

Climate warming and the rainforest birds of the Australian Wet Tropics: Using abundance data as a sensitive predictor of change in total population size

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Abstract

Global average surface temperatures have increased rapidly over the last 100 years and there is accumulating evidence that climate change is already causing shifts in species' distributions. We use extensive abundance data and expected range shifts across altitudinal gradients to predict changes in total population size of rainforest birds of Australian tropical rainforests in response to climate warming. According to our most conservative model scenario, 74% of rainforest birds of north-eastern Australia are predicted to become threatened (including 26 critically endangered species) as a result of projected mid-range warming expected within the next 100 years. Extinction risk varies according to where along the altitudinal gradient a species is currently most abundant. Upland birds are most affected and are likely to be immediately threatened by even small increases in temperature. In contrast, there is a capacity for the population size of lowland species to increase, at least in the short term. We conclude that abundance data collected across climatic gradients will be fundamental to gaining an understanding of population size change associated with climate warming.

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1. Introduction

Recent analyses suggest that climate warming is likely to be a major driver of biodiversity change in the future (Sala et al., 2000; Thomas et al., 2004) with increasing evidence that measurable impacts on species' traits may already be apparent (Hughes, 2000; Walther et al., 2002; Parmesan and Yohe, 2003; Root et al., 2003). Documented shifts in species' distributions along climatic gradients (e.g. Parmesan et al., 1999; Thomas and Lennon, 1999; Hill et al., 2002; Konvicka et al.,

2003; Brommer, 2004; Hickling et al., 2005) have contributed to evidence for a biological response to contemporary climate change. Estimates of extinction risk following range shifts have largely been derived from modelled projections of "climatic envelopes" where risk has been inferred from predicted change in the relative size of species' distributions under future climate change (for a recent review see Pearson and Dawson, 2003). Such models suggest that large numbers of species will potentially experience dramatic decreases in distribution area under predicted climate change scenarios (e.g. Williams et al., 2003; Hilbert et al., 2004; Thomas et al., 2004). Quantitative estimates of change in population size during range contraction or expansion, however, have been prevented by a lack of data on the spatially

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variable patterns of abundance within a species' range. This is despite assertions that population size and trend are the best correlates of extinction risk (O'Grady et al., 2004) and the wide application of these measures in determining the conservation status of species (e.g. IUCN, 2001 criteria). It is imperative that we now go beyond broad distribution modelling and consider the implications of abundance patterns on predicting climate change impacts to population size.

The rainforest vertebrate fauna of the Wet Tropics region of north-eastern Australia provides a unique opportunity to address this deficiency. Rugged topography imposes a high degree of turnover in temperature conditions across a discrete, relatively small area of rainforest (ca. 10 000 km²). The altitudinal gradient dominates the historical biogeography of the region (Nix and Switzer, 1991; Williams et al., 1996) and predictions from climate envelope models suggest widespread displacement of species' distributions along the altitudinal gradient as a result of future climate warming (Williams et al., 2003; Hilbert et al., 2004). Finally, altitudinal variation in abundance has already been documented for a number of rainforest species within the region (Trenerry, 1993; Kanowski et al., 2001; Shoo and Williams, 2004).

Here we draw upon extensive data describing the altitudinal abundance pattern of 55 rainforest birds (including 12 regional endemics) and demonstrate the potential for such data to be used to quantify change in population size of species as a consequence of climate warming. Specifically, we use expected upslope shifts in species' distributions with increasing temperature and empirical altitude-abundance patterns to predict change in the relative population size of species under a range of probable future climates. This is a novel analysis that extends projections of species responses to climate change to the population level, enabling us to make explicit predictions about the changes to total population size, a key criteria in estimating IUCN conservation status.

2. Methods

2.1. Predicted shifts in distribution

Rainforest predominantly occurs across windward slopes in the Wet Tropics of north-eastern Australia where we would expect temperature to decrease at the saturated adiabatic lapse rate of about 1 °C per 200 m altitude under most conditions. Established lapse rates are supported by field measurements collated from 21 weather stations distributed across the Wet Tropics region (Commonwealth Bureau of Meteorology). A 1 °C decline in temperature corresponds to an upward shift in altitude of between 142 and 250 m, based on minimum and maximum temperatures respectively (mean monthly maximum temperature = -0.004 meters

altitude + 28.587, $r^2 = 0.562$, $p < 0.001$; mean monthly minimum temperature = -0.007 m altitude + 20.152, $r^2 = 0.807$, $p < 0.001$). The magnitude of change in temperature from field measurements is essentially equivalent to that expected following a saturated adiabatic lapse rate.

