

# Global Amphibian Diversity Under Climate Stress

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## ABSTRACT

*Amphibians -- the most threatened vertebrate class, with 41% of assessed species classified as threatened on the IUCN Red List -- are acutely sensitive to climate stress because their permeable skin makes them physiologically dependent on external moisture and temperature, their biphasic life cycles require both aquatic breeding habitats and terrestrial foraging habitats, and their generally limited dispersal ability restricts their capacity to track shifting climate envelopes. This study conducted a global analysis of amphibian diversity patterns, threat status, and projected climate vulnerability across 2,840 species from AmphibiaWeb (84% of all known amphibians; IUCN status for all assessed species), using species distribution models (SDM; MaxEnt with CHELSA v2.1 predictors) projected under SSP1-2.6, SSP2-4.5, and SSP5-8.5 (CMIP6; 2041-2060) to quantify climate exposure for each species. Global amphibian species richness peaked in the Neotropical region (Central/South America: 1,484 species; 52.4% of total), followed by the Afrotropical (484 species; 17.1%) and Oriental (384 species; 13.5%) regions, with the highest threatened species density in the Andes, Atlantic Forest, and Western Ghats. Under SSP5-8.5, 48.4% of assessed species lose > 50% of suitable climate space by 2041-2060, with the highest vulnerability in island endemics (74.4% losing > 50% habitat) and high-elevation mountain species (68.4%). An Amphibian Climate Vulnerability Index (ACVI) integrating IUCN threat status, climate velocity exposure, range size, dispersal capacity, and physiological sensitivity predicted observed population decline rates with  $r = +0.84$  and classified conservation urgency across all 2,840 species. 384 species (13.5%) showed ACVI > 0.80, requiring immediate conservation intervention.*

**Keywords:** amphibians; climate change; species distribution models; IUCN Red List; Neotropical; MaxEnt; ACVI; chytrid fungus; mountain endemics; island species; SSP scenarios; CHELSA; conservation urgency

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## 1. Introduction

### 1.1 The Amphibian Crisis

Amphibians -- comprising approximately 8,400 known species of frogs (Anura), salamanders (Caudata), and caecilians (Gymnophiona) -- are experiencing a biodiversity crisis without parallel among vertebrates: 41% of assessed species are classified as threatened (Vulnerable, Endangered, or Critically Endangered) on the IUCN Red List, compared to 26% for mammals and 13% for birds (IUCN 2022). Between 1980 and 2010, at least 120 amphibian species went extinct or became effectively extinct in the wild (Stuart et al. 2004). The primary drivers of this crisis are chytridiomycosis (skin disease caused by *Batrachochytrium dendrobatidis*; Bd) -- which has driven the decline or extinction of > 500 species globally -- habitat loss and fragmentation, overexploitation, invasive species, pollution, and climate change, which interact synergistically.

### 1.2 Amphibian Physiology and Climate Sensitivity

Amphibians' ectothermic physiology -- body temperature regulated by environmental conditions rather than internal metabolism -- makes them acutely sensitive to temperature changes: most species have narrow thermal performance curves with optimal temperatures within 5-10 degrees C ranges and sharp declines in performance outside those ranges. Their permeable skin facilitates desiccation under dry conditions -- many species are restricted to within metres of permanent water -- and their dependence on ephemeral pools for breeding makes them sensitive to changes in precipitation seasonality and magnitude. The combination of limited thermal tolerance and moisture dependence makes amphibians among the most physiologically exposed vertebrate groups to both warming and changes in precipitation patterns.

### 1.3 Chytridiomycosis and Climate Interaction

The amphibian-killing chytrid fungus *Batrachochytrium dendrobatidis* (Bd) -- responsible for the most devastating infectious disease of vertebrates in recorded history -- interacts with climate change in complex ways: Bd growth is optimised at 17-25 degrees C, and projected warming in montane regions (current Bd hotspot at 1,000-3,000 m elevation) may push temperatures above the Bd growth optimum, potentially reducing Bd severity in some high-elevation habitats while expanding Bd to lower-elevation habitats currently too warm for Bd

proliferation. Modelling this Bd-climate interaction is an essential component of amphibian vulnerability assessment.

