ORIGINAL RESEARCH

Revising vulnerability assessments of montane birds in the colombian páramo to account for threats from climate change

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Abstract
Tropical montane ecosystems are highly vulnerable to global climate change, but their species-level conservation vulnerability assessments generally do not incorporate climate threats. The Colombian páramo is a highly diverse montane ecosystem but it contains relatively few species currently identified as threatened on the IUCN Red List. We explore whether current assessments need revising to account for climate change threats for páramo species. We use a climate change vulnerability assessment framework to evaluate the risks and opportunities from climate change for 60 bird species within the Colombian páramo. We explore two potential climate change scenarios (RCP 2.6 and RCP 8.5), representing best and worst-case projections. We find that more than half (52–68%, depending on the scenario) of bird species will be threatened by climate change by the end of the century, but a very poor agreement between the current conservation status of species and their climate vulnerability score. We find ~ 90% of species identified as climate-threatened are not currently identified as being of conservation concern, representing a substantial new suite of priority species within the Colombian páramo. Overall, we identify up to 34 páramo bird species that are threatened by climate change but not currently listed as being of conservation concern. Similar mismatches may also occur in other montane taxa and so updating species risk assessments to account for climate change is urgently needed. Implementation of appropriate conservation actions is also needed to reduce species' risks from climate change.

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Introduction

Many species are declining and these declines are projected to accelerate as a consequence of global climate change (Scheffers et al. 2016; Warren et al. 2018). Assessments of which species and populations are threatened by climate change are rarely carried out, but are essential if we are to establish conservation priorities to maintain global biodiversity (De Grammont and Cuarón 2006; Mace et al. 2008). Climate change vulnerability assessments (CCVAs) are increasingly being used to assess future extinction risk for species under a changing climate (Pacifici et al. 2015). These CCVAs potentially allow for earlier and appropriate conservation interventions to be implemented and therefore help to slow-up or prevent species declines and extinctions (Akçakaya et al. 2014).

Assessing the vulnerability of species to climate change is essential in order to develop effective long-term strategies to protect them, where this is feasible. In general, CCVAs score different components of climate risk (exposure, sensitivity, and adaptability) for each species. These different components are then combined into a single overall vulnerability score that can be easily compared across the species being assessed. These scores are generated by taking a range of trait information about a species (e.g., dispersal ability, generation length), as well as observed or projected distribution/population trends where available (Wheatley et al. 2017; Foden et al. 2019).

The use of CCVAs has increased amongst conservation managers, planners, policymakers, and researchers working on many different taxonomic groups and at a range of spatial scales (Foden et al. 2019). Failure to account for climate change in risk assessments could potentially delay the implementation of important conservation interventions for threatened species (Trull et al. 2018). Hence, it is crucial to incorporate climate threats within species current conservation assessments to ensure effective conservation priority setting.

Tropical montane ecosystems support unique biodiversity, which is particularly vulnerable to climate change, from elevation shifts to mountaintop extinctions (Chen et al. 2011; Ayebare et al. 2018; Urban 2018; Freeman et al. 2021; Neate-Clegg et al. 2021). These climate change impacts affect a range of montane taxa, including birds, which generally have narrow ranges and few opportunities to reach cooler refugia (Jetz et al. 2007; Newbold 2018). Tropical montane birds also comprise large numbers of endemic species whose ranges are projected to contract in future (Williams et al. 2003; Young et al. 2011), continuing the uphill shifts that are already evident from empirical studies (e.g. Neate-Clegg et al. 2018; Williams and de la Fuente 2021). This evidence of range shifting has been used to update risk assessments of some tropical bird species to include threats from climate change (Garnett and Baker 2021). However, despite the mounting evidence of the damaging impacts of climate change, most tropical montane bird species are not currently identified as threatened under current vulnerability assessments (Şekercioğlu et al. 2012). The majority of high-elevation bird species are listed as 'least concern' or 'near threatened' under the IUCN Red List process, ignoring the likely high level of climate threats for these montane species (Renjifo et al. 2020).