2.2. Abundance estimates

Abundance data for rainforest bird fauna were collated from standardized field surveys throughout the region (723 surveys at 362 separate locations, years 1996–2003). Each survey consisted of a 30 min, 150 m transect through rainforest using both visual observations and calls to identify species. Surveys were conducted between 0600 and 0830 h to coincide with peak calling activity and only carried out on clear mornings under low wind conditions where detection probability was high, thereby allowing best possible estimates of abundance to be made. Five major mountain ranges and associated lowlands were sampled covering much of the latitudinal range within the region (S16°15'–S19°00' including the Spec Uplands, Kirrama Uplands, Atherton Uplands, Bellenden-Ker/Bartle-Frere Range, Carbine Uplands and Cairns-Cardwell and Mossman Lowlands (see Williams et al., 1996 for subregional boundaries).

2.3. Population size change

An index of total population size was derived by multiplying the mean abundance of a species across survey transects located within each 100 m altitudinal interval by the total available area of rainforest (km²) within corresponding altitudinal intervals and summing values across the entire gradient. Rainforest area was determined for 100 m altitudinal intervals from a Geographic Information System (GIS) using regional vegetation mapping based on Tracey and Webb (1975) and subsequently updated by the Wet Tropics Management Authority and an 80 m resolution digital elevation model. The altitudinal range and estimates of mean abundance at altitudinal intervals within the range were then shifted upward by increments of 100 m to simulate successive increases of 0.5 °C in temperature (e.g. Grey-headed Robin, Fig. 1). The index of population size was then recalculated for scenarios ranging from 0 m shift (current, assuming no temperature increase) to 1400 m shift (i.e. +7 °C). In doing so, we assume that: (1) species will respond to increasing temperature by shifting along the altitudinal gradient; and (2) the integrity of the altitudinal abundance pattern will be retained as a species shifts along the altitudinal gradient. Change in the index of total population size was presented as a proportion relative to the current scenario estimate (i.e. 0 m shift) for each species.

