregion and its relationships with species and endemic richness. Left: The stability of rainforest habitat (based on 'high dispersal dynamic model' from (Graham et al 2010). The areas in green have been most stable in the past. Right: the relationship between rainforest habitat stability and species richness (top), and between habitat stability and endemic richness (bottom) (CTBCC, unpublished data).

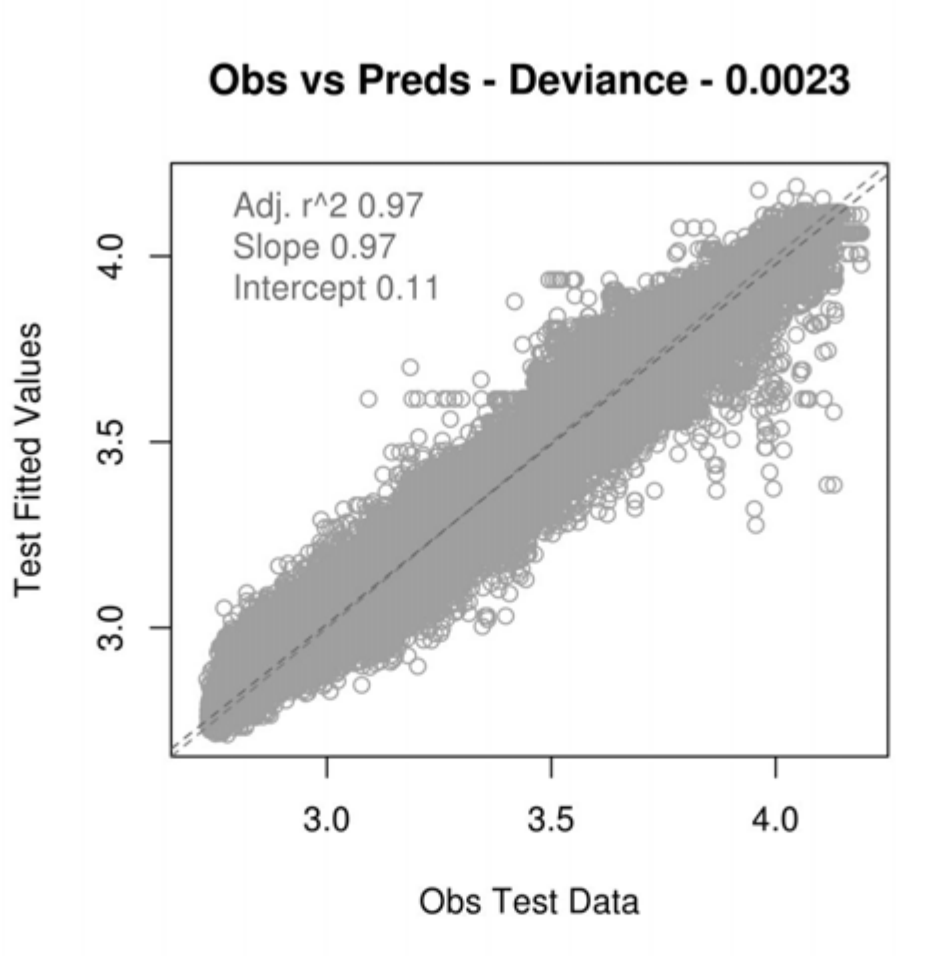

Figure 9. Scatterplot showing the relationship between the observed versus the fitted values of our best assemblage-level model.

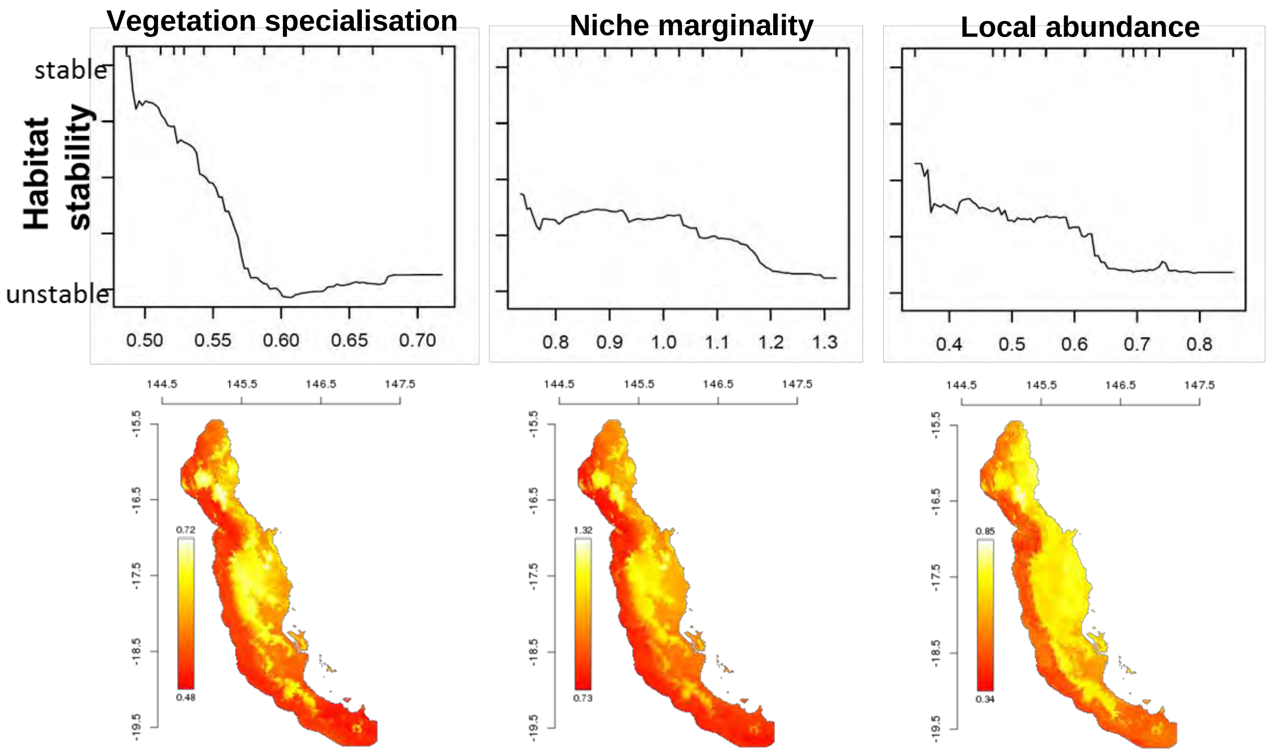

Figure 10. (top row) plots showing the relationships between the assemblage-level pixel values of vegetation specialisation, niche marginality, and local abundance versus rainforest habitat stability; (bottom row) maps of the Wet Tropics bioregion showing the actual assemblage-level pixel values of vegetation specialisation, niche marginality, and local abundance.

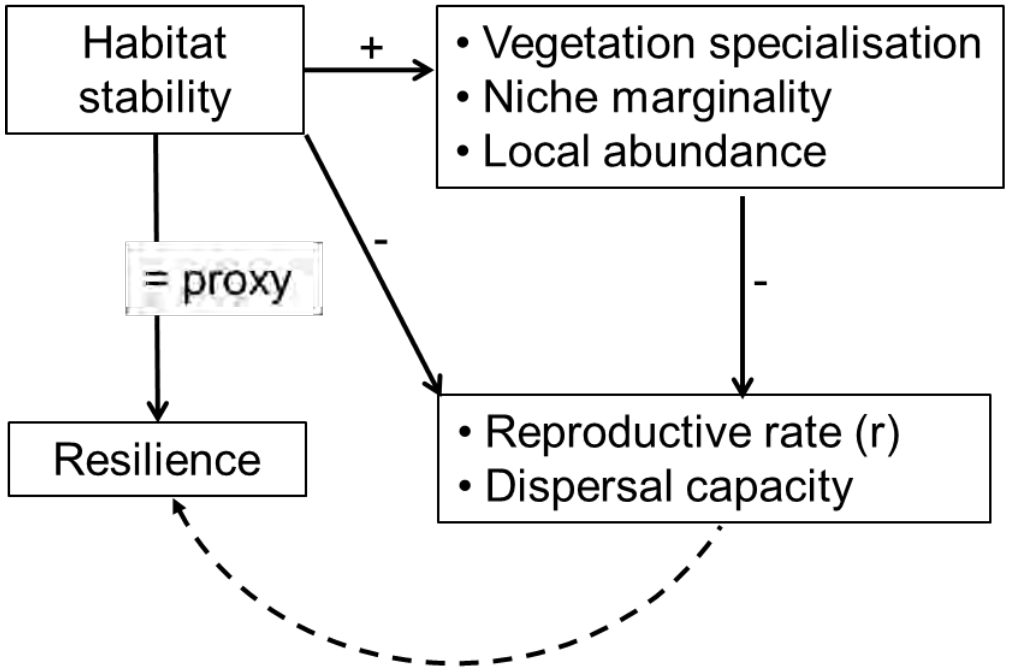

Figure 11. A schematic representation of our justification for using rainforest habitat stability (Graham et al 2010) as a valid proxy for 'resilience'. 'Habitat stability' shows positive relationships with vegetation specialisation, niche marginality, and local abundance. In turn, these are negatively related to reproductive rate and dispersal capacity, factors that are known to be critical for a population's ability to recover from an environmental insult (= resilience).

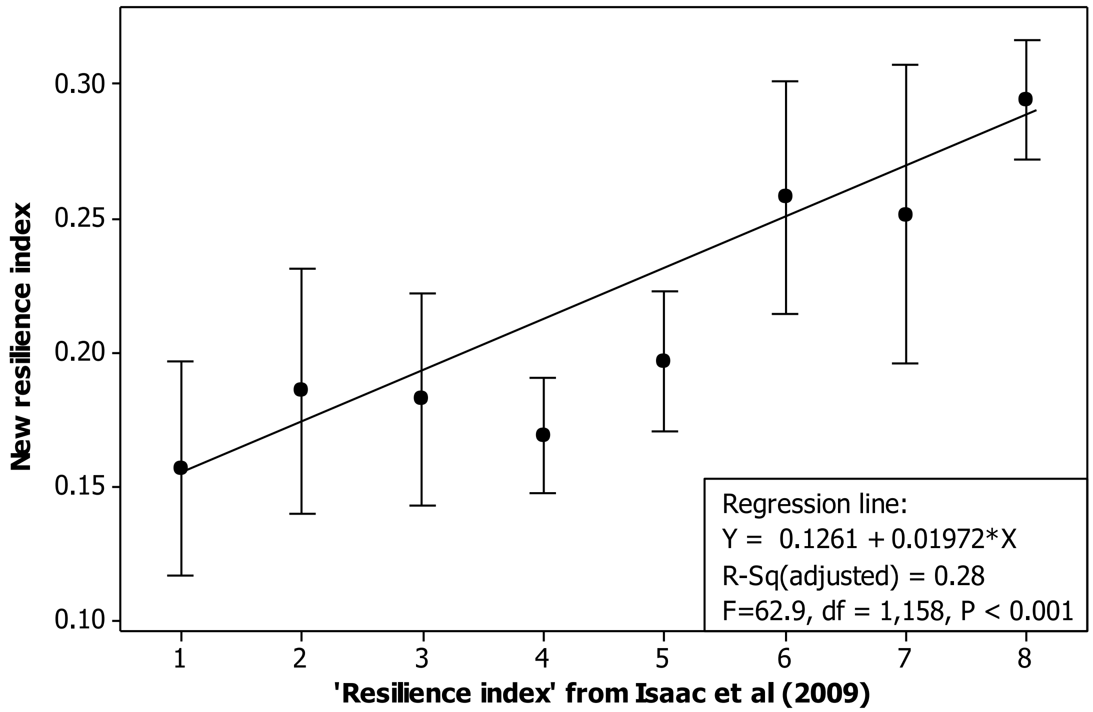

Figure 12. The 'resilience index' from Isaac et al (2009) versus our new index of species resilience (based on mean species' rainforest habitat stability (Graham et al 2010), validated against traits that are thought to promote species' resilience). For both indexes higher values indicate greater resilience.

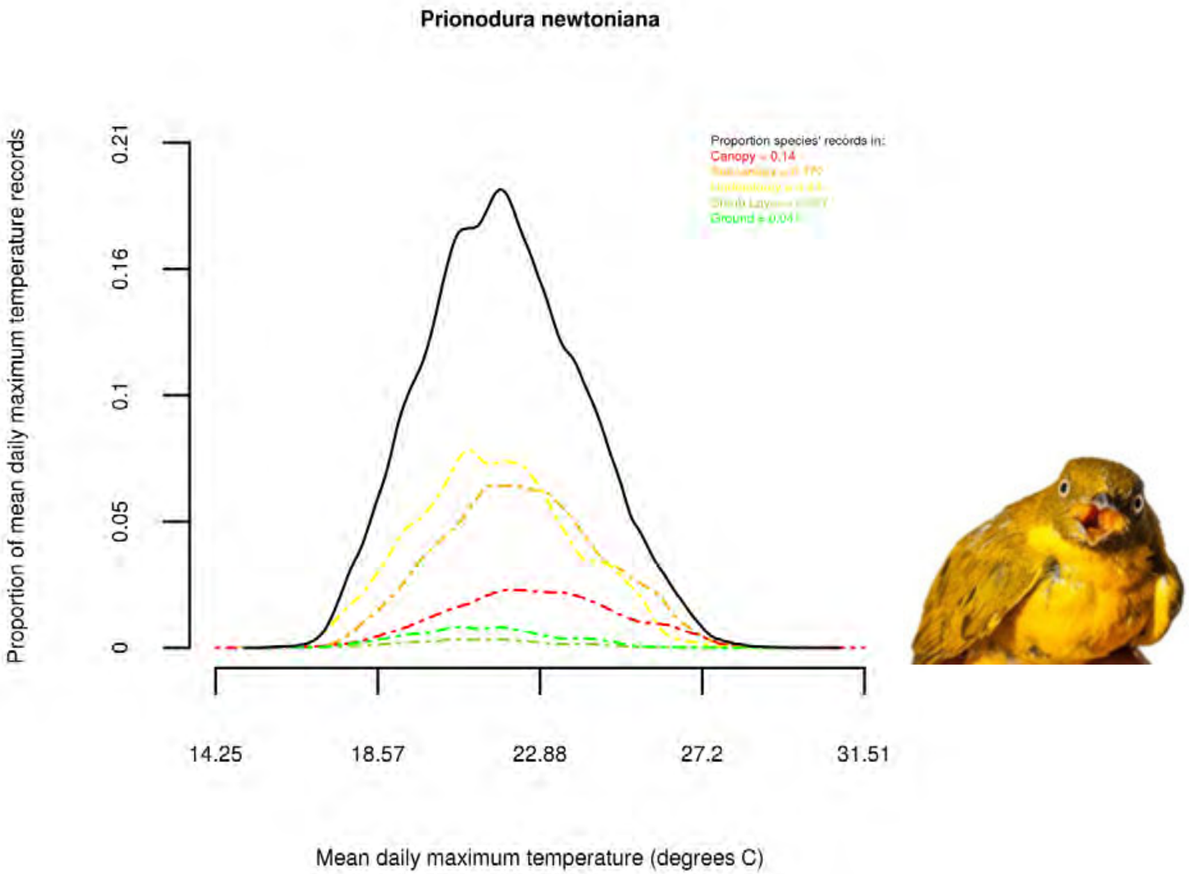

Figure 13. The daily maximum temperature exposure of the golden bowerbird *Prionodura newtoniana* since 1950. The black line shows the proportions of all the daily maximum temperatures that golden bowerbirds have potentially been exposed to in the Wet Tropics since 1950. The coloured curves show the relative contributions of the different microhabitats that the species inhabits, weighted by the number of empirical records of the species in each microhabitat. Picture credit: Johan Larson