Identifying which montane species are most in need of conservation intervention under the likely impacts of climate change is urgently needed to prevent the loss of unique montane biodiversity. The Colombian páramo is a highly biodiverse tropical montane region, containing many endemic species threatened by climate change (Fjeldså et al. 2012; Madriñán et al. 2013; Velásquez-Tibatá et al. 2013; Manes et al. 2021). Colombia contains over

half of all páramo habitat globally, with excellent biodiversity data compared to similar ecosystems elsewhere, providing opportunities to update species risk status (e.g., for birds, Renjifo et al. 2020) to include threats from climate change.

The main aim of our study is to carry out climate change vulnerability assessments (CCVAs) of páramo bird species in order to assess the risks and opportunities for these species from the impacts of climate change. To achieve this aim, we incorporate bird species records from the Global Biodiversity Information Facility (GBIF) into species distribution models to project future range changes, for two climate scenarios (representing a 'best' (RCP 2.6) and 'worst' (RCP 8.5) case climate future). We use these projected distribution trends, together with species trait data, to carry out a trend-based CCVA (Thomas et al. 2011). The aim of our study is to: (i) identify broad patterns of climate risk or opportunity for birds across the Colombian páramo, (ii) test if current IUCN Red List assessments are in agreement with the threats to species from climate change, and (iii) identify species that are not currently of conservation concern under the IUCN Red List process but where our CCVA indicates they are threatened by climate.

Methods

Study area

Our study focuses on tropical montane bird species of the northern Andean páramo in Colombia. The northern Andean páramo primarily consists of grass and scrublands above the forest tree-line (most commonly between the elevations of 2800–4700 m). Páramo habitat also includes a variety of lakes, peat bogs and elfin forest patches (Buytaert et al. 2006). We used the World Wildlife Fund For Nature Terrestrial Ecoregions of the World (TEoW) boundaries to identify the páramo study area (Olson et al. 2001). The species we are assessing are páramo specialists, and so we modelled their distributions within the minimum bounding box that encompasses all páramo habitat (Supplementary Figure S1). This approach allows us to model range changes across the páramo, whilst also including any parts of the species' distributions that occur outside páramo habitat.

Biodiversity data

Avian biodiversity data were obtained from the Global Biodiversity Information Facility (GBIF), selecting all biodiversity records from all sources and species within Colombia (GBIF 2019). Records that are likely to be affected by taxonomic and geographical errors, common amongst digitised natural history collections (Maldonado et al. 2015), were removed using the R package "CoordinateCleaner" (Zizka et al. 2019). Species records from 2010 to 2019 were selected for subsequent analysis (~ 140,000 records used), to represent the current distributions of study species.

We focus on páramo species, defined as those species with >40% of their records within the páramo, and which are described as páramo species with an upper elevation limit >2800 m in their IUCN Red List assessment (Birdlife International 2016). Applying these filters produced a total of 67 páramo specialist bird species to be considered for assess-

ment using our CCVA approach. However, sufficient data to run the full CCVA were only available for 60 of these species (Table S1).

Species distribution models

In order to estimate projected changes to species distribution extents needed for the CCVA, species distribution models (SDMs) were produced for each of our 60 study species using presence-only occurrence data (1 km grid resolution). We used an Integrated nested Laplace approximation (INLA) approach to produce these models (Rue et al. 2009; Lindgren and Rue 2015), which is computationally efficient compared to alternatives, and robustly accounts for spatial autocorrelation. The INLA approach involves fitting Bayesian hierarchical models (latent Gaussian random field models) using accurate approximations of posterior marginals to improve computational efficiency (Rue et at. 2009; see Appendix 1 for more details on SDM methods). We incorporated data on climate, elevation, soil properties, and a measure of observer effort (Simmonds et al. 2020) into the models as predictors of species occupancy (see Appendix 1 for full details). Following recommendations of best practice (Williams et al. 2003), we reduced the 18 climate variables available in the World-Clim v1.4 database (Hijmans et al. 2005) to a smaller number of five climate variables for inclusion as covariates in SDMs (see Appendix 1 for methods of variable selection; Figure S2 shows the correlation matrix among all 18 WorldClim variables). These five variables were: annual mean temperature (°C), temperature seasonality (a measure of within year temperature variation), temperature annual range (°C), precipitation of the wettest month (mm) and precipitation seasonality. These climate variables include measures of temperature and precipitation that are important abiotic factors limiting species ranges (Williams et al. 2003; Suggitt et al. 2017).