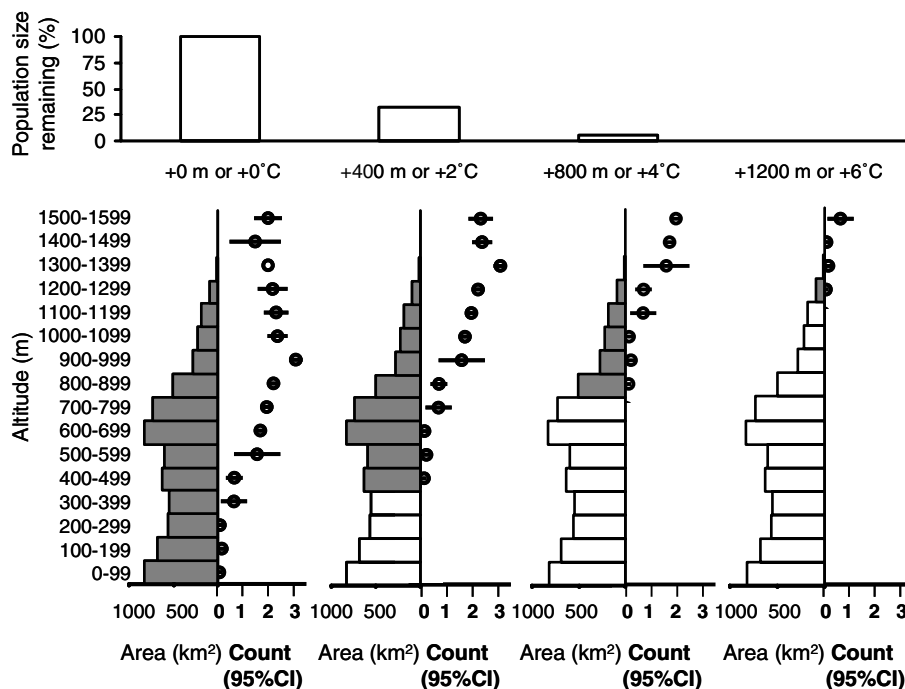


Fig. 1. Diagrammatic representation of Scenario 1 altitudinal shifts in the abundance pattern of the upland Grey-headed Robin (*Heteromyias albispecularis*) with increasing temperature against a breakdown of available rainforest area across the altitudinal gradient. 0.5°C equates to approximately 100 m upward shift in altitude associated with climate warming. We assume that a species is incapable of occupying newly created climatic habitat such that the abundance pattern does not extend beyond the currently observed distribution (Scenario 1). Shaded bars highlight the altitudinal range of rainforest habitat predicted to be occupied with consecutive increases in temperature. Abundance estimates were multiplied by the corresponding area of rainforest at each altitude and summed across the gradient to provide an index of current population size. Altitude-abundance pattern is the mean count of individuals per 150 m survey transect with bars representing 95% confidence intervals of the mean.

The estimate of available rainforest area within each 100 m altitudinal interval represents the combined available area summed across multiple disjunct mountain ranges. Within the Wet Tropics region, individual species of the rainforest bird fauna are widespread among rainforest isolates (Williams et al., 1996). With the possible exception of the Atherton Scrubwren (*Sericornis keri*), that is absent from the southern ranges of the Spec and Halifax Uplands, no species are known to exhibit localised, patchy distributions or significant distribution gaps on a broad scale that would render the use of a combined area estimate unreasonable. It is expected, however, that the same considerations are unlikely to apply to all taxa and regions and that finer resolution, subregional estimates of available habitat area may be necessary in some applications of the method.

Under climate warming, environmental space currently not available in the region will be created at the lowest altitudes. While it is likely that lowland species will take advantage of the additional climatic habitat, no equivalent environmental space is currently available in the region to measure the response of species. In the absence of quantitative information we examine two potential scenarios. That is, that either: a species is incapable of occupying newly created climatic habitat such

that the abundance pattern does not extend beyond the currently observed distribution (Scenario 1); or, that a species is capable of occupying newly created habitat beyond its currently observed distribution (Scenario 2). Assuming that the current distribution represents the full range of climates within the physiological tolerance of a species (Scenario 1), and not just an artefact of a physical barrier, is likely to portray a pessimistic view of the response of lowland species to climatic habitat to which no current analogue exists. Similarly, assuming that abundance continues to increase indefinitely in response to newly created climatic space is likely to be overly optimistic. In the absence of better information, for model Scenario 2 an abundance pattern symmetrically distributed about the abundance maxima was adopted as an intermediate scenario to infer abundance of lowland species (i.e. abundance maxima <800 m altitude) in newly created climatic habitat (e.g. Graceful Honeyeater, Fig. 2).

Seventy six species of birds effectively confined to rainforest in the region were recorded during surveys. For the purpose of analysis, we excluded 15 species that were recorded on fewer than 30 surveys as the level of sampling was considered to be insufficient to establish a meaningful estimate of the altitude-abundance pattern