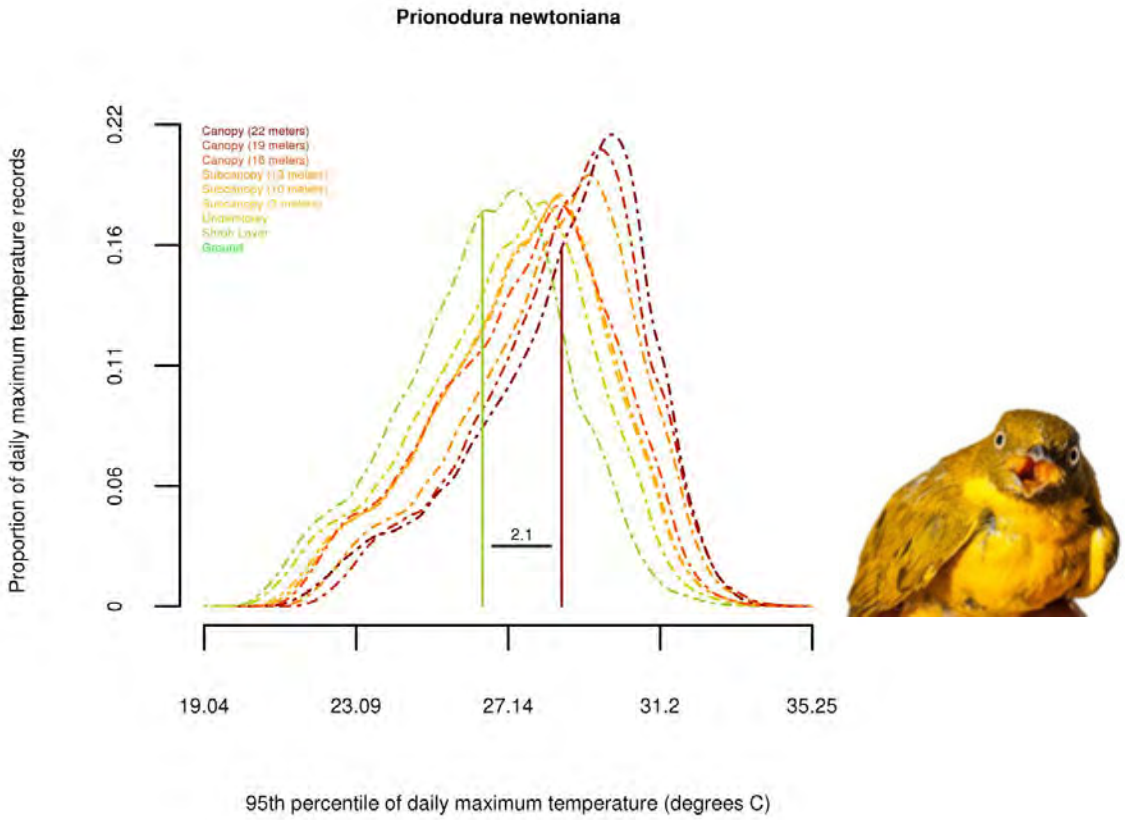

Figure 14. The thermal behavioural plasticity of golden bowerbirds, *Prionodura newtoniana* in response to extreme heat events (here defined as the 95th percentile of maximum daily temperatures found in its range) by moving to their most thermally favourable habitat. The coloured curves show the 95th percentiles of daily maximum temperature in each of the microhabitats used by the species. The red drop line shows the mean exposure in the least thermally favourable habitat and the green drop line shows the mean exposure in the most thermally favourable habitat. The difference (2.1 degrees C) represents the maximum reduction in realised thermal exposure that results when, during a hot, 95th percentile day, birds move into the microhabitat that is most thermally favourable and available to them. Picture credit: Johan Larson

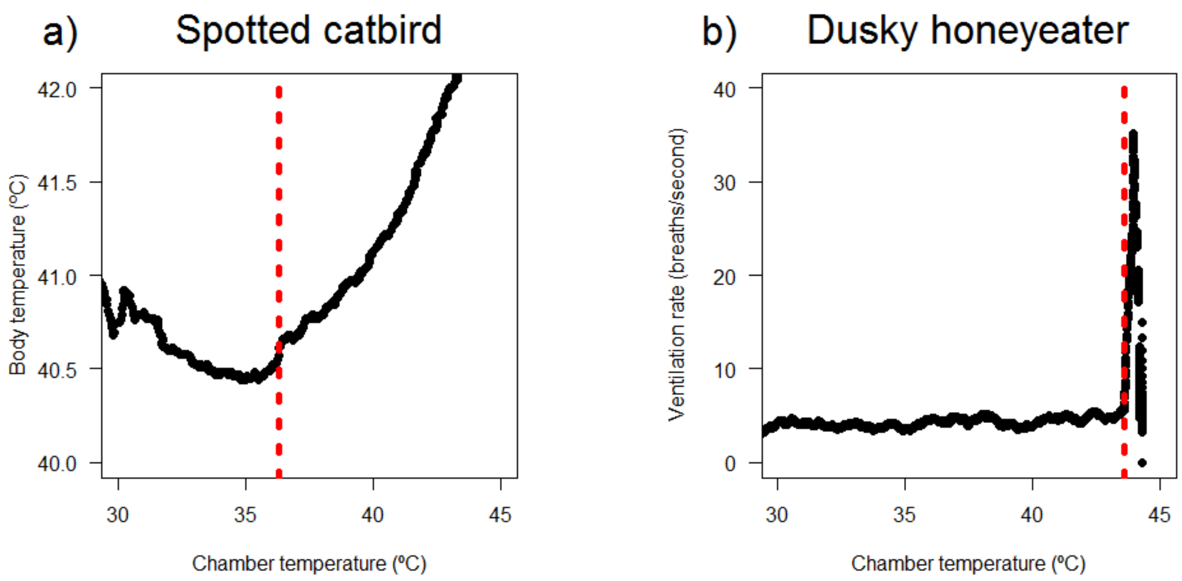

Figure 15. Thermo-physiology experimental chamber temperature plotted against (a) body temperature for a spotted catbird (*Ailuroedus melanotis*) and (b) ventilation rate of a dusky honeyeater (*Myzomela obscura*). Red dotted lines indicate the chamber temperature following which body temperature or ventilation rate increase consistently over a window of at least 30 s. Thus the thermo-physiological threshold for the spotted catbird is 36.29 °C and the threshold for the dusky honeyeater is 43.57 °C

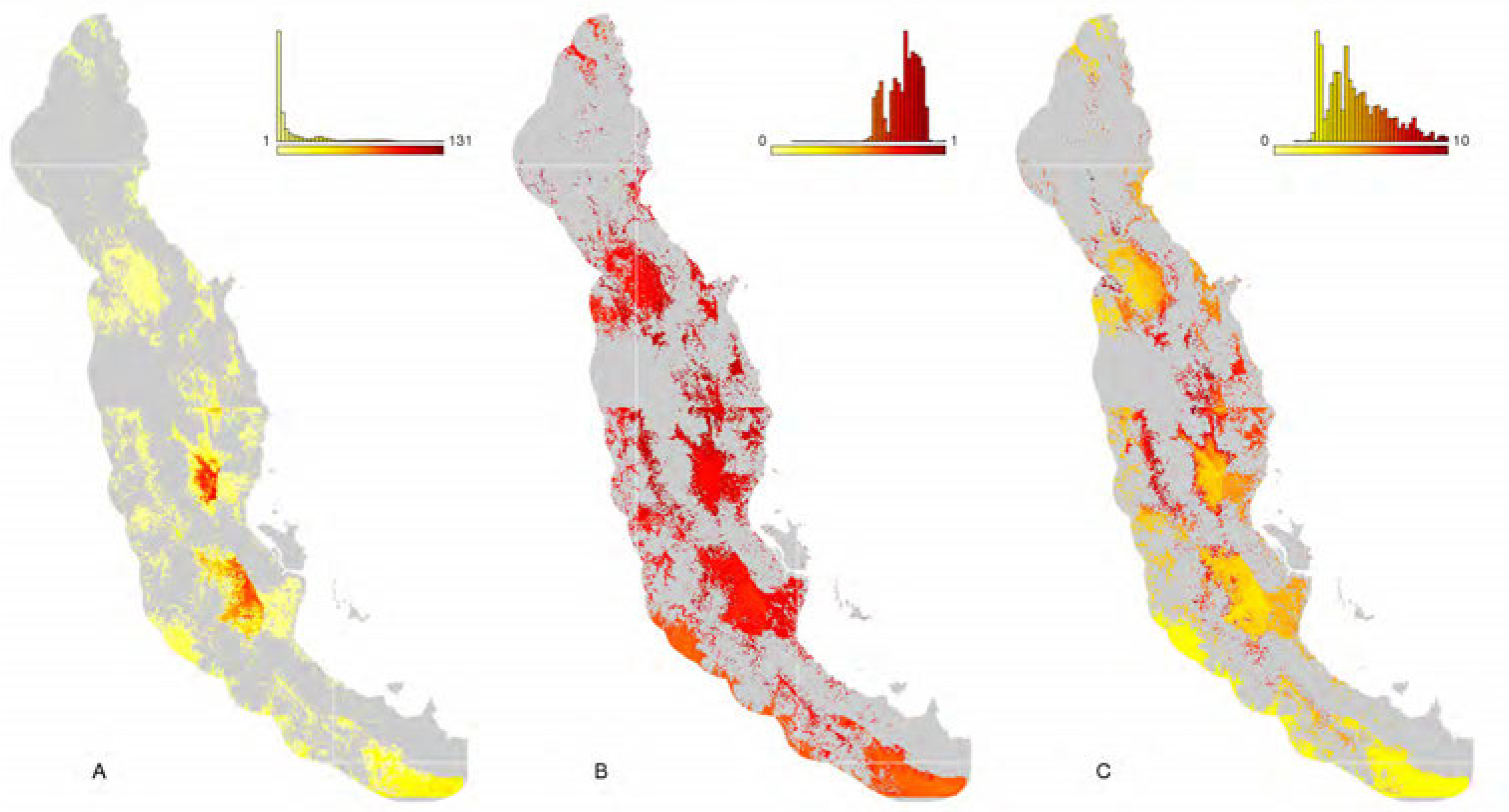

Figure 16. Current thermal hotspots for <u>all vertebrates</u> of the Wet Tropics (see details in text). A: areas with the number of species exposed to extreme heat events (here a species is 'exposed' when it experiences temperatures exceeding the 95th percentile of the 1950-present temperature distribution in its coolest microhabitat; locations in red have the *highest* number of exposed species). B: areas with the mean resilience of exposed species (locations in red have the *lowest* mean in the local distribution of resilience values of exposed species). C: areas with the current vulnerability of species to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in red have the *highest* number of species with the *lowest* mean resilience].

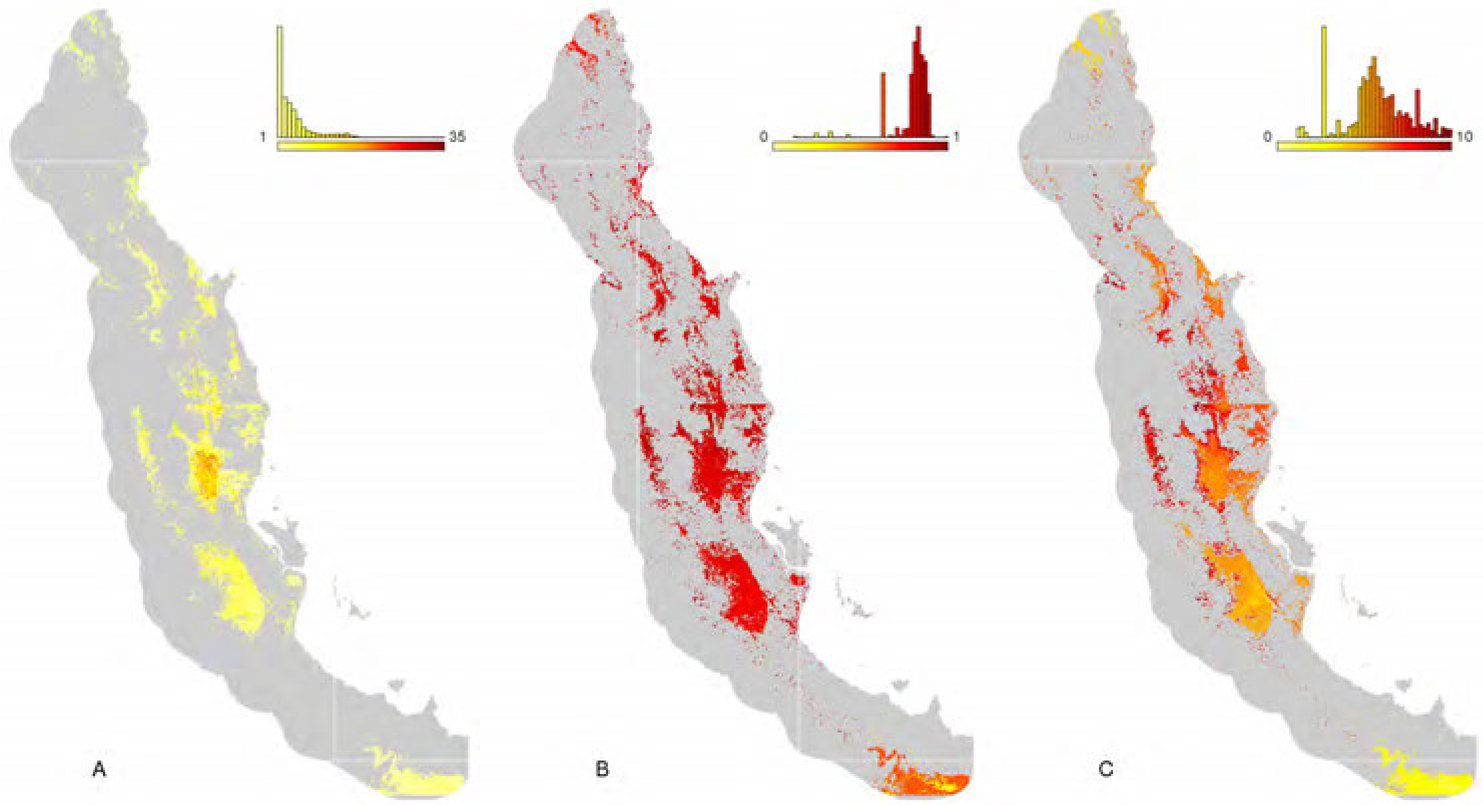

Figure 17. Current thermal hotspots for the endemic vertebrates of the Wet Tropics (see details in text). A: areas with the number of species exposed to extreme heat events (here a species is 'exposed' when it experiences temperatures exceeding the 95th percentile of the 1950-present temperature distribution in its coolest microhabitat; locations in red have the *highest* number of exposed species). B: areas with the mean resilience of exposed species (locations in red have the *lowest* mean in the local distribution of resilience values of exposed species). C: areas with the current vulnerability of species to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in red have the *highest* number of species with the *lowest* mean resilience].

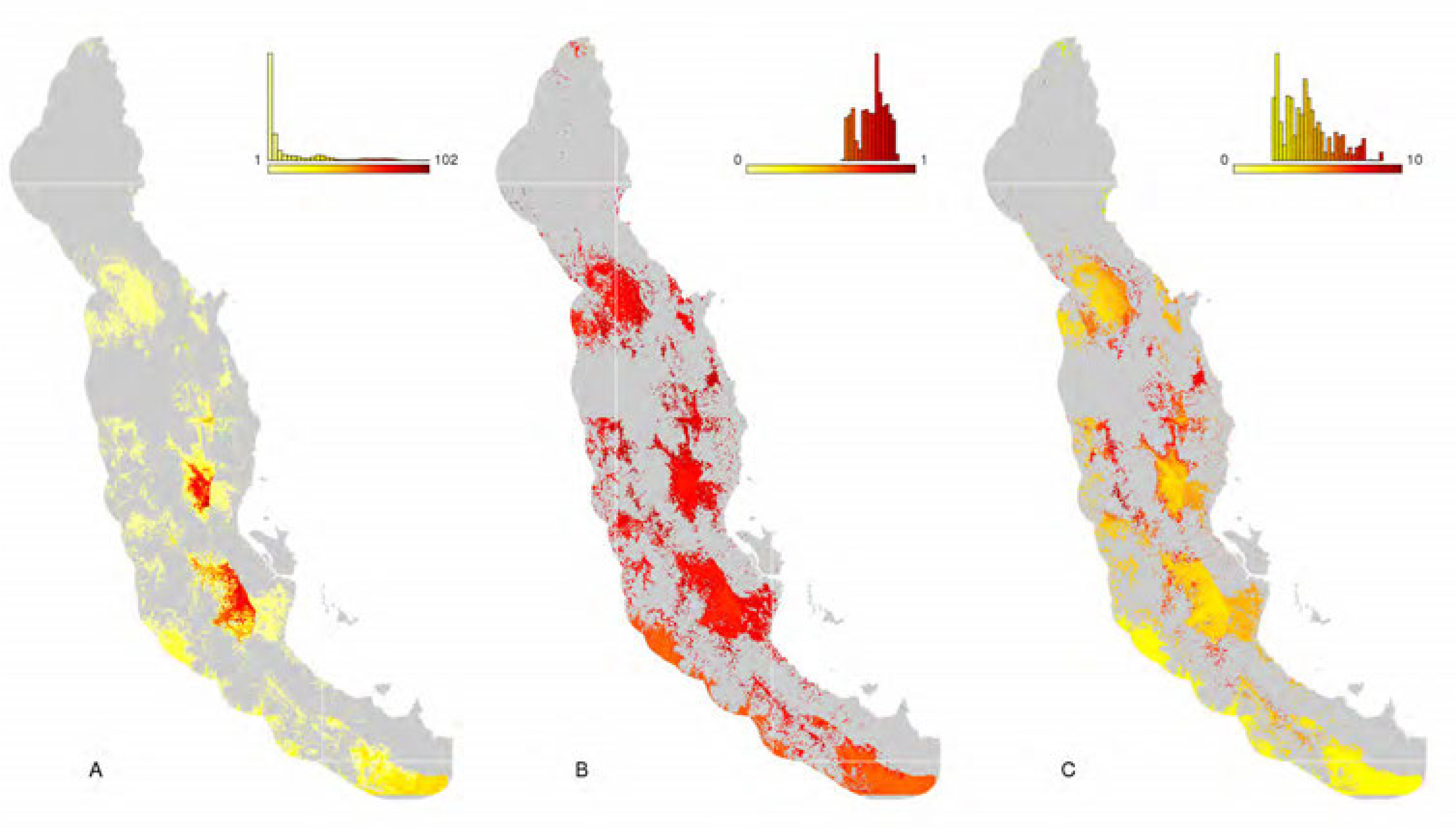

Figure 18. Current thermal hotspots for the non-endemic vertebrates of the Wet Tropics (see details in text). A: areas with the number of species exposed to extreme heat events (here a species is 'exposed' when it experiences temperatures exceeding the 95th percentile of the 1950-present temperature distribution in its coolest microhabitat; locations in red have the *highest* number of exposed species). B: areas with the mean resilience of exposed species (locations in red have the *lowest* mean in the local distribution of resilience values of exposed species). C: areas with the current vulnerability of species to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in red have the *highest* number of species with the *lowest* mean resilience].