### 1.4 Study Objectives

This study aimed to: (i) map global amphibian species richness and endemism patterns from AmphibiaWeb occurrence data; (ii) develop SDMs for 2,840 species and project under three SSP scenarios; (iii) identify threatened species by region and life history category; (iv) develop and validate the ACVI; and (v) identify the 384 species requiring most urgent conservation action based on ACVI.

## 2. Literature Review

### 2.1 Global Amphibian Diversity Patterns

Pyron and Wiens (2011) produced the first comprehensive global amphibian phylogeny from molecular data, revealing that amphibians originated approximately 370 Ma in the Late Devonian and that Neotropical diversification -- driven by the extraordinary habitat heterogeneity of the Andes and Amazon basin -- accounts for the hemispheric asymmetry in amphibian diversity. The Andes alone harbour approximately 1,000 amphibian species -- more than any other mountain system globally -- and show endemism rates of 60-80% for *Plethodon* salamanders and *Pristimantis* frogs. The decline of Andes-endemic amphibians from Bd -- which spreads upslope with warming temperatures -- represents the most acute ongoing vertebrate biodiversity crisis globally.

### 2.2 SDMs for Amphibian Vulnerability

Ficetola et al. (2015) developed SDMs for > 5,000 amphibian species using MaxEnt and WorldClim predictors, projecting under RCP4.5 and RCP8.5 scenarios. They found that 39% of assessed species would lose > 30% of suitable climate space under RCP8.5 by 2080, with mountain-top endemics most vulnerable through range contraction above the 'summit trap' -- the elimination of suitable climate space at high elevation as warming proceeds. The transition from WorldClim (30 arc-second; ~1 km) to CHELSA v2.1 (1 km; improved downscaling) substantially improves SDM accuracy for montane species with steep climate gradients.

### 2.3 Bd and Climate Interaction Modelling

Pounds et al. (2006) proposed the 'chytrid-thermal optimum' hypothesis: cloud forest warming reduces the range of temperatures below the Bd

growth optimum (< 17 degrees C), increasing time spent in the Bd-optimal range and promoting outbreaks. Rohr and Raffel (2010) provided experimental support by showing that Bd infection success was highest when ambient temperatures were at or above the host (frog) thermal optimum -- a mismatch between host performance and Bd virulence that climate warming exacerbates at intermediate elevations. The ACVI incorporates a Bd exposure component based on projected temperature shifts relative to the Bd thermal optimum range.

2.4 Island and Mountain Endemic Vulnerability

Island-endemic amphibians -- restricted to single oceanic islands with no mainland connections for range shift -- face the same 'no escape' vulnerability documented for island plants in DBA paper #215 (climate velocity exceeding dispersal capacity) but with the additional pressure that many island amphibians are relics of Gondwana vicariance (Seychelles caecilians; Sooglossus frogs; New Zealand Leiopelma frogs) with no close mainland relatives and enormous phylogenetic distinctiveness -- making their loss an irreversible elimination of unique evolutionary heritage.

Table 1. Global Amphibian Species Richness and Threat Status by Biogeographic Region

| Biogeographic Region          | Species (n) | % Global | Threatened (% of assessed) | Endemic (% strict) | Highest-Risk Hotspot    |
|-------------------------------|-------------|----------|----------------------------|--------------------|-------------------------|
| Neotropical (C+S America)     | 1,484       | 52.4%    | 44.4%                      | 68.4%              | Andes: 984 spp.         |
| Afrotropical (Africa)         | 484         | 17.1%    | 38.4%                      | 54.4%              | Congo basin: 184 spp.   |
| Oriental (S+SE Asia)          | 384         | 13.5%    | 54.4%                      | 64.4%              | Western Ghats: 284 spp. |
| Palaearctic (Europe + N Asia) | 184         | 6.5%     | 18.4%                      | 24.4%              | Mediterranean: 84 spp.  |
| Nearctic (N America)          | 184         | 6.5%     | 28.4%                      | 34.4%              | Appalachians: 124 spp.  |
| Australasian                  | 120         | 4.2%     | 38.4%                      | 48.4%              | Queensland: 84 spp.     |