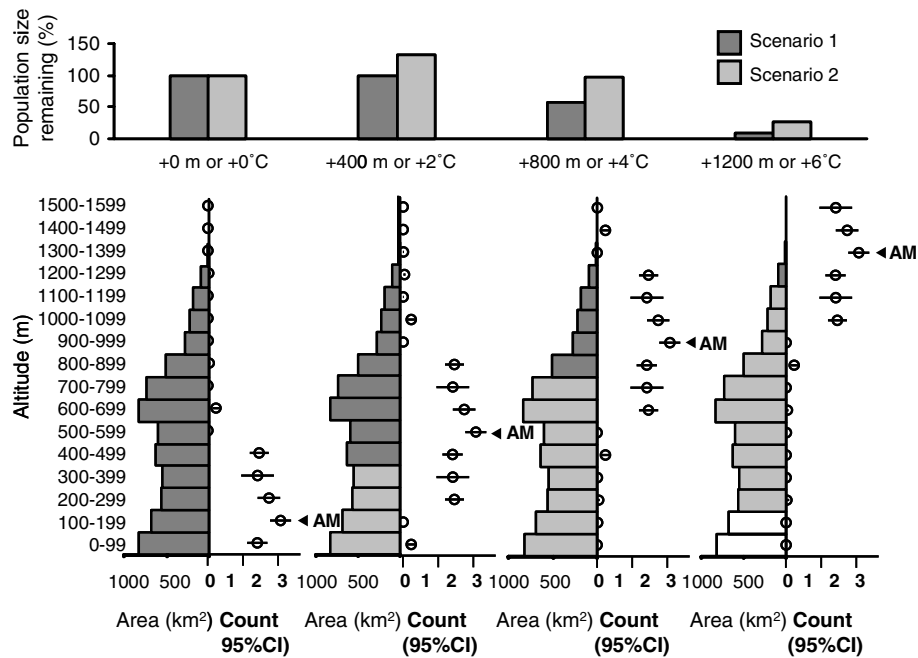


Fig. 2. Diagrammatic representation of Scenario 2 altitudinal shifts in the abundance pattern of the lowland Graceful Honeyeater (*Meliphaga gracilis*) with increasing temperature against a breakdown of available rainforest area across the altitudinal gradient. $0.5\text{ }^{\circ}\text{C}$ equates to approximately 100 m upward shift in altitude associated with climate warming. An abundance pattern symmetrically distributed about the abundance maxima was adopted to infer abundance of the species in newly created climatic habitat at low altitude (Scenario 2). The altitudinal range of rainforest habitat predicted to be occupied under Scenario 1 (dark shaded bars) is less than that occupied under Scenario 2 (dark and light shaded bars combined) where allowance has been made for the potential colonisation of newly created habitat with consecutive increases in temperature. Abundance estimates were multiplied by the corresponding area of rainforest at each altitude and summed across the gradient to provide an index of current population size. Projected change in population size arising from Scenario 2 is compared to that where no occupation of newly created climatic habitat was inferred (Scenario 1). Altitude-abundance pattern is the mean count of individuals per 150 m survey transect with bars representing 95% confidence intervals of the mean.

for these species. To allow a direct comparison of results from both model scenarios we only present data for 55 of the remaining 61 species for which a symmetric abundance pattern could be inferred. That is, those species that displayed an identifiable peak in abundance along the altitudinal gradient (i.e. abundance maxima) that could be used as an inflection point for a symmetric abundance pattern.

2.4. Extinction risk

Species were allocated to extinction risk categories within the region according to their projected decline in population size in response to increasing temperature. Species were classified as either “Extinct” (100% decline), “Critically Endangered” ($\geq 80\%$ decline), “Endangered” ($\geq 50\%$ decline), “Vulnerable” ($\geq 30\%$ decline) or “Not Threatened” (all other remaining species). Extinction risk thresholds were consistent with IUCN Red List Categories and Criteria (Criterion A; IUCN, 2001) utilising the maximum 100 year timescale to allow for chronic population declines attributable to climate change. Three temperature projections for the year 2100 were discussed recognising the uncertainty in

future projections of global climate warming (Cubasch et al., 2001). These were “maximum” ($+5.8\text{ }^{\circ}\text{C}$), “mid-range” ($+3.6\text{ }^{\circ}\text{C}$) and “minimum” ($+1.4\text{ }^{\circ}\text{C}$) scenarios relative to the year 1990. Projections for coastal north-eastern Queensland (Walsh et al., 2002) are essentially equivalent to those produced from global models (Cubasch et al., 2001) with approximately one degree of regional warming predicted per degree of global warming.

3. Results

As climate warming proceeds, many of the climate types that support species at high density are expected to shift off extensive areas of rainforest at low and middle altitudes onto limited areas of rainforest distributed across mountaintops within the region (e.g. Grey-headed Robin, Fig. 1). At the same time, there is a potential for lowland species to expand into new climatic habitat created at the lowest altitudes (e.g. Graceful Honeyeater, Scenario 2, Fig. 2).