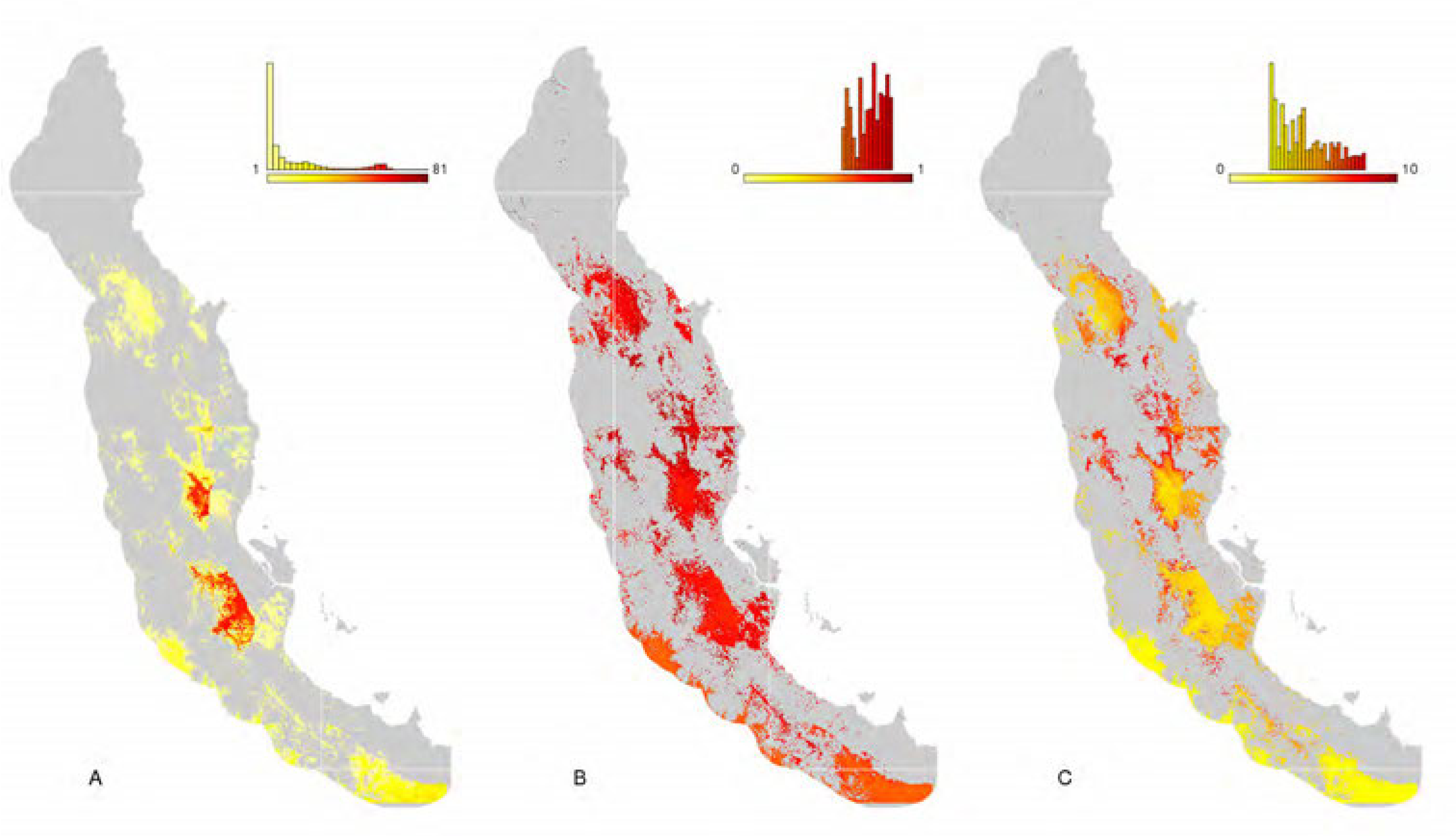

Figure 19. Current thermal hotspots for the birds of the Wet Tropics (see details in text). A: areas with the number of species exposed to extreme heat events (here a species is 'exposed' when it experiences temperatures exceeding the 95th percentile of the 1950-present temperature distribution in its coolest microhabitat; locations in red have the *highest* number of exposed species). B: areas with the mean resilience of exposed species (locations in red have the *lowest* mean in the local distribution of resilience values of exposed species). C: areas with the current vulnerability of species to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in red have the *highest* number of species with the *lowest* mean resilience].

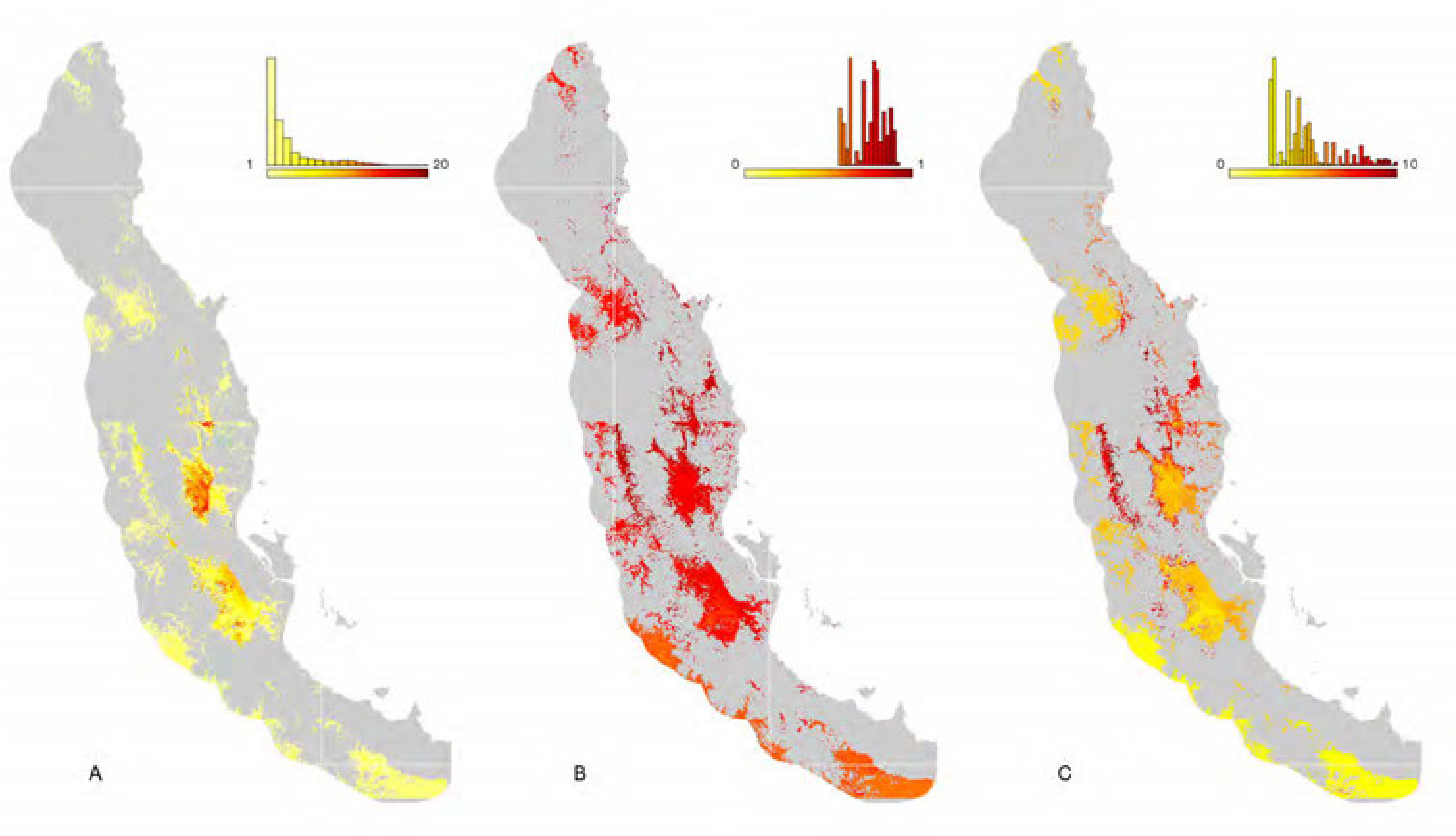

Figure 20. Current thermal hotspots for the mammals of the Wet Tropics (see details in text). A: areas with the number of species exposed to extreme heat events (here a species is 'exposed' when it experiences temperatures exceeding the 95th percentile of the 1950-present temperature distribution in its coolest microhabitat; locations in red have the *highest* number of exposed species). B: areas with the mean resilience of exposed species (locations in red have the *lowest* mean in the local distribution of resilience values of exposed species). C: areas with the current vulnerability of species to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in red have the *highest* number of species with the *lowest* mean resilience].

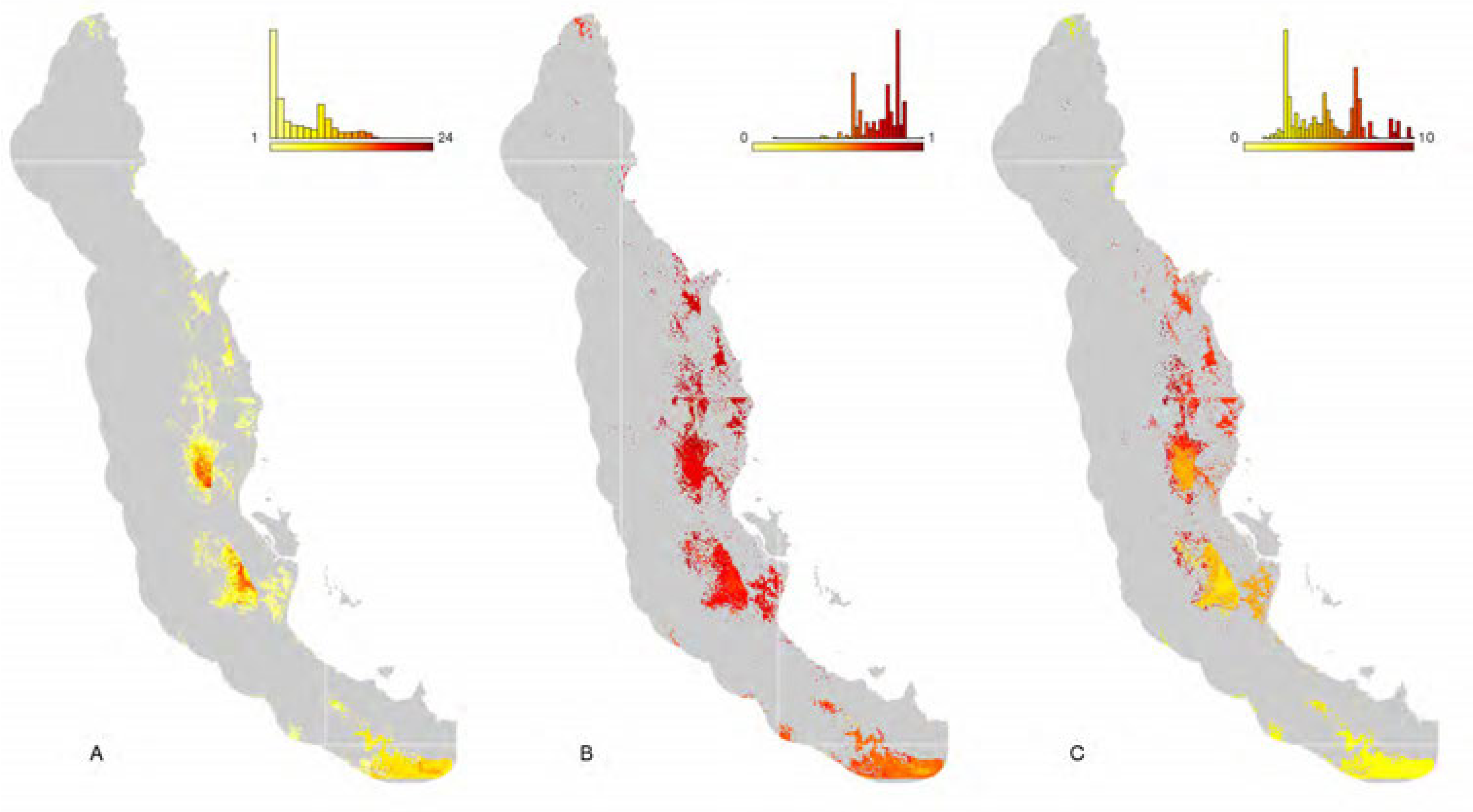

Figure 21. Current thermal hotspots for the reptiles of the Wet Tropics (see details in text). A: areas with the number of species exposed to extreme heat events (here a species is 'exposed' when it experiences temperatures exceeding the 95th percentile of the 1950-present temperature distribution in its coolest microhabitat; locations in red have the *highest* number of exposed species). B: areas with the mean resilience of exposed species (locations in red have the *lowest* mean in the local distribution of resilience values of exposed species). C: areas with the current vulnerability of species to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in red have the *highest* number of species with the *lowest* mean resilience].

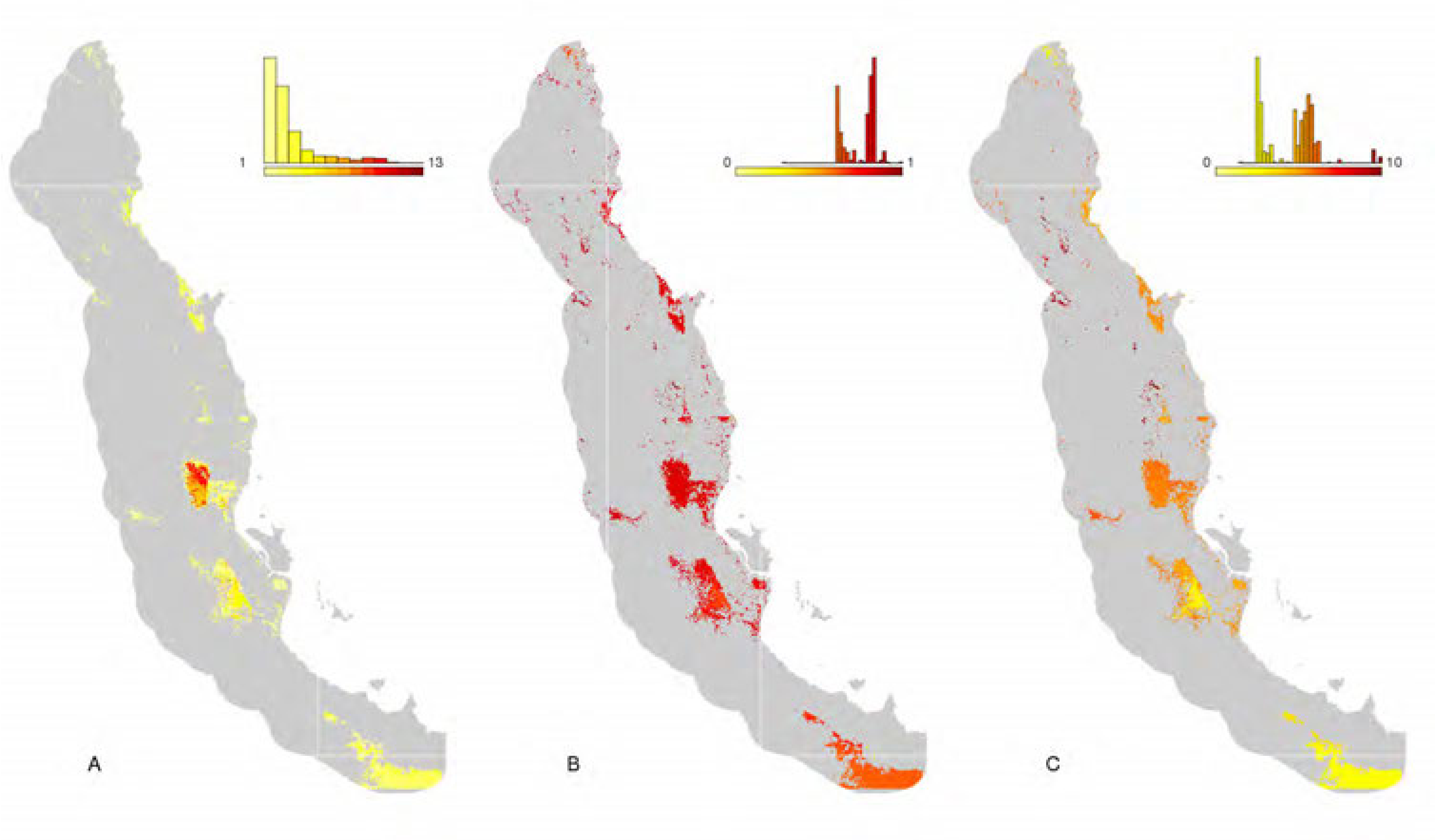

Figure 22. Current thermal hotspots for the amphibians of the Wet Tropics (see details in text). A: areas with the number of species exposed to extreme heat events (here a species is 'exposed' when it experiences temperatures exceeding the 95th percentile of the 1950-present temperature distribution in its coolest microhabitat; locations in red have the *highest* number of exposed species). B: areas with the mean resilience of exposed species (locations in red have the *lowest* mean in the local distribution of resilience values of exposed species). C: areas with the current vulnerability of species to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in red have the *highest* number of species with the *lowest* mean resilience].