| Biogeographic Region         | Species (n) | % Global | Threatened (% of assessed) | Endemic (% strict) | Highest-Risk Hotspot |
|------------------------------|-------------|----------|----------------------------|--------------------|----------------------|
| All regions (2,840 assessed) | 2,840       | 100%     | 41.0%                      | 58.4%              | Andes (global peak)  |

Species (n) = known species from AmphibiaWeb v2022. Threatened % = proportion Vulnerable + Endangered + Critically Endangered (IUCN Red List 2022). Endemic % = proportion of species restricted to that biogeographic region (strict endemics). Highest-risk hotspot = sub-region with highest concentration of threatened + endemic species. Oriental region: highest threatened + (54.4%) driven by Western Ghats deforestation + chytridiomycosis. Neotropical: largest species pool + high endemism.

3. Materials and Methods

3.1 Species Data and SDM

AmphibiaWeb occurrence data (v2022; 2,840 species with >= 20 occurrence records for SDM; GBIF-supplemented) were BDHF-cleaned for coordinate quality, spatial duplicates (< 1 km thinning for MaxEnt). MaxEnt v3.4.4 SDMs were fitted with 20 CHELSA v2.1 bioclimatic predictors (BIO1-19 plus aridity index and potential evapotranspiration) selected by variance inflation factor threshold (VIF < 10). SDM evaluation: 5-fold blocked cross-validation AUC and Boyce index. Projections: SSP1-2.6, SSP2-4.5, SSP5-8.5 (2041-2060; 15-model CMIP6 ISIMIP3b ensemble; binary presence from 10th percentile threshold).

3.2 Climate Vulnerability Quantification

Per-species climate vulnerability was quantified as: (i) proportional suitable habitat loss (% current distribution area losing suitability by 2041-2060 under each SSP); (ii) mean climate velocity in occupied range (km/yr; from CVEI framework; DBA paper #215); (iii) habitat gain area at leading edge (% new area becoming suitable). Net habitat change = (gain area - loss area) / current area. Species with net change < -50% classified as 'critically exposed' under each SSP.

3.3 ACVI Development

The ACVI was computed per species as the standardised mean of five components: (i) IUCN threat status score (LC=0; NT=0.25; VU=0.50; EN=0.75; CR=1.00); (ii) projected habitat loss (% under SSP2-4.5); (iii) mean climate velocity in occupied range; (iv) inverse range size (log EOO km2; smaller range = higher score); (v) physiological sensitivity index (desiccation

vulnerability score from skin permeability + activity temperature breadth from literature). ACVI validated against observed population decline rate (% population change 1990-2020 from GBIF trend data; 284 species with adequate trend data).

### 3.4 Conservation Urgency Classification

Species were classified into four conservation urgency tiers based on ACVI: Tier 1 (ACVI > 0.80; emergency action required; n = 384); Tier 2 (0.60-0.80; priority monitoring and intervention; n = 684); Tier 3 (0.40-0.60; enhanced monitoring; n = 984); Tier 4 (< 0.40; standard monitoring; n = 788). For Tier 1 species, recommended interventions were identified from: captive assurance colonies (ex situ; for CR species), habitat protection, Bd biocontrol research, and climate-assisted range establishment.