We estimated future extinction risk in response to three projections of climate change (and range shifts of

corresponding magnitude) for the year 2100 (Cubasch et al., 2001) using two model scenarios (Table 1, Fig. 3). For our most conservative model scenario (i.e. assuming occupancy of new climates at low altitudes, Scenario 2), under maximum climate change projections (i.e. +5.8 °C) we estimate that 55 (100%) species of rainforest birds will become threatened with 31 (56.4%) species critically endangered and 7 (12.7%) species extinctions. Less severe climate projections (i.e. +1.4–3.6 °C) also suggest high levels of threatened species but no extinctions. For the mid-range projections (i.e. +3.6 °C), 41 (74.5%) species are expected to become threatened with 26 (47.3%) species reaching critically endangered status. For the minimum projection (i.e. +1.4 °C), 29 (52.7%) species are expected to become threatened with 4 (7.3%) species critically endangered. Under the assumption of no occupation of newly created climatic habitat for lowland species (Scenario 1), more species are expected to be listed as threatened following minimum and mid-range climate projections and species are predicted to progress more rapidly through the hierarchy of threat status with increasing temperature (Table 1). Regardless, all 55 species are expected to become threatened under both model scenarios using the maximum (i.e. +5.8 °C) climate projection.

Projected extinction risk varied according to where along the altitudinal gradient a species was most abundant (i.e. position of abundance maxima). We find that the population size of upland species declines rapidly with even a small increase in temperature (Fig. 4a,b). This response corresponds to the strong decrease in available rainforest area at high altitude (Fig. 1). In contrast, lowland species experience lower levels of threat as population size declines more slowly with increasing temperature. Further, decline in population size for lowland species may be buffered, or even countered in the short term, through the colonization of newly created habitat at the lowest altitudes (Scenario 2, Fig. 4b).

Table 1

Accumulated number of rainforest bird species expected to qualify for threatened status within the region as a consequence of decline in population size with increasing temperature

Threat category	Model Scenario 1						Model Scenario 2					
	Min (+1.4 °C)		Mid (+3.6 °C)		Max (+5.8 °C)		Min (+1.4 °C)		Mid (+3.6 °C)		Max (+5.8 °C)	
	No.	(%)	No.	(%)	No.	(%)	No.	(%)	No.	(%)	No.	(%)
Not threatened (<30% decline)	19	(34.5)	1	(1.8)	0	(0)	26	(47.3)	14	(25.5)	0	(0)
Vulnerable (≥ 30% decline)	15	(27.3)	5	(9.1)	0	(0)	9	(16.4)	4	(7.3)	3	(5.5)
Endangered (≥ 50% decline)	17	(30.9)	16	(29.1)	0	(0)	16	(29.1)	11	(20.0)	14	(25.5)
Critically endangered (≥ 80% decline)	4	(7.3)	33	(60.0)	47	(85.5)	4	(7.3)	26	(47.3)	31	(56.4)
Extinct (100% decline)	0	(0)	0	(0)	8	(14.5)	0	(0)	0	(0)	7	(12.7)
Total threatened	36	(65.5)	54	(98.2)	55	(100)	29	(52.7)	41	(74.5)	55	(100)

Thresholds of population decline follow IUCN Red List Categories and Criteria (Criterion A, IUCN, 2001). Results from two alternative model scenarios are shown: (a) no occupation of newly created climatic habitat at low altitudes was inferred (Scenario 1, $n = 55$ species); or (b), an abundance pattern symmetrically distributed about the abundance maxima was adopted to infer abundance of the species in newly created climatic habitat (Scenario 2, $n = 55$ species).