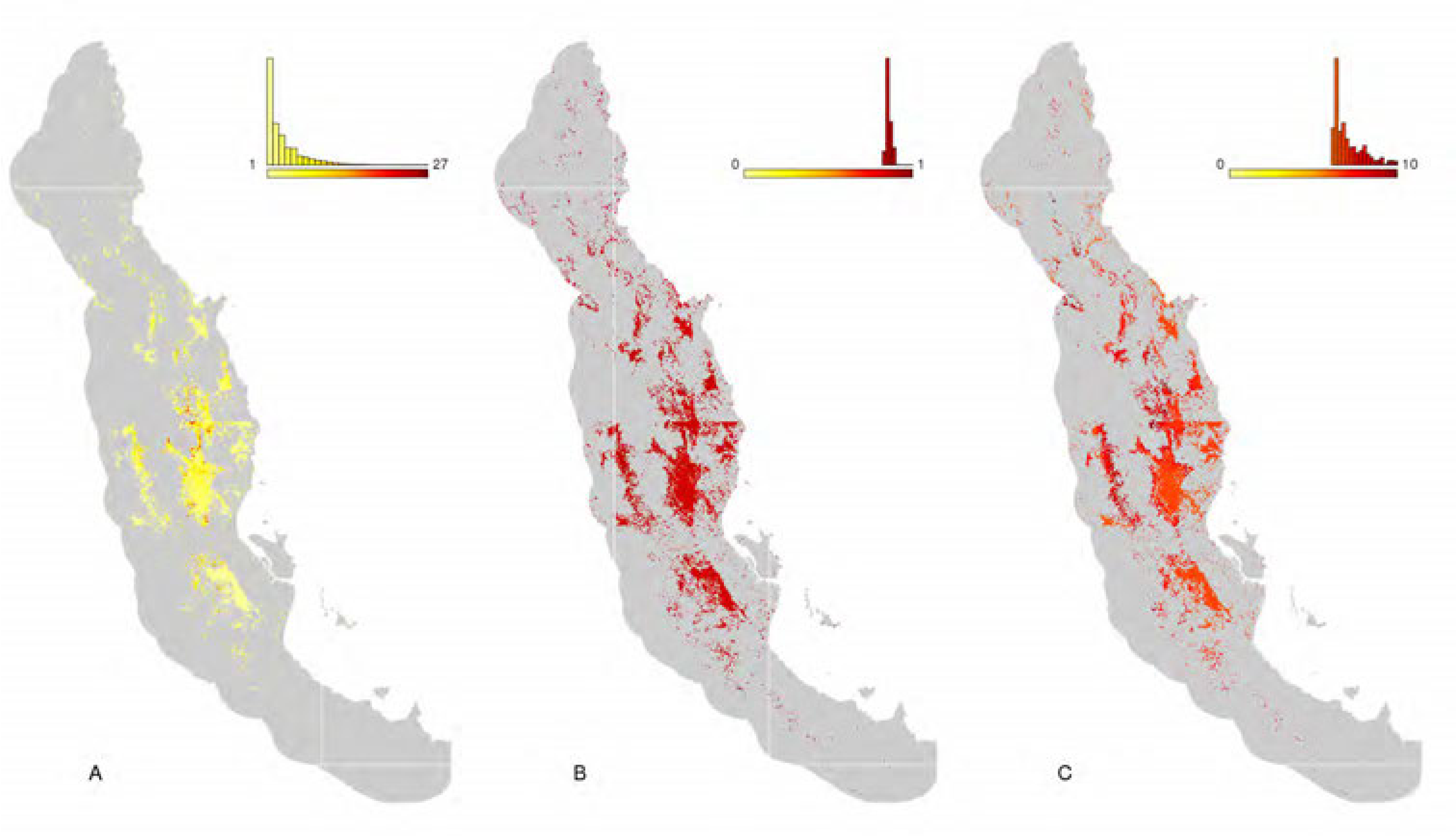

Figure 23. Current thermal hotspots for the 25% least-resilient vertebrates of the Wet Tropics (see details in text). A: areas with the number of species exposed to extreme heat events (here a species is 'exposed' when it experiences temperatures exceeding the 95th percentile of the 1950-present temperature distribution in its coolest microhabitat; locations in red have the *highest* number of exposed species). B: areas with the mean resilience of exposed species (locations in red have the *lowest* mean in the local distribution of resilience values of exposed species). C: areas with the current vulnerability of species to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in red have the *highest* number of species with the *lowest* mean resilience].

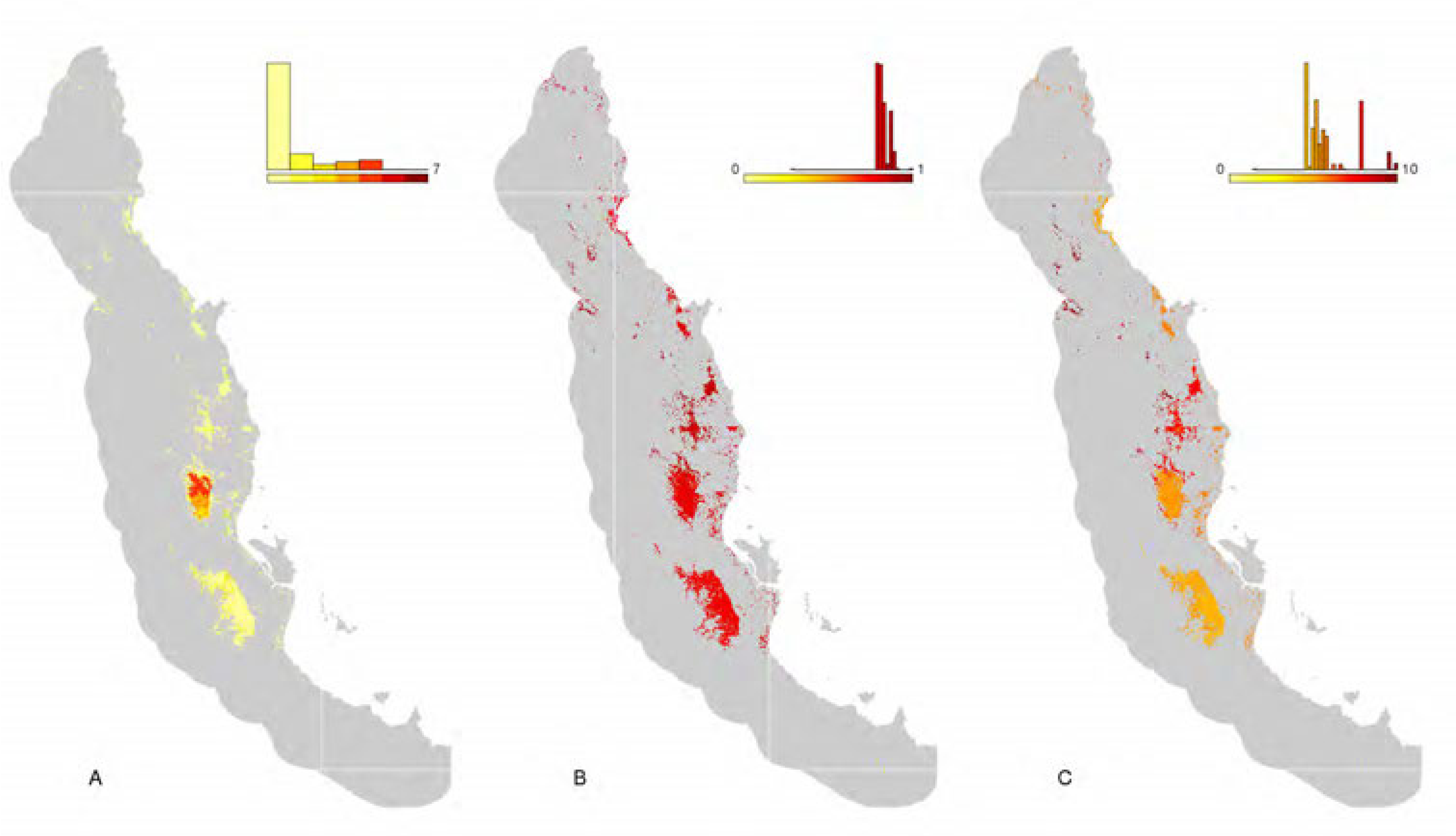

Figure 24. Current thermal hotspots for the vertebrates Redlisted as 'Near Threatened' (NT) or worse in the Wet Tropics (see details in text). A: areas with the number of species exposed to extreme heat events (here a species is 'exposed' when it experiences temperatures exceeding the 95th percentile of the 1950-present temperature distribution in its coolest microhabitat; locations in red have the *highest* number of exposed species). B: areas with the mean resilience of exposed species (locations in red have the *lowest* mean in the local distribution of resilience values of exposed species). C: areas with the current vulnerability of species to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in red have the *highest* number of species with the *lowest* mean resilience].

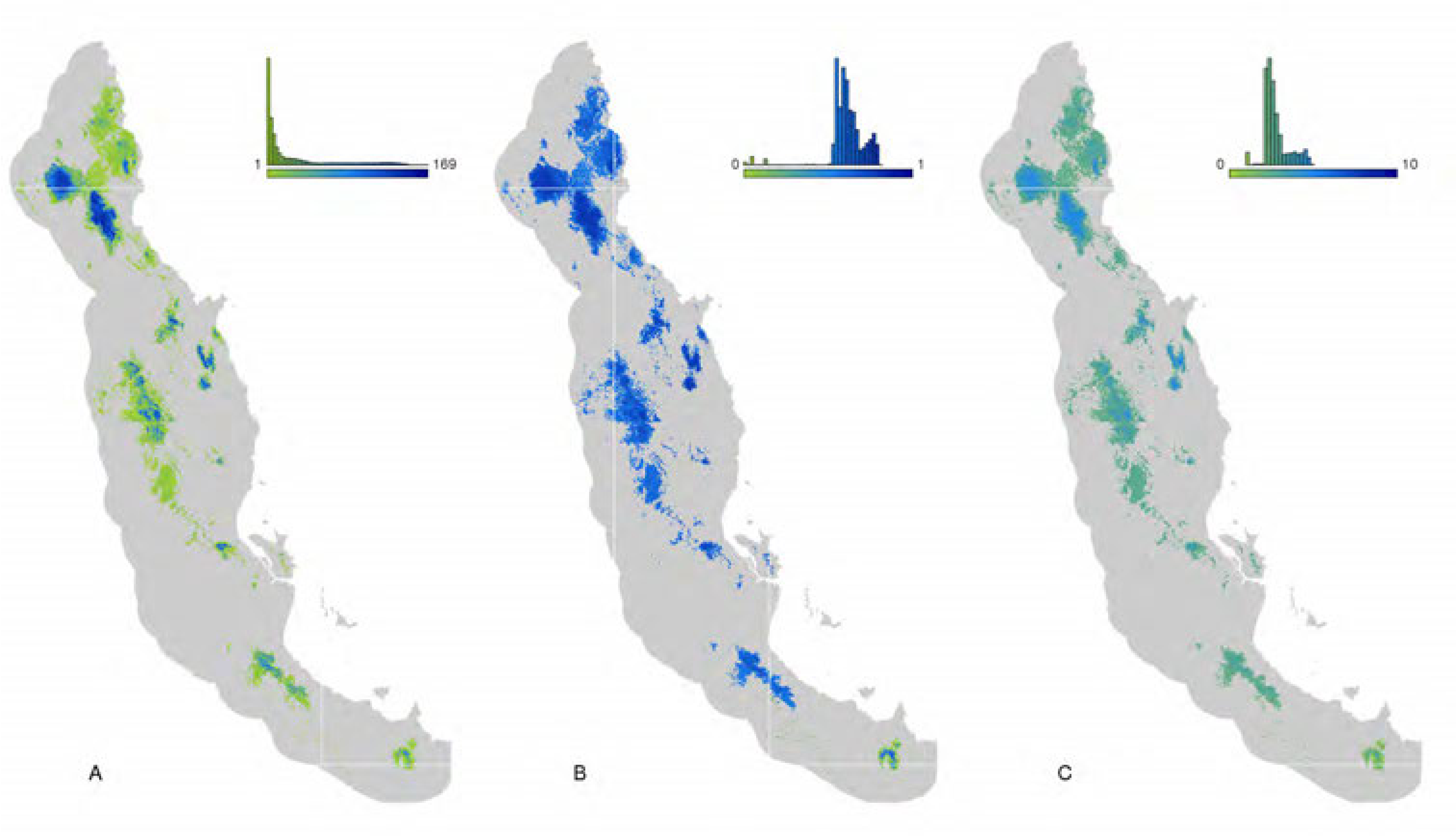

Figure 25. Current thermal refugia for all vertebrates of the Wet Tropics (see details in text). A: areas with the number of species sheltered from exposure to extreme heat events [here species are 'sheltered' where, during an extreme heat event (as in figures 1-9a), individuals experience minimum microhabitat temperatures that are below the 5th percentile of those experienced concurrently by other individuals across the species' range; locations in blue have the *highest* number of sheltered species). B: areas with the mean resilience of sheltered species (locations in blue have the *lowest* mean in the local distribution of resilience values of sheltered species). C: areas that provide the most shelter to species currently vulnerable to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in blue have the *highest* number of sheltered species with the *lowest* mean resilience].