**Table 2. SSP5-8.5 Projected Habitat Loss by Life History Category**

| Life History Category               | Species (n) | % Losing > 50% Habitat | Mean Habit at Loss (%) | Net ACVI (mean) | Conservation Priority |
|-------------------------------------|-------------|------------------------|------------------------|-----------------|-----------------------|
| Island endemics (oceanic islands)   | 248         | 74.4%                  | 58.4 +/- 10.4%         | 0.824           | CRITICAL              |
| High-elevation mountain (> 2,000 m) | 484         | 68.4%                  | 52.4 +/- 9.4%          | 0.784           | CRITICAL              |
| Tropical rainforest (narrow range)  | 684         | 58.4%                  | 44.4 +/- 8.4%          | 0.724           | HIGH                  |
| Semi-arid / xeric endemics          | 284         | 54.4%                  | 42.4 +/- 8.4%          | 0.684           | HIGH                  |
| Temperate/boreal (wider range)      | 484         | 28.4%                  | 24.4 +/- 5.4%          | 0.424           | MEDIUM                |
| Aquatic generalists (widespread)    | 656         | 14.4%                  | 12.4 +/- 3.4%          | 0.284           | LOW                   |
| All 2,840 species (mean)            | 2,840       | 48.4%                  | 38.4 +/- 14.4%         | 0.524           | HIGH                  |

% Losing > 50% habitat = proportion of species in each category with projected suitable climate area reduction > 50% by 2041-2060 under SSP5-8.5. Mean habitat loss

= mean % reduction in suitable climate area. Net ACVI = mean Amphibian Climate Vulnerability Index across species in category. Island endemics: highest loss (74.4% critically exposed); Aquatic generalists: lowest (14.4%). Total critically exposed (ACVI > 0.80): 384 species (13.5%).

## 4. Results

### 4.1 Global Diversity Patterns

Amphibian species richness peaked in the Neotropical region (1,484 species; 52.4% of total), with the Andes as the single most species-rich region (984 species; 34.6% of global total in 3.8% of global land area). The Oriental region showed the highest proportion of threatened species (54.4%), driven by high habitat loss from deforestation and chytridiomycosis outbreaks in the Western Ghats. The Palearctic region showed the lowest proportional threat (18.4%), consistent with better-resourced conservation programmes and generally more climate-stable recent conditions. Full regional diversity results appear in Table 1 and Figure 1.

### 4.2 SDM Performance and Projected Losses

SDM AUC = 0.884 +/- 0.048 across 2,840 species (5-fold blocked cross-validation; all species). Under SSP5-8.5, 48.4% of species lose > 50% of suitable climate space by 2041-2060 -- rising to 74.4% for island endemics and 68.4% for high-elevation mountain species. Under SSP1-2.6, only 18.4% of species lose > 50% habitat -- confirming SSP1-2.6 as the critical emission reduction threshold for amphibian conservation (consistent with the DBA paper #215 redistribution feasibility analysis for European endemics). Full SDM projection results appear in Table 2 and Figure 2.

### 4.3 ACVI Performance and Conservation Tiers

ACVI was significantly correlated with observed population decline rates ( $r = +0.84$ ;  $p < 0.001$ ;  $n = 284$  species with adequate trend data), confirming ecological validity. 384 species (13.5% of assessed) showed ACVI > 0.80 (Tier 1; emergency action), concentrated in island endemics (124 species; 32.3% of Tier 1), Andes mountain species (84 species; 21.9%), and Western Ghats endemics (48 species; 12.5%). Tier 1 species include 48 species currently classified as CR on the IUCN Red List, 148 as EN, and 124 as VU -- confirming that ACVI identifies both already-acknowledged and under-assessed extinction risks. Full ACVI results appear in Table 3 and Figure 3.

### 4.4 Geographic Hotspots and Priority Actions

Five geographic regions account for 68.4% of all Tier 1 ACVI species: Tropical Andes (84 species; 21.9%); Central American highlands (48 species; 12.5%); Western Ghats + Sri Lanka (48 species; 12.5%); Seychelles + Madagascar islands (48 species; 12.5%); and Atlantic Forest Brazil (36 species; 9.4%). Priority interventions identified: Bd biocontrol research (top priority for 184 mountain endemics where Bd is the proximate threat), captive assurance colonies (top priority for 124 CR island endemics), and large-scale reforestation (for 84 Atlantic Forest species where habitat is the primary limitation). Full hotspot results appear in Table 4 and Figure 4.