We accounted for sampling biases in the GBIF data (e.g., biases due to ease of access to survey sites, proximity to major cities, etc.), by calculating a measure of observer effort for each 1 km grid cell in our study area. Effort was computed as the proportion of species observed within the cell relative to the number of species expected to occupy the cell, using FRESCALO software (Hill 2012). FRESCALO compares the number of observed species in a cell against those found in a compositionally similar nearby neighbourhood of cells. We used the proportion of different habitat types within each cell as our measure of compositional similarity (Sullivan et al. 2017; Wheatley et al. 2017). Habitat data were based on the Copernicus Global Land Service 2015 100 m Land Cover map (Buchhorn et al. 2019), with the FRESCALO process implemented in R using the 'sparta' package (August et al. 2015). Our measure of observer effort was then included in our model as a fixed effect term.

We used the SDMs to project future distributions of our study species by incorporating climate data for 2070–2100. These climate data were from the Hadley Centre Global Environment Model version 2 earth series (HADGEM2-ES) global circulation model for Representative Concentration Pathways (RCP) 2.6 and 8.5 (Jones et al. 2011). This approach allowed us to consider the impact of climate change on the distributions of páramo bird species, based on two scenarios representing the lowest and highest projected emissions pathways (i.e., the best/worst case climate futures for the Colombian páramo).

Climate change vulnerability assessment (CCVA)

We used a trend-based climate change vulnerability assessment framework to assess the climate vulnerability of páramo bird species following the methods set out in Thomas et al. (2011). The framework scores four components of climate change impacts on a species: observed recent decline of the species in terms of populations or range size (Stage I), projected future decline within the species current range (Stage II), observed recent expansion (Stage III), and projected future expansion (Stage IV). Projected changes in species distributions were derived from our SDMs and converted to decadal rates of change. Stage I and III used current information available for 2010-19, and stage II and IV used the difference between SDMs for 2010-19 and each future climate scenario. The CCVA was performed separately for the two future climate scenarios we considered (RCP 2.6 and RCP 8.5). We also included information on potential exacerbating factors, such as a species having limited dispersal ability, or low levels of habitat availability, using data from the IUCN Red List assessments (BirdLife International 2016), and the Handbook of the Birds of the World Alive (del Hoyo et al. 2016). All input data used for the CCVA is presented in Appendix 2.

The scores for the two decline components were combined into a single score, as were the two expansion components, and each score had one of four possible values: 'low', 'medium', 'high' and 'very high' (Thomas et al. 2011). The decline and expansion scores were then combined into a single score using a risk matrix, assigning species to one of three vulnerability categories: 'low', 'medium' and 'high' climate vulnerability (i.e., slightly modifying the number of categories proposed by Thomas et al. 2011; Table S2).

Assessing agreement between our CCVA and conventional red listing assessments

We assessed whether the current IUCN Red List categories underestimate the threats caused by climate change. We examined agreement between our CCVA risk categories for species and their Red List assessment vulnerability category using Spearman's rank correlation, to establish how consistently species were assigned to similar levels of risk by the two approaches. In addition, for the most vulnerable species, we examined agreement between their Red List assessment and our CCVA, simplifying the risk categories to binary categories of 'not threatened' or 'threatened'. 'Threatened' species were designated as those in the Red List categories of 'Vulnerable' or 'Endangered', and the CCVA 'medium' or 'high' risk categories. We then used Cohen's Kappa (Byrt et al. 1993), which is a measure of inter-rater reliability, to compare agreement between the two assessments. All analysis was conducted in R v.3.6.0 (R Core Team 2016).

Results

Reduction in distribution size

We extracted GBIF data for 67 species of páramo birds, of which 60 species had sufficient data (ranging between 20 and 4970 records per species) to model their distributions and be included in our climate change vulnerability assessment analyses. As expected for montane species, most species (57/60) are projected to decline in their distribution size in future

under both RCP climate scenarios (Fig. 1). Only three species are projected to increase, and these by only a relatively small extent (Fig. 1). Distributions are projected to decline to approximately a third their size in future (RCP 2.6, mean=38% reduction, range 65% reduction to 27% increase; RCP 8.5, mean=39% reduction, range 65% reduction to 19% increase). Hence, the distributions of nearly all páramo birds are likely to decline considerably due to climate change.