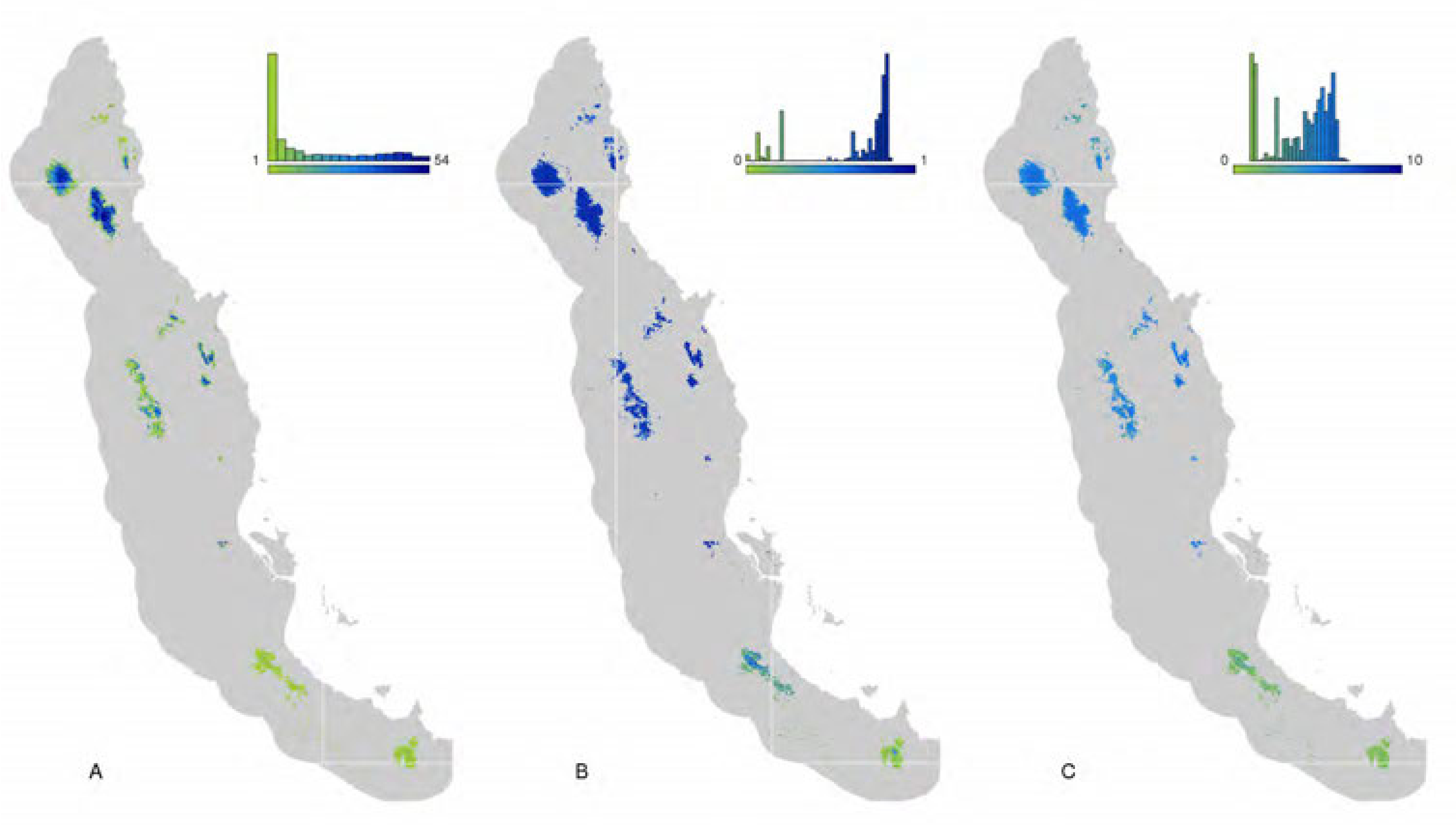

Figure 26. Current thermal refugia for the endemic vertebrates of the Wet Tropics (see details in text). A: areas with the number of species sheltered from exposure to extreme heat events [here species are 'sheltered' where, during an extreme heat event (as in figures 1-9a), individuals experience minimum microhabitat temperatures that are below the 5th percentile of those experienced concurrently by other individuals across the species' range; locations in blue have the *highest* number of sheltered species). B: areas with the mean resilience of sheltered species (locations in blue have the *lowest* mean in the local distribution of resilience values of sheltered species). C: areas that provide the most shelter to species currently vulnerable to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in blue have the *highest* number of sheltered species with the *lowest* mean resilience].

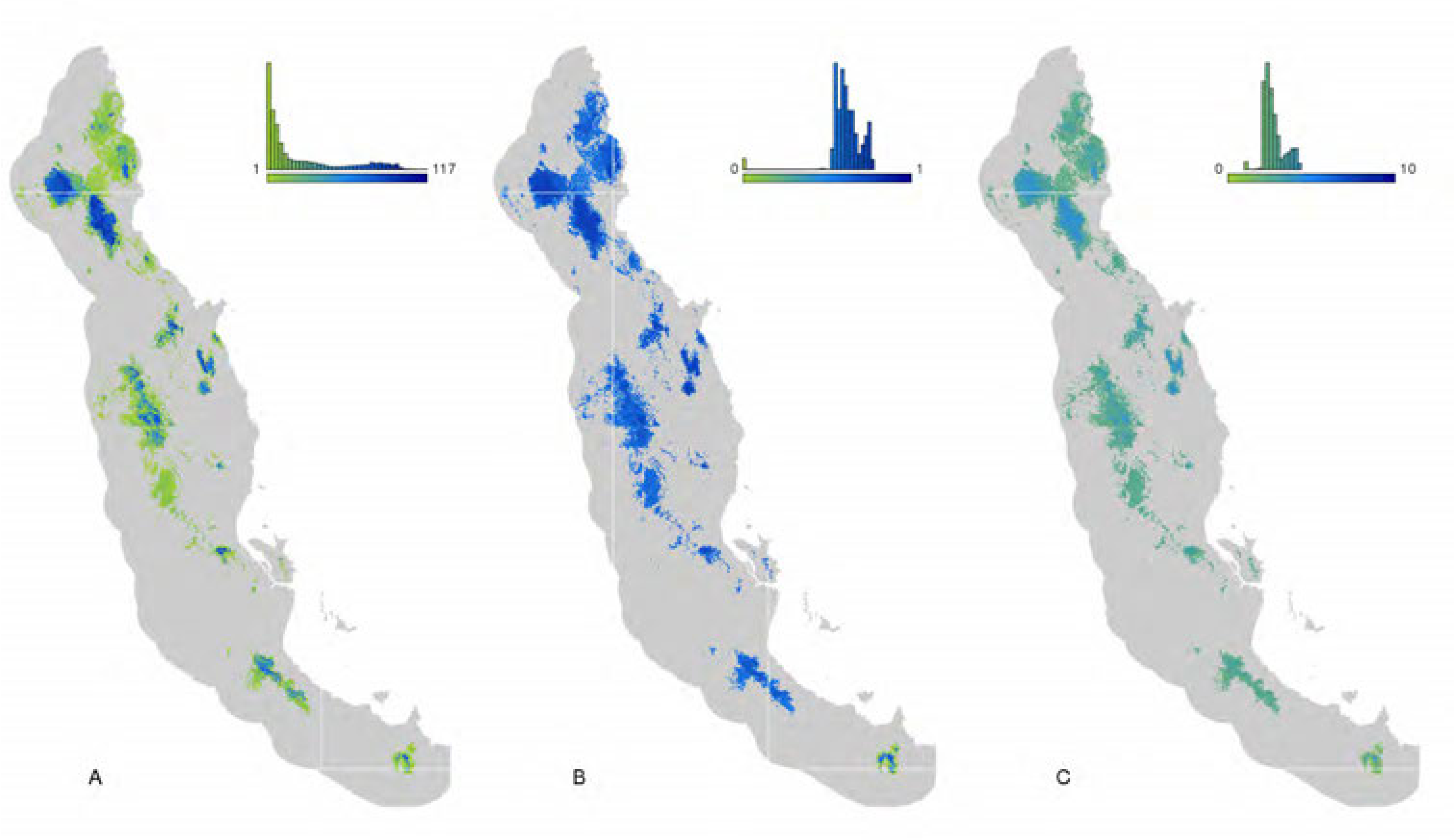

Figure 27. Current thermal refugia for the non-endemic vertebrates of the Wet Tropics (see details in text). A: areas with the number of species sheltered from exposure to extreme heat events [here species are 'sheltered' where, during an extreme heat event (as in figures 1-9a), individuals experience minimum microhabitat temperatures that are below the 5th percentile of those experienced concurrently by other individuals across the species' range; locations in blue have the *highest* number of sheltered species). B: areas with the mean resilience of sheltered species (locations in blue have the *lowest* mean in the local distribution of resilience values of sheltered species). C: areas that provide the most shelter to species currently vulnerable to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in blue have the *highest* number of sheltered species with the *lowest* mean resilience].

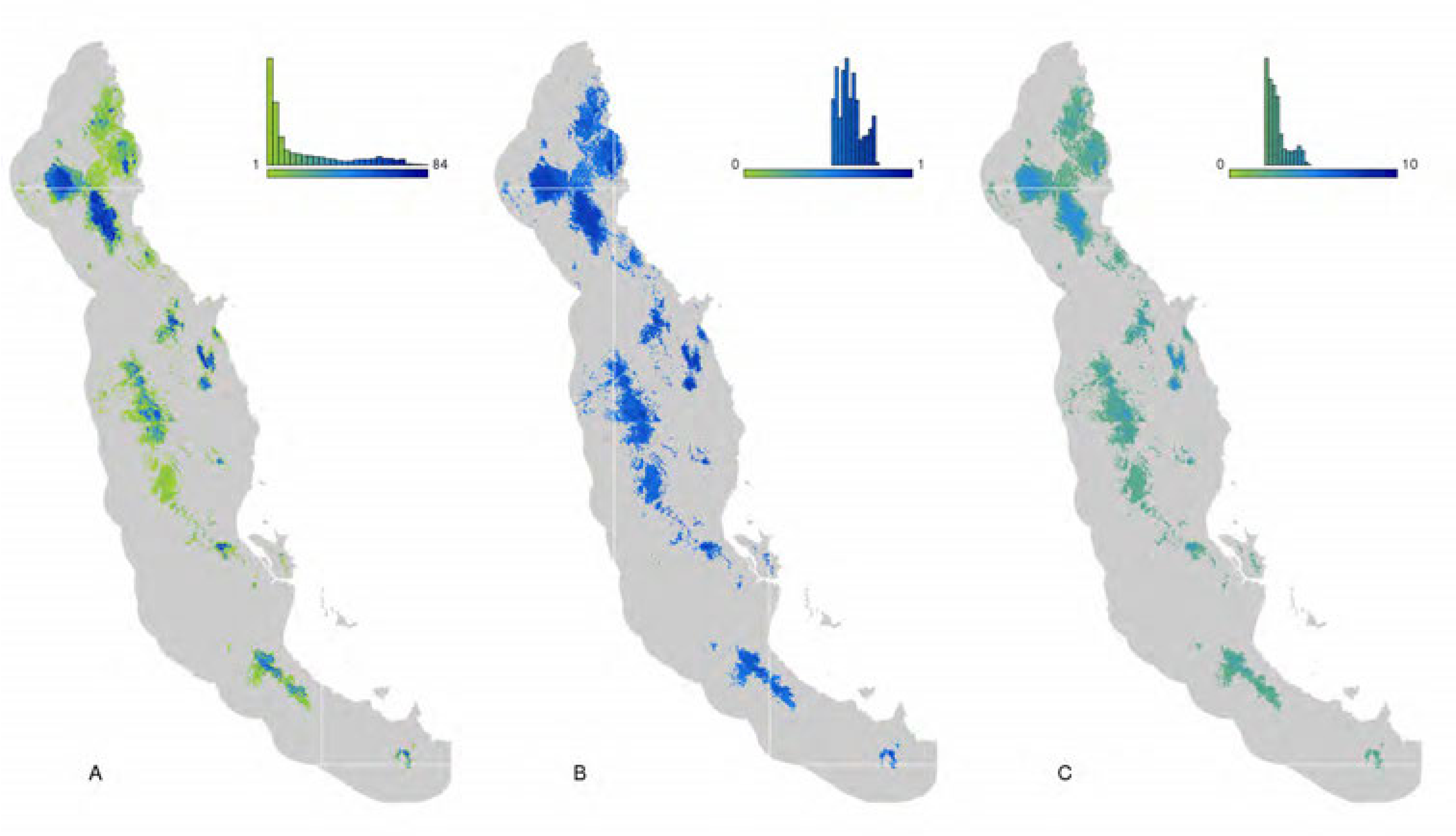

Figure 28. Current thermal refugia for the birds of the Wet Tropics (see details in text). A: areas with the number of species sheltered from exposure to extreme heat events [here species are 'sheltered' where, during an extreme heat event (as in figures 1-9a), individuals experience minimum microhabitat temperatures that are below the 5th percentile of those experienced concurrently by other individuals across the species' range; locations in blue have the *highest* number of sheltered species). B: areas with the mean resilience of sheltered species (locations in blue have the *lowest* mean in the local distribution of resilience values of sheltered species). C: areas that provide the most shelter to species currently vulnerable to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in blue have the *highest* number of sheltered species with the *lowest* mean resilience].

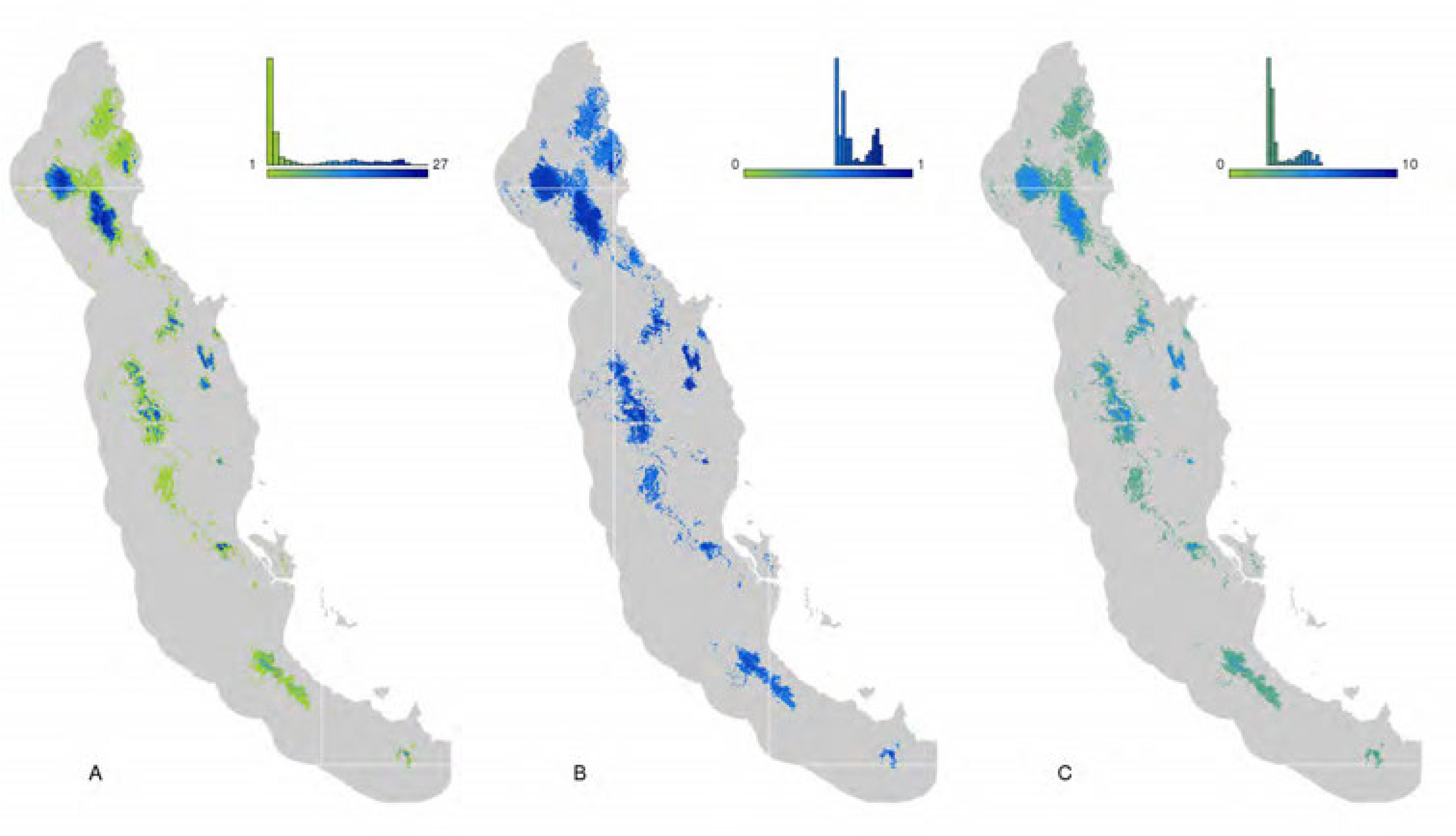

Figure 29. Current thermal refugia for the mammals of the Wet Tropics (see details in text). A: areas with the number of species sheltered from exposure to extreme heat events [here species are 'sheltered' where, during an extreme heat event (as in figures 1-9a), individuals experience minimum microhabitat temperatures that are below the 5th percentile of those experienced concurrently by other individuals across the species' range; locations in blue have the *highest* number of sheltered species). B: areas with the mean resilience of sheltered species (locations in blue have the *lowest* mean in the local distribution of resilience values of sheltered species). C: areas that provide the most shelter to species currently vulnerable to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in blue have the *highest* number of sheltered species with the *lowest* mean resilience].