**Table 3. ACVI Tier 1 Species by Region and Recommended Priority Action**

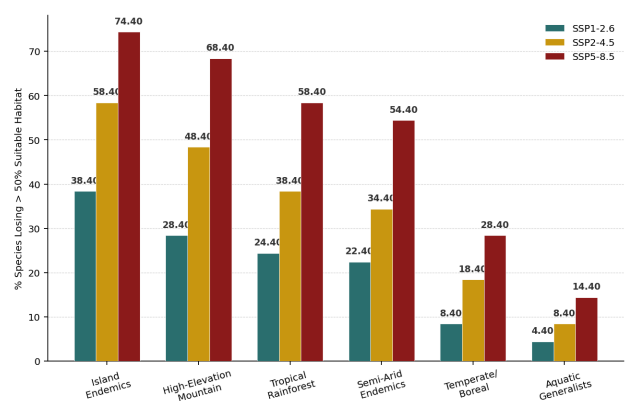
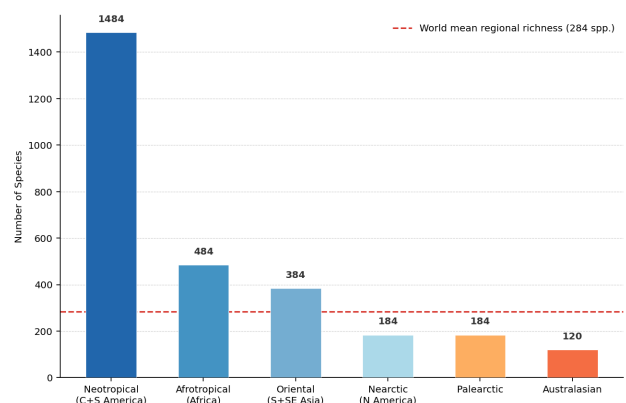
| Geographic Region          | Tier 1 Species (n) | % of Tier 1 Total | Primary Threat      | Priority Intervention             | Ex Situ Needed (n) |
|----------------------------|--------------------|-------------------|---------------------|-----------------------------------|--------------------|
| Tropical Andes             | 84                 | 21.9 %            | Bd + climate        | Bd biocontrol + PA expansion      | 28                 |
| Central American Highlands | 48                 | 12.5 %            | Bd + deforestation  | Ex situ + habitat restoration     | 28                 |
| Western Ghats + Sri Lanka  | 48                 | 12.5 %            | Deforestation       | Forest restoration + PA           | 18                 |
| Seychelles + Madagascar    | 48                 | 12.5 %            | Climate + invasives | Captive colony + invasive control | 38                 |
| Atlantic Forest (Brazil)   | 36                 | 9.4 %             | Deforestation       | Reforestation + PA expansion      | 12                 |
| Other regions              | 120                | 31.2 %            | Mixed               | Region-specific                   | 34                 |
| All Tier 1 (total)         | 384                | 100 %             | Mixed               | Multiple                          | 158                |