Climate change vulnerability assessment (CCVA)

We identify that between 52% (31/60 species under RCP 2.6) and 70% (42/60 species under RCP 8.5) of páramo bird species are at 'medium' or 'high' risk from climate change (Fig. 2 and Table S1). As expected, the threats from climate change increase with the increasing magnitude of projected climate change, with many species moving from 'low' to 'medium' risk under RCP8.5 compared with RCP 2.6 (Fig. 2). Under RCP 2.6, 29 species (48%) are assessed as 'low' risk from climate change, of which nine species move up into the 'medium' risk category under RCP 8.5. A total of 15 species (25%) are classified as 'high' risk under both RCP climate scenarios.

The CCVA combines the risk of species decline and the opportunity for expansion. The risk matrix (Fig. 3) highlights the limited opportunity for expansion by páramo bird species, with just a single species (*Scytalopus griseicollis*) scored as having a moderate opportunity for expansion, whereas all the remaining species are scored as low opportunity. The risk matrix also highlights the relatively even spread of species across the 'low', 'medium' and
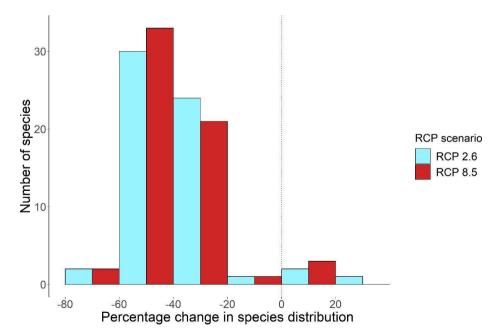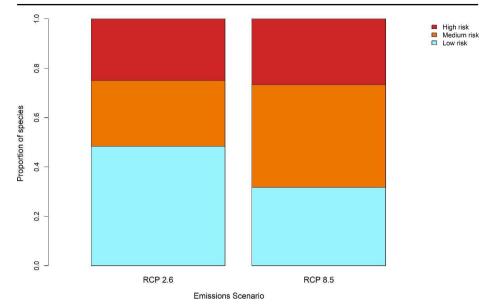

Fig. 1 Histogram of projected percentage change in bird range size due to the impacts of climate change. Data are from SDM outputs comparing range size change from the present day (2010–2019) to the end of the century (2100) under RCP 2.6 (blue) and RCP 8.5 (red) emissions scenarios

Fig. 2 Plot shows the proportion of páramo bird species (n=60 species) classified into each of three CCVA risk categories ('high' risk (red), 'medium' (orange), 'low' (light blue)) under RCP 2.6 or RCP 8.5 future climate scenarios

RCP 8.5		Risk of Decline			
		Very high	**High**	**Moderate**	**Low**
Opportunity for expansion	**Low**	2	14	25	18
	Moderate	0	0	0	1
	High	0	0	0	0
	Very high	0	0	0	0

Fig. 3 CCVA risk matrix for páramo bird species under the RCP 8.5 scenario. Numbers within each cell give the number of species within each pairwise combination of the risk of decline and the opportunity for expansion under climate change. The top left cell represents the most at-risk species while the bottom right cell represents species with the highest opportunity from climate change. Cell colours represent the overall risk category from the combination of the two scores (light blue = 'low' risk, orange = 'medium' risk and red = 'high' risk)

'high' decline categories, with only two species (*Vultur gryphus* and *Scytalopus canus*) scoring as 'very high' risk of decline under the RCP 8.5 scenario.

Comparison of our CCVA with the current IUCN Red-list conservation status

We found no correlation between species' CCVA risk category and their current Red List risk assessment for either RCP 2.6 climate change scenario ($r_s = 0.10$, p=0.27), or RCP 8.5 ($r_s = -0.02$, p=0.87). This lack of agreement was supported by a finding of 'no agreement' (McHugh 2012) according to Cohen's Kappa inter-related reliability analysis (RCP 2.6: κ=0.12, 95% CI = -0.06, 0.30; RCP 8.5: κ=0.01, 95% CI = -0.13, 0.15).