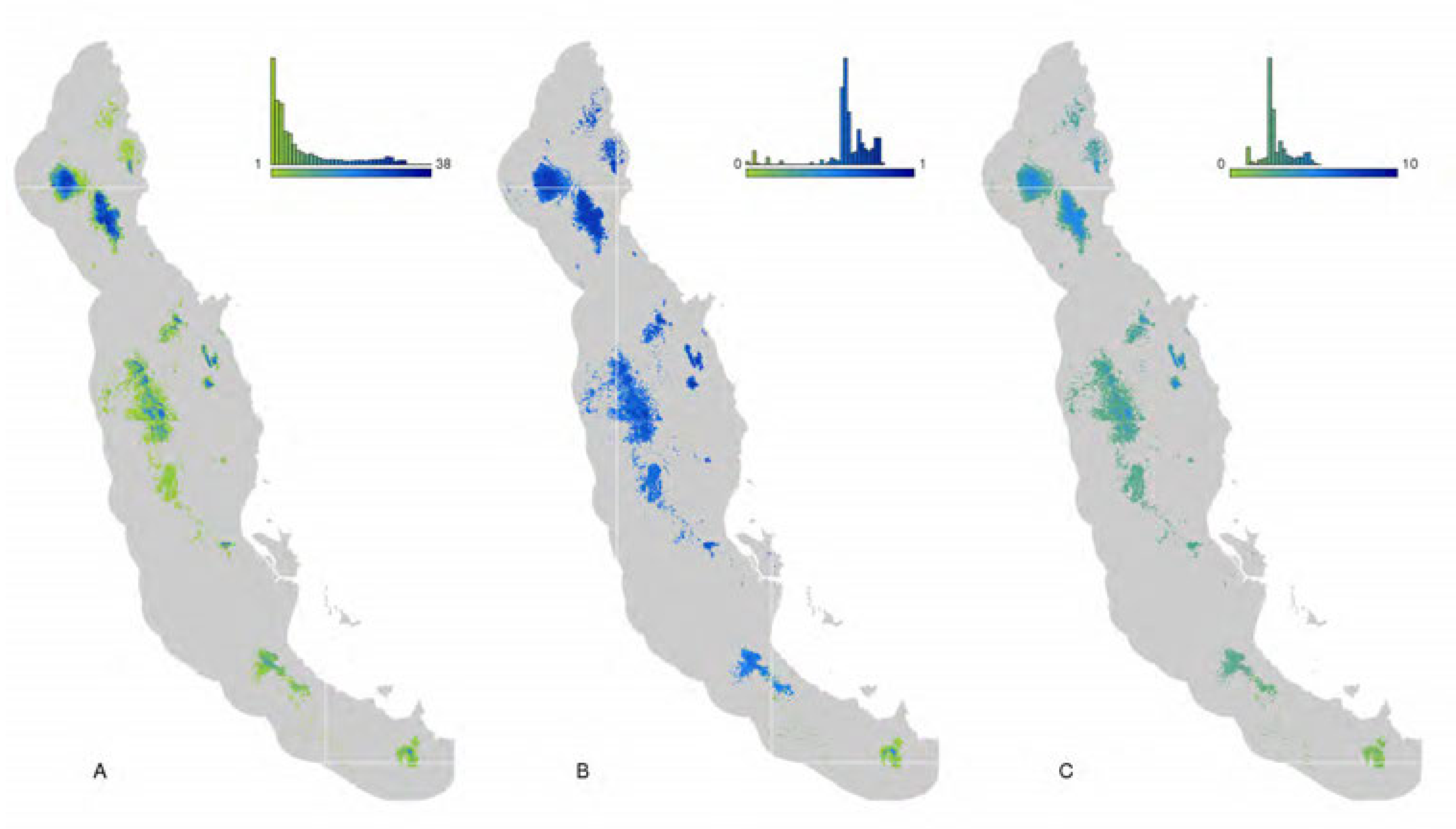

Figure 30. Current thermal refugia for the reptiles of the Wet Tropics (see details in text). A: areas with the number of species sheltered from exposure to extreme heat events [here species are 'sheltered' where, during an extreme heat event (as in figures 1-9a), individuals experience minimum microhabitat temperatures that are below the 5th percentile of those experienced concurrently by other individuals across the species' range; locations in blue have the *highest* number of sheltered species). B: areas with the mean resilience of sheltered species (locations in blue have the *lowest* mean in the local distribution of resilience values of sheltered species). C: areas that provide the most shelter to species currently vulnerable to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in blue have the *highest* number of sheltered species with the *lowest* mean resilience].

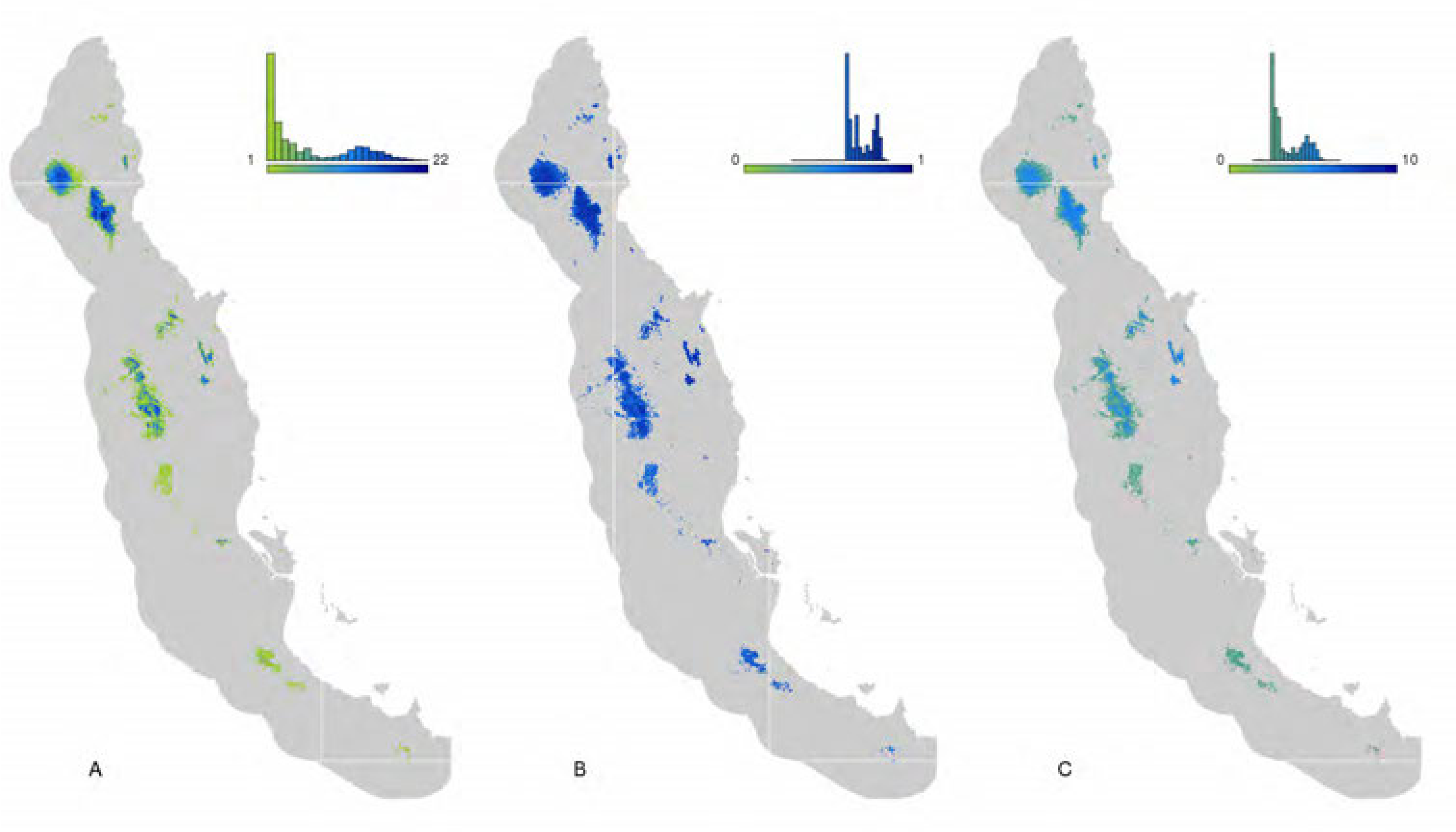

Figure 31. Current thermal refugia for the amphibians of the Wet Tropics (see details in text). A: areas with the number of species sheltered from exposure to extreme heat events [here species are 'sheltered' where, during an extreme heat event (as in figures 1-9a), individuals experience minimum microhabitat temperatures that are below the 5th percentile of those experienced concurrently by other individuals across the species' range; locations in blue have the *highest* number of sheltered species). B: areas with the mean resilience of sheltered species (locations in blue have the *lowest* mean in the local distribution of resilience values of sheltered species). C: areas that provide the most shelter to species currently vulnerable to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in blue have the *highest* number of sheltered species with the *lowest* mean resilience].

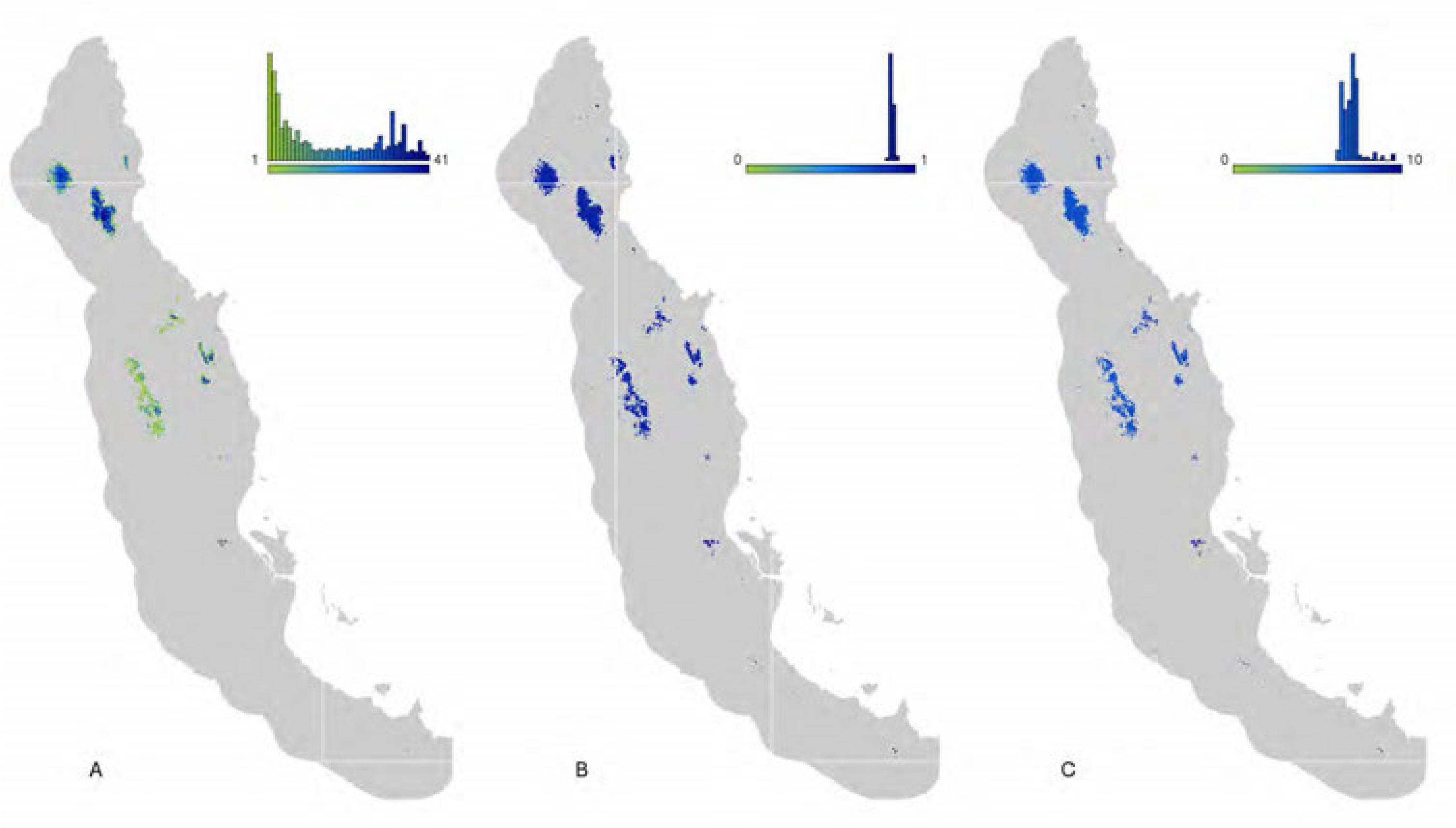

Figure 32. Current thermal refugia for the 25% least-resilient vertebrates of the Wet Tropics (see details in text). A: areas with the number of species sheltered from exposure to extreme heat events [here species are 'sheltered' where, during an extreme heat event (as in figures 1-9a), individuals experience minimum microhabitat temperatures that are below the 5th percentile of those experienced concurrently by other individuals across the species' range; locations in blue have the *highest* number of sheltered species). B: areas with the mean resilience of sheltered species (locations in blue have the *lowest* mean in the local distribution of resilience values of sheltered species). C: areas that provide the most shelter to species currently vulnerable to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in blue have the *highest* number of sheltered species with the *lowest* mean resilience].

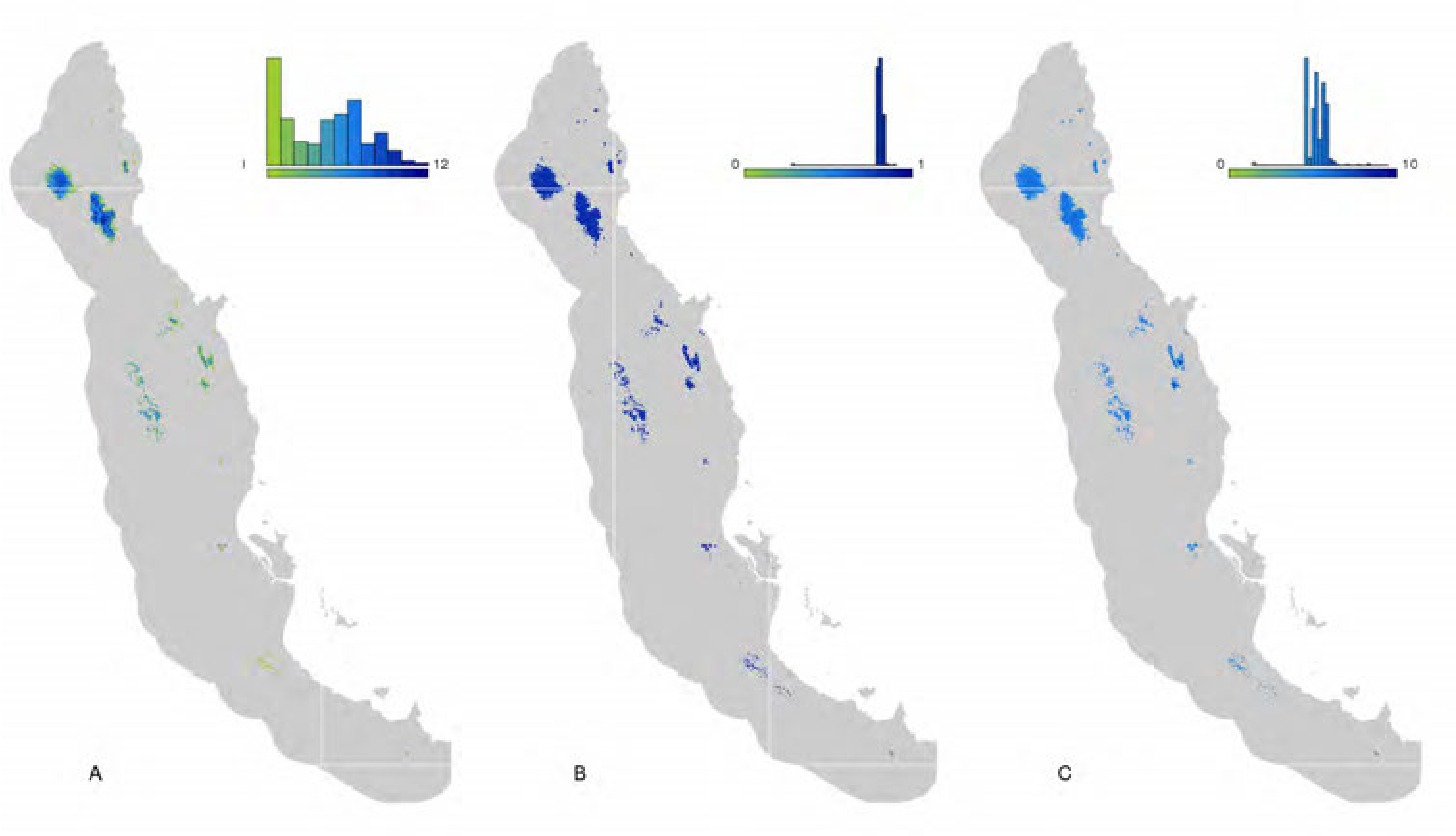

Figure 33. Current thermal refugia for the vertebrates Redlisted as 'Near Threatened' (NT) or worse of the Wet Tropics (see details in text). A: areas with the number of species sheltered from exposure to extreme heat events [here species are 'sheltered' where, during an extreme heat event (as in figures 1-9a), individuals experience minimum microhabitat temperatures that are below the 5th percentile of those experienced concurrently by other individuals across the species' range; locations in blue have the *highest* number of sheltered species). B: areas with the mean resilience of sheltered species (locations in blue have the *lowest* mean in the local distribution of resilience values of sheltered species). C: areas that provide the most shelter to species currently vulnerable to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in blue have the *highest* number of sheltered species with the *lowest* mean resilience].