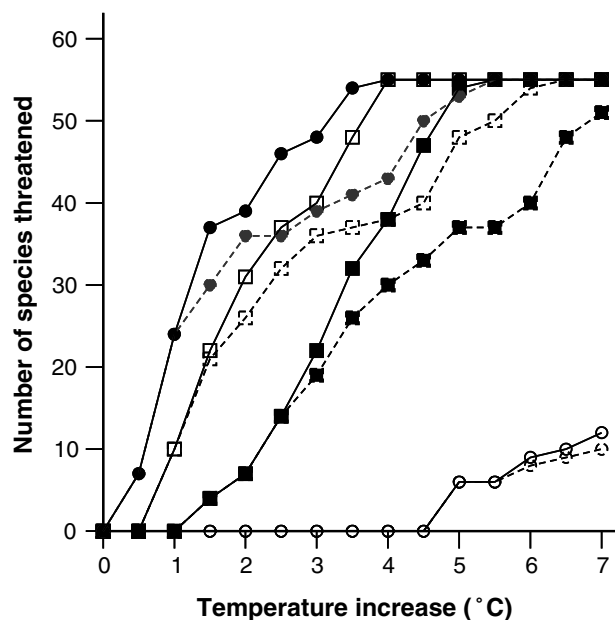


Fig. 3. Accumulated number of rainforest bird species expected to qualify for threatened status as a consequence of decline in population size with increasing temperature. Thresholds of population decline follow IUCN Red List Categories and Criteria (Criterion A, IUCN, 2001) and correspond to the following threat categories: Vulnerable (filled circles), Endangered (open squares), Critically Endangered (filled squares) and Extinct (open circles). Results from two alternative model scenarios are shown: (a) no occupation of newly created climatic habitat at low altitudes was inferred (Scenario 1, solid lines, $n = 55$ species); or (b), an abundance pattern symmetrically distributed about the abundance maxima was adopted to infer abundance of the species in newly created climatic habitat (Scenario 2, broken lines, $n = 55$ species).

4. Discussion and conclusions

4.1. Climate change impacts on population size

The approach presented here represents a significant advance on previous attempts to estimate extinction risk from climate change that have employed modeled

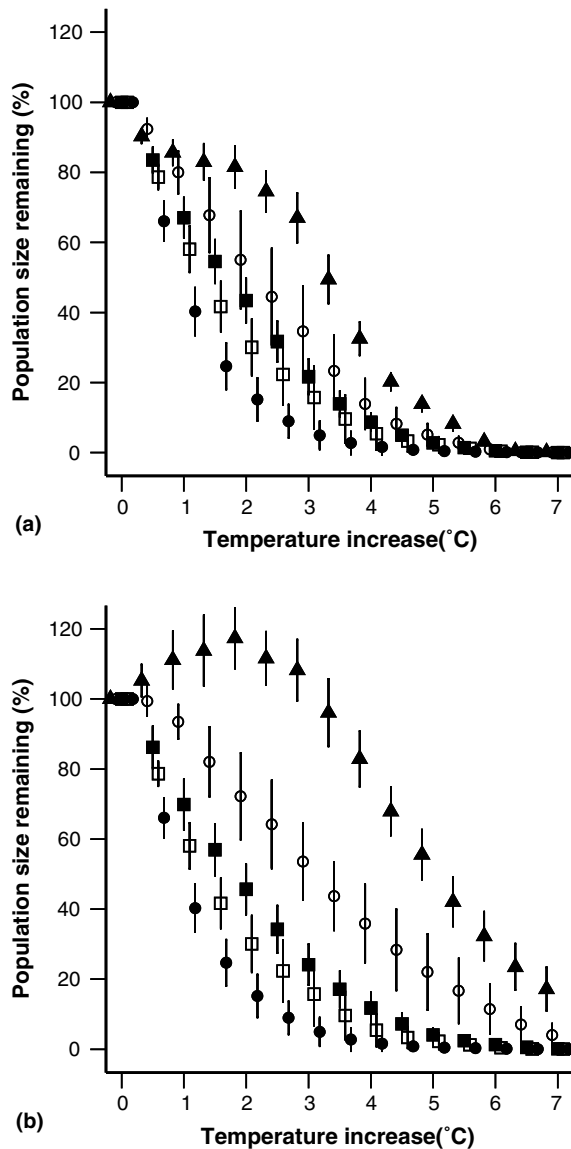


Fig. 4. Across-species mean decline in population size of rainforest birds within the region with increasing temperature under two alternative model scenarios: (a) no occupation of newly created climatic habitat at low altitudes was inferred (Scenario 1, $n = 55$ species); or (b), an abundance pattern symmetrically distributed about the abundance maxima was adopted to infer abundance of the species in newly created climatic habitat (Scenario 2, $n = 55$ species). Population size is expressed as a percentage of current population size. Species were classified into altitudinal groups based on the altitudinal position of their abundance maxima: 0–299 m (filled triangles, $n = 12$); 300–599 m (open circles, $n = 12$); 600–899 m (filled squares, $n = 15$); 900–1199 m (open squares, $n = 6$); 1200–1499 m (filled circles, $n = 10$). Data points were staggered to reveal overlapping values. Bars represent 95% confidence intervals of the mean.

projections of climatic envelopes to predict the relative size of species' distributions under climate change (Williams et al., 2003; Hilbert et al., 2004; Thomas et al., 2004). Although the qualitative results are similar and suggest that climate change is a major threatening process for rainforest birds of the north-eastern Australia,

they provide quantitative estimates of the impact on the most important conservation threat index, population size (O'Grady et al., 2004). We conclude that montane fauna of the region is likely to be immediately threatened by projected warming with dramatic crashes in population size predicted with even small amounts of warming.