For both RCP scenarios, we found that more than half of the species that are not currently threatened according to the IUCN Red List are threatened by climate change (Fig. 4). Hence, these species threatened by climate change are not currently priorities for conservation intervention. Under the RCP 2.6 scenario, 26 (52%) 'least-concern' species were scored as 'low' climate risk, with 11 (22%) at 'medium' risk and 13 (26%) at 'high' risk. Under the RCP 8.5 scenario, there is a shift amongst the 'least-concern' species to become 'medium' risk, with 16 (32%) species scored as 'low' risk, 20 (40%) as 'medium' risk and 14 (28%) as 'high' risk. Of the five species identified by the IUCN as 'near threatened', we scored one species in the CCVA as 'low' climate risk, three as 'medium' climate risk and one as 'high' risk, again highlighting the lack of consensus between the two risk assessment approaches.
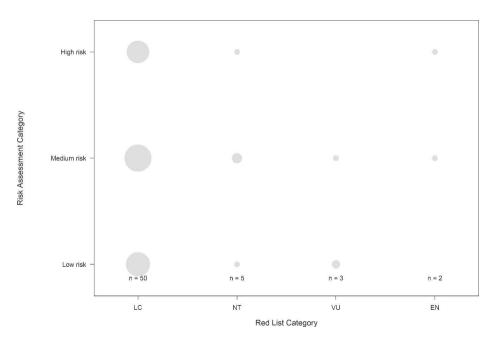

Fig. 4 Lack of agreement in páramo bird species risk assessments based on IUCN Red List and CCVA approaches (n=60 species). The size of the circle represents the proportion of species classified into each risk category according to their CCVA and Red List assessment risk category (LC - Least Concern, NT - Near Threatened, VU - Vulnerable, EN - Endangered). Species are assessed using the high emission RCP 8.5 scenario

Discussion

Climate change vulnerability assessment

The results of our climate change vulnerability assessment (CCVA) predict substantial detrimental impacts of climate change on páramo bird species, but there is variation among species. Under the RCP 2.6 scenario, we find an almost 50:50 split between the species that are threatened (scored as 'medium' or 'high' climate risk) and not threatened (scored as 'low' climate risk). However, under the RCP 8.5 scenario, almost 70% of species are threatened by climate change ('medium' or 'high' risk). Thus, even under the best-case climate future (RCP 2.6), our CCVA suggests that more than half of the páramo bird species are likely to be threatened by climate change. These climate change threats are in addition to the other threats already acting upon páramo birds. A total of 15 species were identified as being at 'high' risk from climate change under both RCP scenarios (Table S1), and so there are several species in urgent need of conservation intervention if they are to persist within the Colombian páramo.

A key finding for all the páramo bird species that we assessed is the limited opportunity for range expansion under climate change, with all but two species scoring as 'low' opportunity for expansion in the CCVA (Fig. 3). Our CCVA and species distribution models assume that species have the dispersal ability to fully track climate changes (Araújo et al. 2004; Pearson 2006; Thuiller et al. 2019), which is probably highly optimistic (Cunze et al. 2013), but new areas to colonise are absent for almost all species. Even when climatically suitable areas are available, dispersal ability is likely to be a limiting factor. Thus species are likely to fail to colonise small and isolated areas of newly-suitable climate, suggesting that opportunities for expansion may be even more restricted than our CCVA assessments suggest.

The patterns of climate-driven upslope range shifts and retractions identified by our SDMs are broadly similar to patterns found more widely in other studies of Andean bird species (Velásquez-Tibatá et al. 2013; Ramirez-Villegas et al. 2014; Avalos and Hernández 2015; Freeman et al. 2018). There are also increasing additional threats from agricultural expansion into the páramo (Buytaert et al. 2006), and so species currently assessed as at 'moderate' or 'low' risk in our CCVA may be of greater conservation concern in the future. Examining the combined impacts of climate change and land use change on páramo species needs further research, to understand how the interactions between these drivers of distribution change affect species' risk assessment.