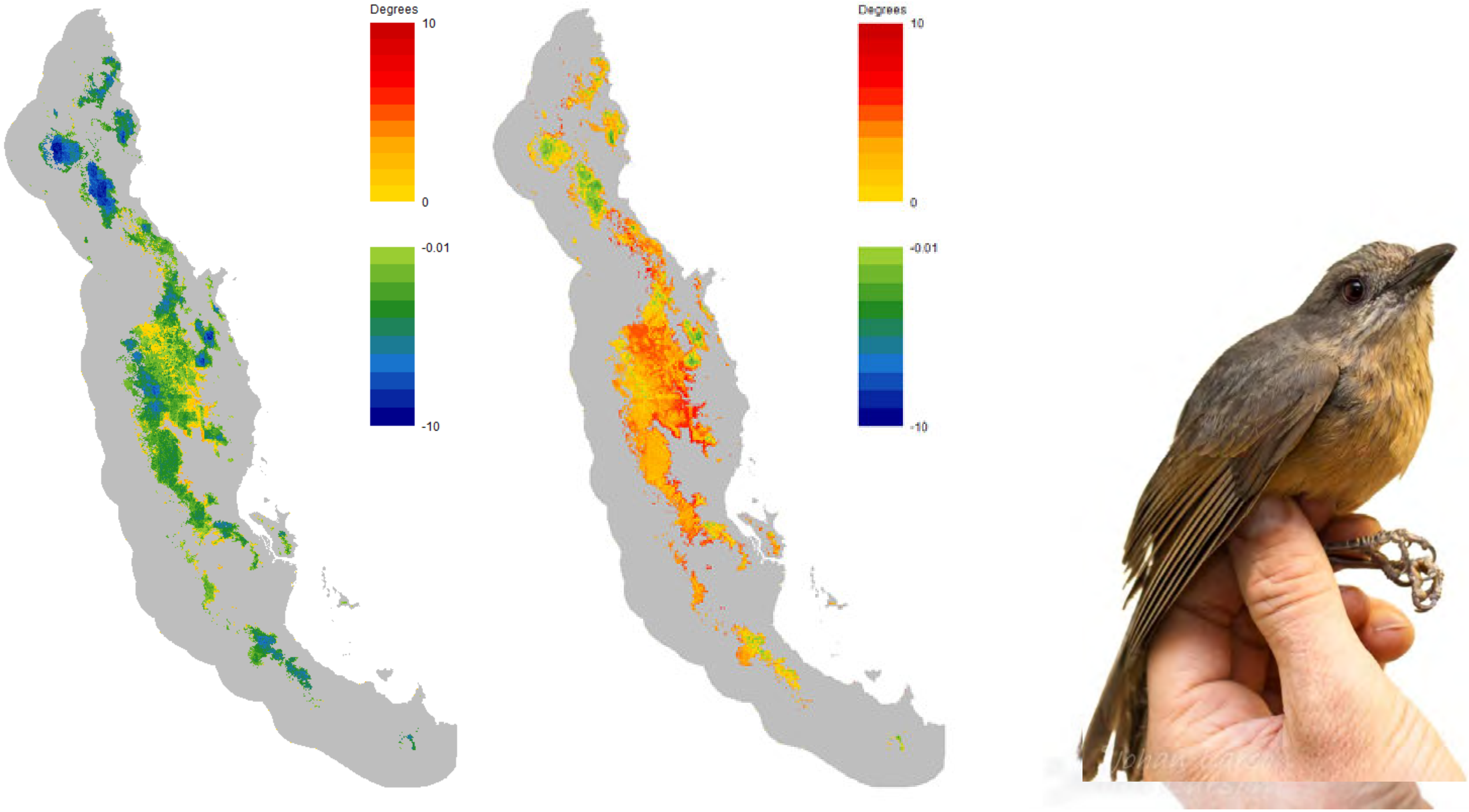

Figure 35. The current vulnerability of the Bowers shrike-thrush *Colluricincla boweri* to heat stress during a 95th percentile hottest day of the year and the hottest day of the year. Colours denote the maximum annual deviation (in °C) from the temperature threshold beyond which individuals are unable to maintain thermostasis in their coolest available microhabitat. Picture credit: Johan Larson

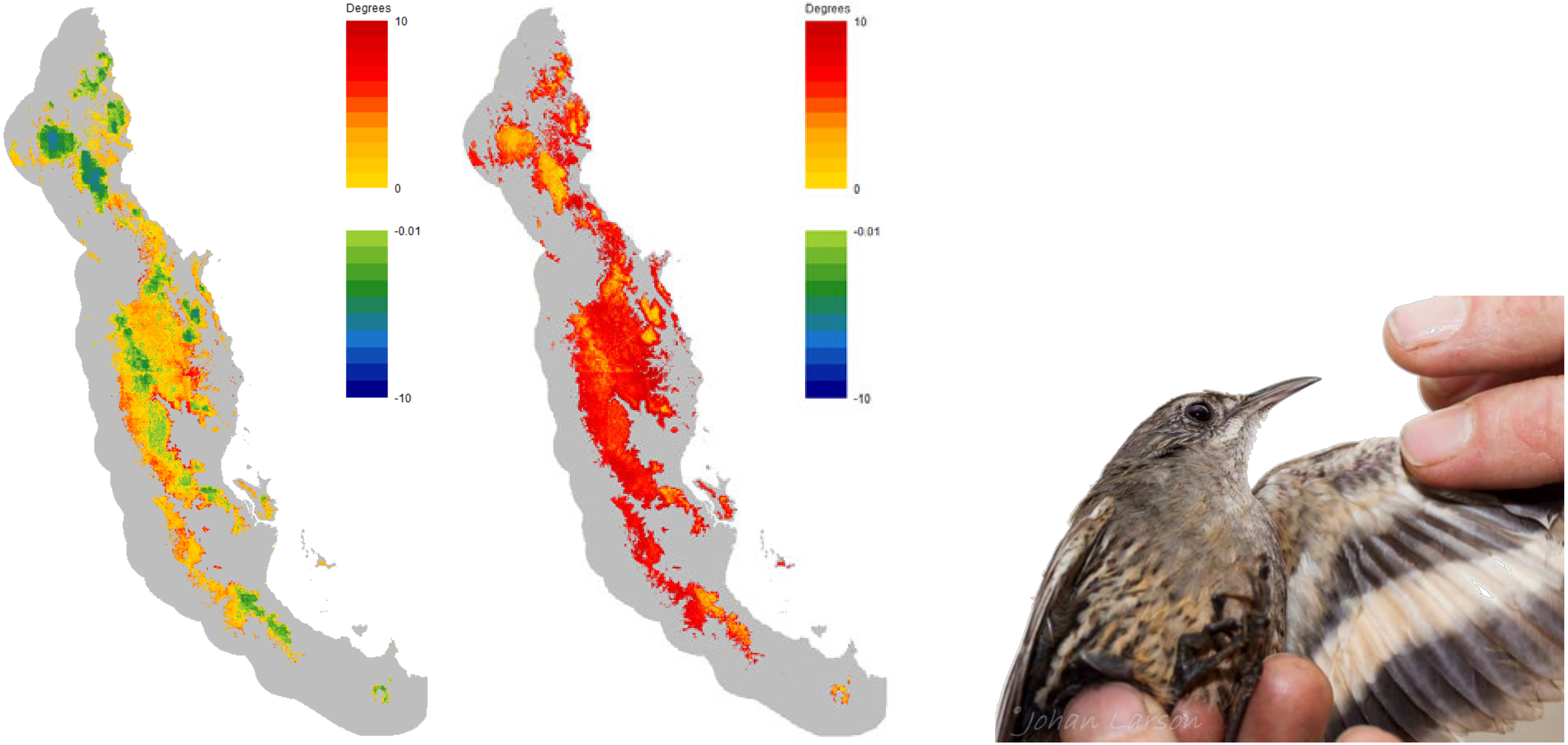

Figure 36. The current vulnerability of the White-throated treecreeper *Cormobates leucophaeus minor* to heat stress during a 95th percentile hottest day of the year and the hottest day of the year. Colours denote the maximum annual deviation (in °C) from the temperature threshold beyond which individuals are unable to maintain thermostasis in their coolest available microhabitat. Picture credit: Johan Larson

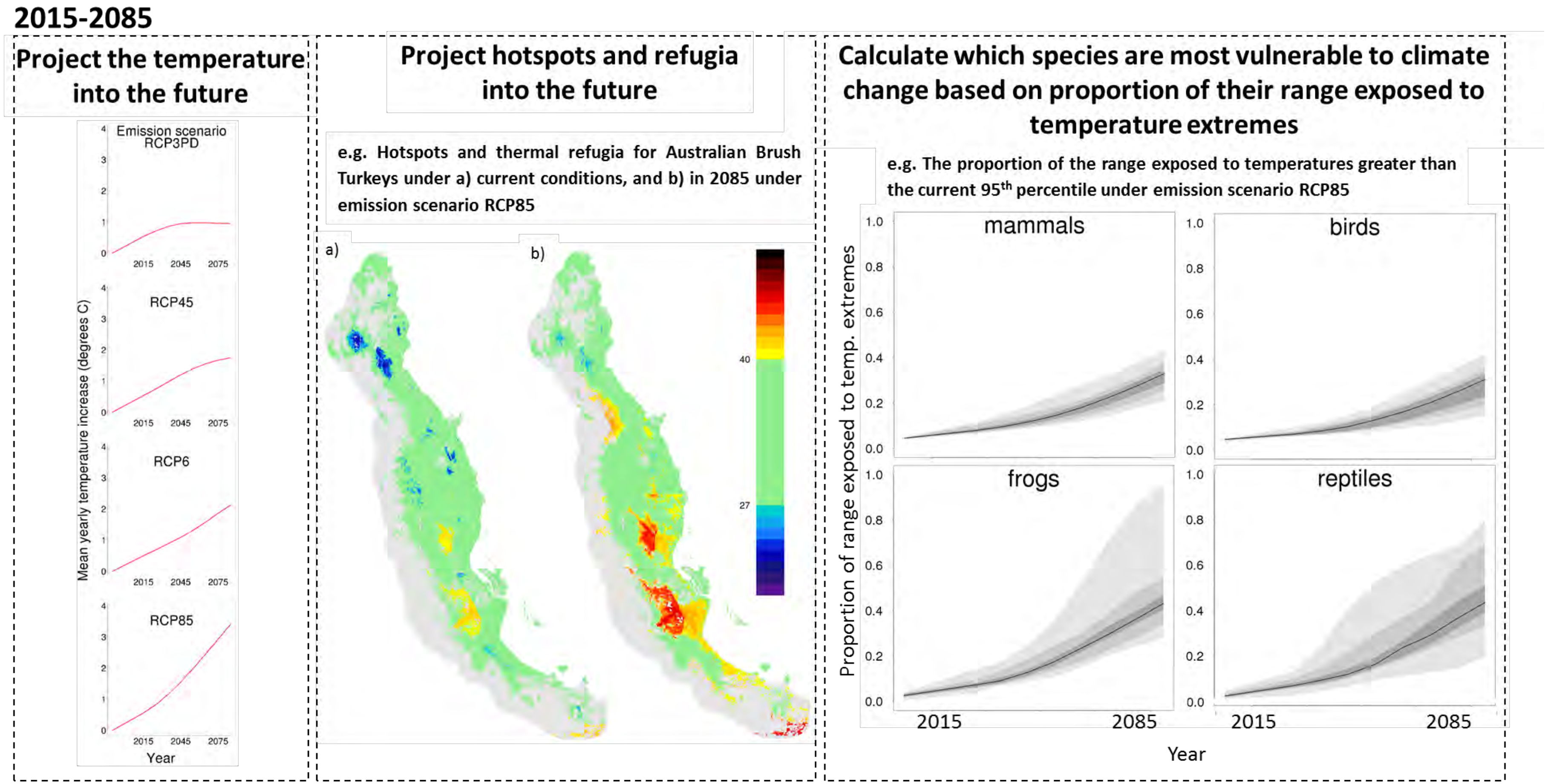

Figure 37. A graphic representation of our procedure for projecting our current species vulnerability estimates into the future, using the latest state-of-the-art temperature projections for the Wet Tropics bioregion (4 RCPs, 18 GCMs; 8 time steps between 2015 and 2085; 250m resolution; VanDerWal et al, unpublished)

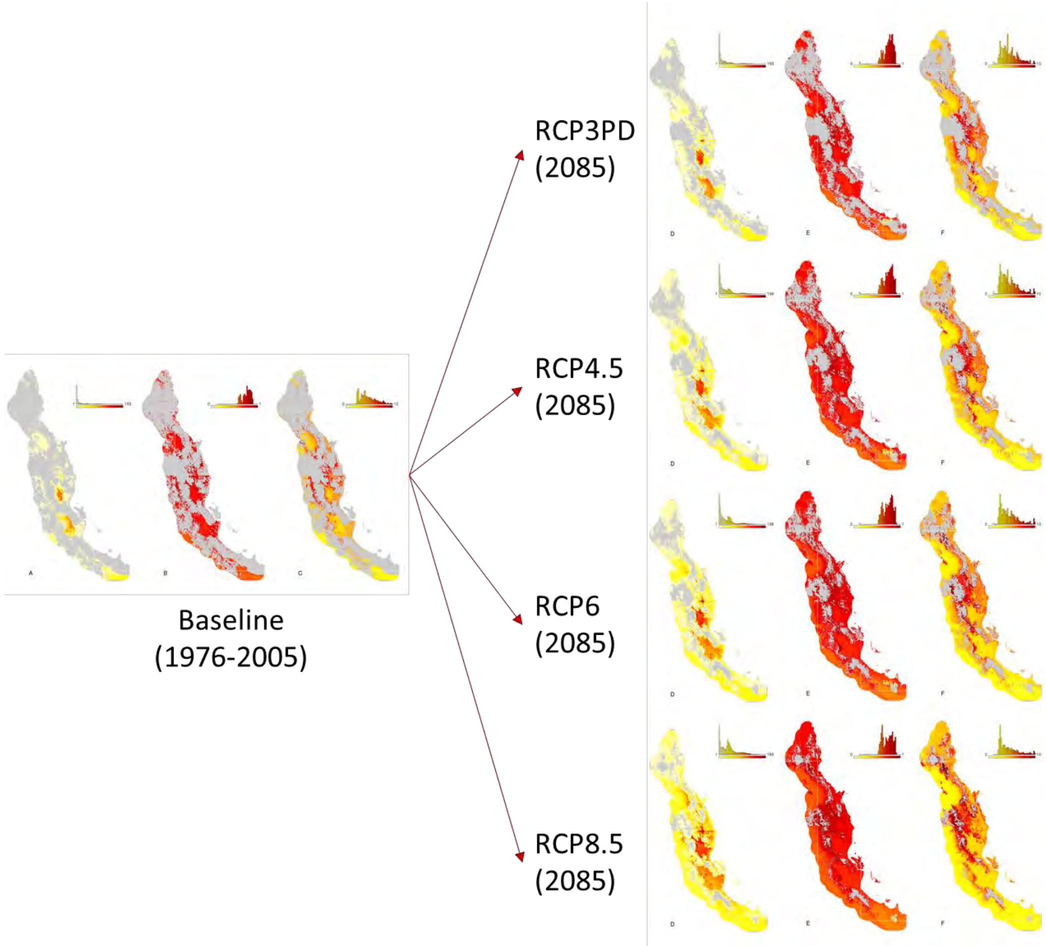

Figure 38. Future thermal hotspots for <u>all vertebrates</u> in 2085 under four different emission scenarios (details in text). A: areas with the number of species exposed to extreme heat events (here a species is 'exposed' when it experiences temperatures exceeding the 95th percentile of the 1950-present temperature distribution in its coolest microhabitat; locations in red have the *highest* number of exposed species). B: areas with the mean resilience of exposed species (locations in red have the *lowest* mean in the local distribution of resilience values of exposed species). C: areas with the current vulnerability of species to extreme heat events [i.e., current exposure (figure A) weighted by resilience (B) = A/(A*B); locations in red have the *highest* number of species with the *lowest* mean resilience]. [*Detailed animated GIFs showing the change in the thermal hotspots over time can be accessed through e-Atlas*]