The projected pattern of change in population size broadly approximates that of range reductions and loss of core environment area predicted by Williams et al. (2003) and Hilbert et al. (2004). Some noticeable discrepancies, however, exist between the predictions and require explanation. Most notably, we report higher variability among species in the trajectory of change with increasing temperature and we report considerably lower extinction rates.

First, previous analyses were confined to endemic vertebrates that are predominantly restricted to cool upland environments (Nix and Switzer, 1991). As we have seen, species restricted to such environments are likely to be disproportionately threatened by climate change. The inclusion of lowland species in our analyses, then, reduces the mean level of threat and inflates the variability among species in population size remaining. Second, unlike the previous multi-species study (Williams et al., 2003), our analysis was confined to birds, a subset of the rainforest vertebrate fauna. In relative terms as a group, birds are under-represented among the extreme geographically restricted vertebrate fauna of the region. This is reflected in the relatively low proportion of endemic birds predicted to lose greater than 50% of their current area of core environment with only 1 °C increase in temperature (Hilbert and Williams, 2003). Third, variability among species in population size change is increased when allowances are made for the colonization of newly created climates under climate change. Previous models have been confined to the projection of climate envelopes whose extent has been delineated by climates available under present conditions only. Finally, the present analysis was based on a temperature response alone and the findings are likely to be conservative where impacts associated with distribution shifts are compounded by other limiting factors such as rainfall.

Predicted range shifts in relation to a changing climate imply that temperature is the primary, overriding mechanism currently limiting the abundance and distribution of species. The capacity for physical change in climate to alter species' distributions and result in localized extinctions is evidenced by numerous studies documenting range shifts of species along climatic gradients in association with contemporary climate warming (Parmesan et al., 1999; Thomas and Lennon, 1999; Hill et al., 2002; Konvicka et al., 2003; Brommer, 2004; Hickling et al., 2005; but see also Archaux, 2004). The literature suggests a pervasive climate related response

with broad congruence in change observed across a diverse taxonomic and ecological range of species. Within the Wet Tropics, impacts of historical climate change are supported by molecular data (Joseph et al., 1995; Schneider et al., 1998; Hugall et al., 2002). Paleodistribution models that predict the location and size of refugia and patterns of extinction and colonization of species as a function of historical climate provide the most parsimonious explanation for current observed patterns of molecular phylogeography. We recognize, however, that other physical factors, disturbance and interactions with other species (Brown and Lomolino, 1998) may also limit the distribution of species. Each of these mechanisms along with evolutionary adaptation (Harte et al., 2004) has the potential to alter the predicted impacts of climate warming on species survival.

4.2. *Limitations of predictive models*

Species interactions, specifically competition, have previously been implicated in limiting the abundance and distribution of species along altitudinal gradients (Diamond, 1973; Remsen and Graves, 1995; Brown and Lomolino, 1998). While case studies suggest that interspecific competition governs the distribution of some species, the pervasiveness of this mechanism is unknown. Terborgh and Weske (1975) provided the only quantitative support for widespread influence of interspecific competition in this context although criticisms of the data set and interpretations suggest that the issue remains unresolved (Graves, 1985; Weins, 1989; Remsen and Graves, 1995).

Although we cannot rule out the possible influence of interspecific competition, it is important to recognize that the mechanism itself does not preclude a response to increasing temperature. If, as Diamond (1973) proposed, altitudinal replacement is governed by underlying, differential adaptations of species to physical conditions that are themselves continuous functions of altitude, it is reasonable to expect that competitive interactions will not prevent but rather be carried through range shifts invoked by increasing temperature. As one species preferentially adapted to cooler temperatures shifts to higher altitude so too will the lower altitude counterpart thereby preserving the enforced segregation but invoking the transition at a new position along the altitudinal gradient. Under this scenario the most likely implication of competitive interaction is the potential for rapid expansion of species where localized extinctions release species from competitive interactions currently preventing species from occupying a wider range of altitudes.