Our CCVA considers species responses to climate change within the portions of their global distributions that occur within Colombia, but they may also persist elsewhere in the Northern Andean páramo, such as Ecuador (Buytaert et al. 2011). However, the relative importance of the Colombian páramo to the global distributions of our study species will likely increase under climate change. It is also highly unlikely that species will show very different responses to climate change in those parts of their distributions outside of Colombia (Ramirez-Villegas et al. 2014). Our assessment included six endemic bird species, for which our CCVA incorporates their entire global distribution. Of these six Colombian endemic species, two were identified as vulnerable to climate change (*Cistothorus apolinari* – 'medium' risk, *Scytalopus canus* – 'high' risk), making them extremely high priority species for conservation action within Colombia.

South America has received relatively little attention with respect to CCVA-type assessments compared with other continents, despite the fact that the region is identified as one containing a high number of the most climate vulnerable species (Pacifici et al. 2015). South America has been identified as the region most threatened by climate change, with 23% of species predicted to go extinct by the end of the century, compared with the global average of just 8% (Urban 2015; Newbold 2018). Our results reveal that between 25 and 27% of all páramo bird species in Colombia are at 'high' risk from climate change, which is consistent with the global meta-analysis (Newbold 2018).

Climate change threats to tropical montane species have not been the subject of CCVA research in South America, but risks to montane species have been considered elsewhere in the world. For example, an assessment of climate change vulnerability using a trait-based assessment in the Eastern Arc mountains of Tanzania concluded that 31% of reptiles are threatened by climate change (Meng et al. 2016), which is similar to our finding that 27% of páramo birds in Colombia are at 'high' risk under RCP 8.5. A climate change vulnerability assessment of vertebrates within Mexican cloud forests found that 24% of species are highly threatened with extinction under climate change (Ponce-Reyes et al. 2012), which is also consistent with our findings. Thus, the results of our CCVA confirm the vulnerability of tropical montane ecosystems to climate change. Analysis of historical records confirm that climate-driven declines are already evident and the rapidity of species responses. For example, the local abundance of montane birds has declined by more than 40% at low elevation sites over the past 17 years in Australia (Williams and de la Fuente 2021) and range retractions are faster in low elevation species (Mamantov et al. 2021). A meta-analysis of climate-driven range shifts shows that rates of shifting are two to three times faster than previously reported (Chen et al. 2011).

Mismatch between climate change vulnerability assessment and IUCN Red-list status

We found poor agreement between risk assessments based on the CCVA and the IUCN Red List approach. None of the 60 species assessed in our CCVA had climate change listed as a threat within their Red List assessment, yet we found up to 34 of these species threatened according to our CCVA (depending on RCP scenario). There are 10 species included in our CCVA assessment at 'medium' or 'high' risk that are also threatened according to the Red List assessment (five species 'near threatened', three 'vulnerable' and two 'endangered'). The Red Listing included land use change as the main threats, as well as other threats from human persecution and non-native species (Renjifo et al. 2020), but not climate change.

Both species currently classified by the Red List assessment as 'endangered' were also at risk according to the CCVA, with one assessed as 'medium' climate risk and the other as 'high' climate risk. Of the three 'vulnerable' species, two were assessed by the CCVA as 'low' risk while the third species was assessed as 'medium' risk by the CCVA. None of these five threatened species have climate change mentioned as a threat within their current conservation assessments, suggesting that risks identified by our CCVA will be in addition to any existing threats already impacting these species.

There is evidence that changes in páramo bird populations are lagging behind climate change (Rosselli et al. 2017), with changes in land use currently a greater driver of species vulnerability. These lags may explain some of the differences between our CCVA results and

species current conservation status. A lack of any observed responses of species to climate change might explain why current Red Listing criteria do not identify climate change as a risk factor (Keith et al. 2014; Trull et al. 2018). However, there are empirical studies from elsewhere reporting climate-driven range shifts in tropical montane species (e.g. Williams and de la Fuente 2021) and climate-driven extirpation of mountaintop species via the 'escalator to extinction' (Urban 2018).