Figure 39. Future thermal refugia for all vertebrates of the Wet Tropics (based on 4 emission scenarios (rows), and 8 time steps between 2015 and 2085 (columns). The 'thermal refugia' are the areas that will provide the greatest shelter to species vulnerable to extreme heat events in the future. The refugia are highlighted in blue and represent those areas that contain the *highest* number of sheltered species with the *lowest* mean resilience (here species are considered 'sheltered' when, during an extreme heat event (as in Fig 1), individuals experience minimum microhabitat temperatures that are below the 5th percentile of those experienced concurrently by other individuals across the species' range).
[*Detailed animated GIFs showing the change in the thermal refugia over time can be accessed through e-Atlas*]

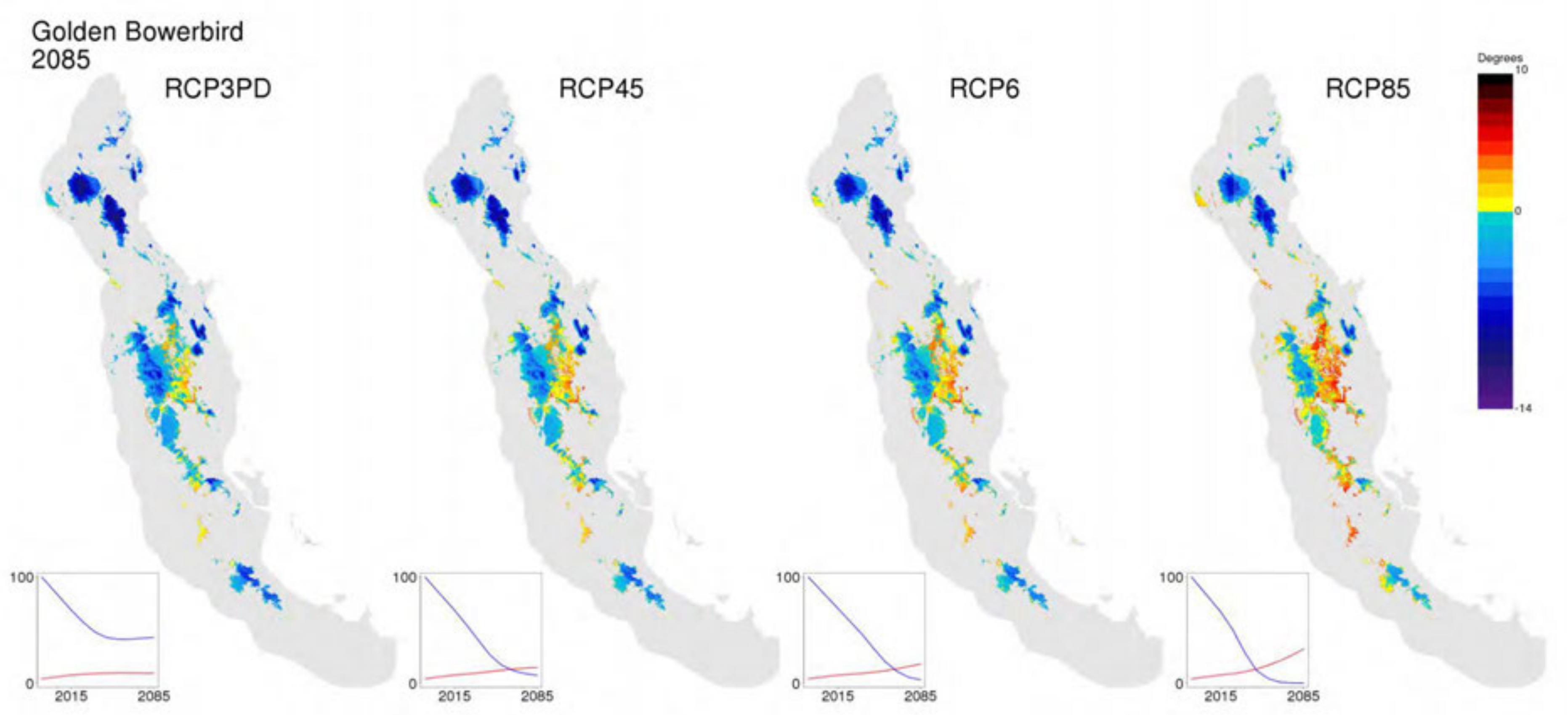

Figure 40. The projected future vulnerability of the golden bowerbird *Prionodura newtoniana* to heat stress in 2085 under four different emission scenarios. Colours denote the maximum annual deviation (in degrees °C) from the temperature threshold beyond which individuals are unable to maintain thermostasis in their coolest available microhabitat (i.e., >33.6 °C, as determined by our thermotolerance experiments). Each colour step represents 1 °C. Each smaller plot shows the proportional reduction in size of thermal refugia (blue line), and increase in size of thermal hotspots (red line) over time, for each emission scenario. [*Detailed animated GIFs showing the change in heat stress vulnerability over time can be accessed through e-Atlas*]

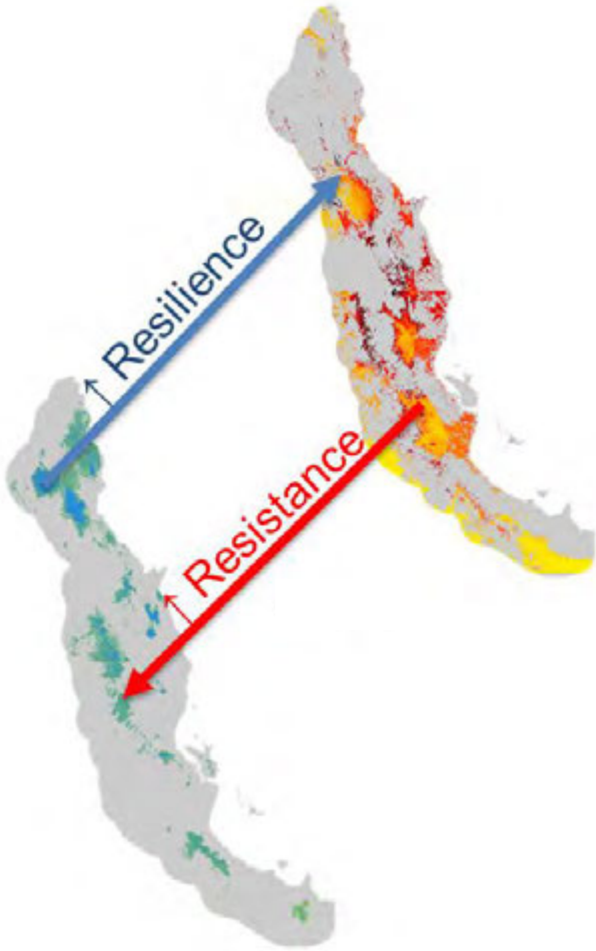

Figure 41. The areas identified are key to enhancing resilience and resistance of the Wet Tropics landscape. Thermal hotspots (a) should be foci for habitat restoration & enhancement; Thermal refugia (b) should be foci for habitat protection. Combined with promoting the connectivity between thermal hotspots and refugia, this will improve the resilience and resistance of wildlife populations to increasingly extreme temperature events.

Table 1. The top 20 *least* resilient species.

RANK	RESILIENCE INDEX	FAMILY	SPECIES	COMMON NAME	IUCN STATUS
1	0.000	Scincidae	*Techmarscincus jigurru*	Bartle Frere cool-skink	NL
2	0.001	Scincidae	*Eulamprus frerei*	Bartle Frere barsided skink	NL
3	0.009	Microhylidae	*Cophixalus neglectus*	Tangerine nursery-frog	EN B1ab(v)+2ab(v)
4	0.087	Pseudocheiridae	*Hemibelideus lemuroides*	Lemuroid ringtail possum	LR NT
5	0.091	Microhylidae	*Cophixalus monticola*	Mountain top nursery-frog	EN B1ab(v)+2ab(v)
6	0.100	Microhylidae	*Cophixalus hosmeri*	Pipping nursery-frog	VU D2
7	0.103	Scincidae	*Lampropholis robertsi*	Grey-bellied sunskink	NL
8	0.104	Phalangeridae	*Trichosurus vulpecula johnstonii*	Coppery brushtail possum	LR LC
9	0.105	Myobatrachidae	*Taudactylus rheophilus*	Northern tinkerfrog	CR A2ac; B2ab(v)
10	0.109	Dasyuridae	*Antechinus godmani*	Atherton antechinus	LR NT
11	0.111	Scincidae	*Saproscincus czechurai*	Saproscincus czechurai	NL
12	0.112	Dasyuridae	*Sminthopsis leucopus*	White-footed dunnart	DD
13	0.116	Scincidae	*Glaphyromorphus mjobergi*	Atherton Tableland mulch-skink	NL
14	0.120	Pseudocheiridae	*Pseudochirulus herbertensis*	Herbert river ringtail possum	LR NT
15	0.123	Acanthizidae	*Acanthiza katherina*	Mountain thornbill	LC
16	0.123	Muridae	*Uromys hadrourus*	Masked white-tailed rat	LR NT
17	0.125	Ptilonorhynchidae	*Prionodura newtoniana*	Golden bowerbird	LC
18	0.128	Ptilonorhynchidae	*Ptilonorhynchus violaceus*	Satin bowerbird	LC
19	0.128	Dasyuridae	*Dasyurus maculatus*	Spotted-tailed quoll	VU C1+2a
20	0.130	Acanthizidae	*Sericornis keri*	Atherton scrubwren	LC

Table 2. The top 20 species *least* 'behaviourally plastic' to an extreme heat event [Here an 'extreme heat event' is defined as a temperature >95th percentile found within the microhabitats of a species on a hot, 95th percentile day during the 1976-2005 baseline period].

RANK	BEHAVIOURAL PLASTICITY (at 95th percentile T)	FAMILY	SPECIES	COMMON NAME	IUCN STATUS
1	0.00	Casuariidae	*Casuarius casuarius*	Southern Cassowary	VU A2bcd
2	2.07	Microhylidae	*Cophixalus monticola*	Mountain Top Nursery-Frog	EN B1ab(v)+2ab(v)
3	2.40	Microhylidae	*Cophixalus concinnus*	Beautiful Nursery-Frog	CR B1ab(v)+2ab(v)
4	2.60	Pseudocheiridae	*Pseudochirulus cinereus*	Daintree River Ringtail Possum	LRNT
5	2.61	Scincidae	*Techmarscincus jigurru*	Bartle Frere cool-skink	NL
6	2.79	Scincidae	*Eulamprus frerei*	Bartle Frere barsided skink	NL
7	2.79	Microhylidae	*Cophixalus hosmeri*	Pipping Nursery-Frog	VU D2
8	2.92	Microhylidae	*Cophixalus aenigma*	Tapping Nursery-Frog	VU D2
9	2.95	Macropodidae	*Dendrolagus bennettianus*	Bennett's Tree-kangaroo	LRNT
10	2.97	Muridae	*Uromys hadrourus*	Masked White-tailed Rat	LRNT
11	3.04	Ptilonorhynchidae	*Prionodura newtoniana*	Golden Bowerbird	LC
12	3.05	Ptilonorhynchidae	*Ptilonorhynchus violaceus*	Satin Bowerbird	LC
13	3.09	Acanthizidae	*Acanthiza katherina*	Mountain Thornbill	LC
14	3.10	Cuculidae	*Cacomantis castaneiventris*	Chestnut-breasted Cuckoo	LC
15	3.11	Psittacidae	*Platycercus elegans*	Crimson Rosella	LC
16	3.11	Burryamyidae	*Cercartetus caudatus*	Long-tailed Pygmy Possum	LRLC
17	3.12	Dasyuridae	*Antechinus godmani*	Atherton Antechinus	LRNT
18	3.13	Pachycephalidae	*Colluricincla boweri*	Bowers Shrike-Thrush	LC
19	3.15	Acanthizidae	*Sericornis citreogularis*	Yellow-throated Scrubwren	LC
20	3.15	Dasyuridae	*Dasyurus maculatus*	Spotted-tailed Quoll	VU C1+2a

Table 3. The top 20 species *most* exposed to extreme temperature events by 2085 under the worst-case emission scenario RCP 8.5. [Here an 'extreme temperature event' is defined as a temperature >95th percentile found within the locally coolest microhabitat of a species on a hot, 95th percentile day during the 1976-2005 baseline period. During the baseline period the median value of this exposure is approximately 0.05].

RANK	PROPORTION OF RANGE EXPOSED	FAMILY	SPECIES	COMMON NAME	IUCN STATUS
1	0.952	Microhylidae	*Cophixalus monticola*	Mountain Top Nursery-Frog	EN B1ab(v)+2ab(v)
2	0.797	Gekkonidae	*Phyllurus amnicola*	Mt. Elliot Leaf-tail gecko	NL
3	0.793	Microhylidae	*Cophixalus concinnus*	Beautiful Nursery-Frog	CR B1ab(v)+2ab(v)
4	0.734	Scincidae	*Carlia rhomboidalis*	Blue-throated Rainbow-skink	NL
5	0.725	Scincidae	*Lampropholis mirabilis*	Saxicoline Sunskink	NL
6	0.718	Scincidae	*Glaphyromorphus clandestinus*	Mt Elliot skink	NL
7	0.711	Gekkonidae	*Phyllurus gulbaru*	Gulbaru Gecko	NL
8	0.679	Elapidae	*Furina tristis*	Brown-headed Snake	NL
9	0.562	Microhylidae	*Cophixalus aenigma*	Tapping Nursery-Frog	VU D2
10	0.551	Elapidae	*Vermicella annulata*	Bandy Bandy	NL
11	0.544	Scincidae	*Saproscincus lewisi*	Lewis' shadeskink	NL
12	0.543	Microhylidae	*Cophixalus mcdonaldi*	Southern Nursery-Frog	EN B1ab(v)+2ab(v)
13	0.538	Microhylidae	*Cophixalus exiguus*	Bloomfield Nursery-Frog	NT
14	0.527	Elapidae	*Furina ornata*	Orange-naped Snake	NL
15	0.526	Elapidae	*Demansia psammophis*	Yellow-faced Whipsnake	NL
16	0.524	Scincidae	*Lampropholis robertsi*	Grey-bellied sunskink	NL
17	0.519	Colubridae	*Tropidonophis mairii*	Keelback	NL
18	0.501	Gekkonidae	*Nactus cheverti*	Chevert's gecko	NL
19	0.499	Myobatrachidae	*Limnodynastes peronii*	Striped Marshfrog	LC
20	0.497	Scincidae	*Cyclodomorphus gerrardii*	Pink-tongued Lizard	NL

Table 4. The top 20 species *most* vulnerable to extreme temperature events by 2085 under worst-case emission scenario RCP 8.5 [here 'vulnerability' is defined as the proportion of range exposed (table 3) weighted by 'resilience' (table 1)].

RANK	VULNERABILITY VALUE	FAMILY	SPECIES	COMMON NAME	IUCN STATUS
1	466.44	Scincidae	*Techmarscincus jigurru*	Bartle Frere cool-skink	NL
2	97.93	Scincidae	*Eulamprus frerei*	Bartle Frere barsided skink	NL
3	32.37	Microhylidae	*Cophixalus neglectus*	Tangerine Nursery-Frog	EN B1ab(v)+2ab(v)
4	10.41	Microhylidae	*Cophixalus monticola*	Mountain Top Nursery-Frog	EN B1ab(v)+2ab(v)
5	5.07	Scincidae	*Lampropholis robertsi*	Grey-bellied sunskink	NL
6	4.05	Pseudocheiridae	*Hemibelideus lemuroides*	Lemuroid Ringtail Possum	LRNT
7	3.79	Myobatrachidae	*Taudactylus rheophilus*	Northern Tinkerfrog	CR A2ac; B2ab(v)
8	3.69	Phalangeridae	*Trichosurus vulpecula j.*	Coppery Brushtail Possum	LRLC
9	2.97	Dasyuridae	*Antechinus godmani*	Atherton Antechinus	LRNT
10	2.81	Microhylidae	*Cophixalus hosmeri*	Pipping Nursery-Frog	VU D2
11	2.73	Microhylidae	*Cophixalus concinnus*	Beautiful Nursery-Frog	CR B1ab(v)+2ab(v)
12	2.04	Scincidae	*Saproscincus czechurai*	Czechura's Litter Skink	NL
13	1.86	Scincidae	*Glaphyromorphus mjobergi*	Atherton Tableland mulch-skink	NL
14	1.51	Pseudocheiridae	*Pseudochirulus herbertensis*	Herbert River Ringtail Possum	LRNT
15	1.46	Gekkonidae	*Carphodactylus laevis*	Chameleon Gecko	NL
16	1.46	Scincidae	*Gnypetoscincus queenslandiae*	Prickly Forest Skink	NL
17	1.41	Muridae	*Uromys hadrourus*	Masked White-tailed Rat	LRNT
18	1.31	Acanthizidae	*Acanthiza katherina*	Mountain Thornbill	LC
19	1.28	Ptilonorhynchidae	*Prionodura newtoniana*	Golden Bowerbird	LC
20	1.26	Psittacidae	*Platycercus elegans*	Crimson Rosella	LC

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