Anthropogenic disturbance has the potential to affect predictions where vegetation clearance or regeneration alters the extent of future available habitat (Warren et al., 2001; Hilbert et al., 2004). Further, models of

vegetation responses under climate warming suggest that significant shifts in the extent and spatial distribution of particular rainforest types are likely (Hilbert et al., 2001). Change in the extent of forest area will also be compounded by pervasive alteration in tree and liana communities in response to the rising concentration of atmospheric CO₂ (Phillips et al., 2002; Laurance et al., 2004). For species potentially restricted to specific rainforest types or communities, the rapidity of conversion from one forest type to another will be crucial in determining whether climatic environments within a species physiological tolerance can be reached and successfully occupied. A detailed understanding of the degree of specialization in rainforest birds and the pace at which vegetation change is expected to proceed would therefore be valuable in refining future projections of population size within the region.

Species may shift less than expected along climatic gradients where evolutionary adaptation increases the climate tolerance of species. The potential for genetic adaptation to climate at the population level, however, is not well known (Harte et al., 2004). Available evidence suggests that rainforest species will have a limited potential to evolve in response to rapid climate change (Hoffmann et al., 2003) and others have argued that “long generation times of macroscopic species will probably prevent adaptation rates from keeping pace with anthropogenic climate change” (Harte et al., 2004). The effect of warming on survival or extinction rates will also depend on the extent of existing differential population level adaptation to variable climates within the distribution of species (Harte et al., 2004).

We used a symmetric altitude-abundance pattern to infer the abundance of species within novel climatic space created under climate warming. Our intention was to highlight the potential for lowland species to benefit, at least initially, from increased temperatures by simultaneously invading upland habitats and taking advantage of additional suitable climatic habitat that becomes available at lowest altitudes with climate change. While a symmetric abundance pattern provides a plausible, intermediate scenario, agreement has yet to be reached on the expected shape of species response curves to an environmental gradient (Austin, 2002) and, in particular, newly created climatic space. It is important to recognize, however, that the assumption relates primarily to already widespread species and does not affect predictions for mountaintop species that are expected to be most severely impacted by climate induced change.

Lastly, we assume that the integrity of the altitudinal abundance pattern will be retained as a species shifts along the altitudinal gradient. While climate induced change in the position of range boundaries has been documented (Parmesan et al., 1999; Thomas and Lennon, 1999; Hill et al., 2002; Konvicka et al., 2003; Brommer, 2004; Hickling et al., 2005), it is currently not

known how well species track change within their distribution. If, for example, abundance at the lagging range boundary deteriorates more rapidly than abundance at the leading range boundary increases, we would expect the abundance pattern to become skewed or compressed. Similarly, under stressful conditions the overall abundance pattern may be depressed or otherwise take on some different, unanticipated form. Unfortunately, at present, a lack of suitable abundance data in long-term monitoring programs impedes our understanding of change in spatial abundance patterns of species.

4.3. Implications

Climate change has already altered the distribution of some species (Parmesan and Yohe, 2003; Root et al., 2003) but direct estimates of change in population size are currently lacking. Here we utilize abundance data and provide a novel approach for documenting change in population size associated with range shifts across the altitudinal gradient. Our predictive models show that upslope movements have the potential to translate into dramatic reductions in the population size of mountaintop species. Twelve percent of all species are expected to become extinct eventually as a result of maximum projected climate change for the year 2100 with the vast majority of remaining species being severely threatened with population loss.

While abundance data and the methodological framework proposed herein provide a valuable, practical tool to quantify important change in population size, large gaps remain in our understanding of change in the spatial pattern of abundance of species within shifting distributions. We strongly advocate, therefore, the collection of systematic abundance data across the distribution of species and emphasise the need for sampling effort to be stratified along climatic gradients over which the greatest change is expected to proceed. Unless we start collecting the appropriate abundance data now, important climate change impacts may proceed completely unnoticed and we will forego the opportunity to test model assumptions and enrich our understanding of change in population size associated with range shifts. Information on the spatial pattern of abundance of species will allow us to move beyond broad accounts of change in range boundaries and distribution area and consider the implication of climate change on the populations themselves.

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