This mismatch between IUCN vulnerability assessments and our CCVA highlights the importance of incorporating climate change vulnerability of species into current conservation planning (Massimino et al. 2017; Attorre et al. 2018; Trull et al. 2018). The majority (90 to 95% depending on RCP scenario) of páramo bird species identified as at risk in our CCVA (either 'medium' or 'high' risk) have not previously been recognised as threatened, and so they represent additional species of conservation concern. Identifying species that are threatened by climate change could buy time for conservation actions to be implemented, rather than waiting for declines to be observed (Akçakaya et al. 2014; Stanton et al. 2015).

Using species distribution modelling to inform climate change risk assessments

In this study, we used a distribution trend-based vulnerability framework to assess species at risk from climate change, of which a core component requires robust modelling of changes in species distributions under climate change. The type of distribution modelling we used performs well in simulation exercises, particularly when including a measure of observer effort and a spatial random effect to correct for bias in the distribution data (Isaac et al. 2020), as we did. Thus, we have confidence in the outputs of these models.

The spatial scale of our modelling was relatively coarse at approximately 1 km x 1 km grid cell resolution across our páramo study area, which was limited by the resolution of the global climate projections for the RCP future scenarios we considered. Nonetheless, the resolution was finer than most previous studies examining climate impacts in tropical ecosystems, which have generally been at coarser 10–50 km resolution (Jetz et al. 2007; Newbold 2018). Our distribution modelling used presence-only data from GBIF collected by citizen scientists, and these data also limit the spatial resolution of our models due to the uneven recorder effort across Colombia and precision of location information. Access to some areas of the páramo has historically been very difficult, therefore some areas have received little survey effort (Krabbe et al. 2006). Some páramo bird species may therefore be under-represented in the GBIF data, or not recorded at all, and so not included in our CCVA. However, the species we did include span a wide range of ecological types and range sizes, and so the overall findings we report here are likely to be representative of the páramo ecosystem, even if we were not able to include all páramo bird species in our CCVA. GBIF includes distribution data for other páramo taxa and so it would be interesting to examine if a lack of consensus in risk assessments is evident in other groups.

Even though our analyses were at 1 km grid cell resolution, they were nonetheless at relatively coarse spatial resolution. However, local microclimates are important for determining the distributions of many taxa, providing local refugia and allowing species to persist in areas that macro-scale models predict are unsuitable (Suggitt et al. 2018). Microclimate refugia are common in montane ecosystems such as the páramo (Buytaert et al. 2006), and so conservation management actions to maintain microclimate heterogeneity could be an important mitigation tool for protecting climate-threatened species. Thus, the 1 km x 1 km

spatial resolution we used in our CCVA may mask some local-scale patterns, and carrying out distribution modelling at finer spatial scales could provide a more robust CCVA of species risk. However, given the limited opportunities for range expansion that we highlight for the vast majority of páramo bird species, it is unlikely that finer-resolution data would alter our conclusions about the considerable threat to montane species from climate change. Our CCVA analyses are based on occurrence records of birds and SDM outputs. Including information on the local abundance trends of populations, particularly at low elevation sites, is likely to provide more information on the vulnerability of species to climate-change threats (Williams and de la Fuente 2021). Occurrence data, and the associated SDM outputs, provide information on species declines only after extirpation of species at locations, whereas local abundance trends provide information on local declines prior to extirpation. Implementing conservation management to protect páramo birds is of high importance if these species are to persist in future, and the current levels of species richness are to be maintained.

Conclusions

Our study provides one of the first quantitative Climate Change Vulnerability Assessments of tropical montane species, highlighting considerable mismatches with species' current risk assessments that do not currently include threats from climate change. Our findings reveal that large numbers of bird species within the Colombian páramo are likely to face increased risk of extinction by the end of the century as a consequence of climate change. Many of these species are not currently conservation priority species but are likely to require increased conservation efforts to ensure their survival. Our study reveals that more than two-thirds of bird species within the Colombian páramo are likely to face increased risk of extinction by the end of the century as a consequence of climate change. Many of these species are not currently conservation priority species. It is important that risk assessments for these species are updated to reflect risks from climate change and that appropriate conservation measures are taken to ensure their survival.

Declarations

Ethical statement All appropriate ethics and other approvals were obtained for the study from the University of York's Animal Welfare and Ethical Review Body (AWERB) for the analysis of unpublished data derived from vertebrate animals.

Competing interests The authors declare no competing interests.

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