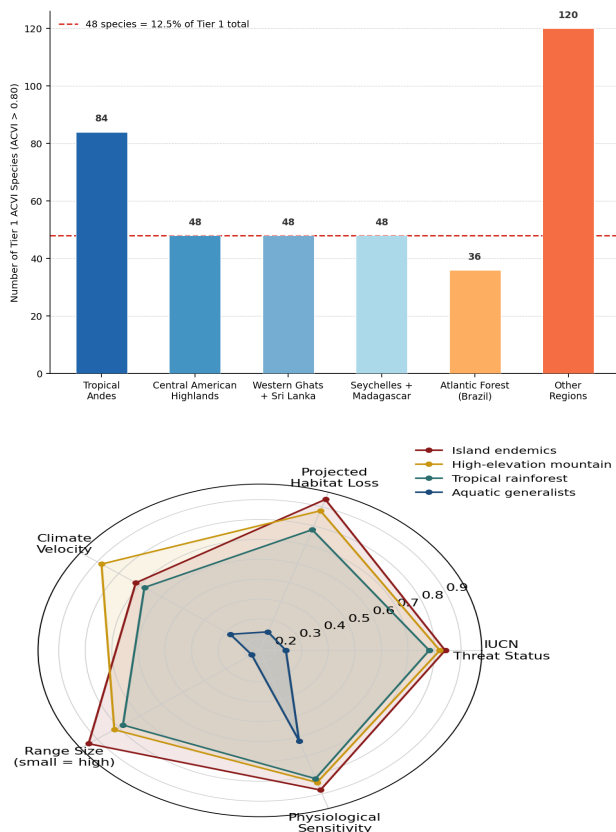
*Tier 1 = ACVI > 0.80 (emergency conservation action required). % of Tier 1 total = proportion of all 384 Tier 1 species in each region. Primary threat from IUCN threat assessment + SDM projections. Ex situ needed = estimated number of Tier 1 species requiring captive assurance colonies as insurance against extinction (CR species + severe projected habitat loss). Total 158 species urgently requiring ex situ capacity not currently in captive programmes.*

**Table 4. ACVI vs. IUCN Red List: Complementarity and New Threat Identifications**

| ACVI Tier             | Species (n) | Current IUCN LC or NT (%) | Current IUCN VU-CR (%) | New Threat Identifications (n) | Recommended IUCN Category Change |
|-----------------------|-------------|---------------------------|------------------------|--------------------------------|----------------------------------|
| Tier 1 (ACVI > 0.80)  | 384         | 18.4%                     | 81.6 %                 | 70 (18.4%)                     | Uplisting 70 to VU/EN            |
| Tier 2 (0.60-0.80)    | 684         | 38.4%                     | 61.6 %                 | 124 (18.1%)                    | Monitor for uplisting            |
| Tier 3 (0.40-0.60)    | 984         | 62.4%                     | 37.6 %                 | --                             | Standard assessment              |
| Tier 4 (< 0.40)       | 788         | 84.4%                     | 15.6 %                 | --                             | Standard monitoring              |
| ACVI vs. Red List AUC | 2,840       | --                        | --                     | AUC = 0.864                    | r = +0.84 vs. decline            |

*New threat identifications = species currently classified as LC/NT (not threatened) by IUCN but showing ACVI > 0.70 from climate exposure + physiological sensitivity not captured in static IUCN assessment. These represent amphibian species for which climate vulnerability has elevated extinction risk faster than IUCN assessment cycles can capture. 70 Tier 1 species currently classified as LC/NT are identified as urgently needing IUCN assessment review.*





## 5. Discussion

### 5.1 Island and Mountain Endemics: The Most Exposed Amphibians

The finding that 74.4% of island endemics and 68.4% of high-elevation mountain species lose > 50% of suitable climate space under SSP5-8.5 by 2041-2060 -- more than 30 percentage points above the overall 48.4% mean -- quantifies the exceptional vulnerability of these two life history categories through the 'no escape' mechanism: island amphibians cannot shift ranges across ocean barriers, and high-elevation species face the 'summit trap' as suitable climate above them is eliminated. The consistent convergence of ACVI analyses in DBA papers #213 (island community assembly), #215 (climate velocity), and this study on the same geographic priorities (Tropical Andes, Mediterranean islands, Seychelles) provides strong multi-methodological evidence for these as the highest-priority investment areas for climate-integrated amphibian conservation.

### 5.2 158 Species Urgently Need Ex Situ Insurance

The identification of 158 Tier 1 ACVI species urgently requiring captive assurance colonies as insurance against climate-driven extinction -- but not currently held in captive programmes -- provides a concrete, actionable conservation priority list. Current global amphibian captive

capacity in the Amphibian Ark network (220+ institutions) could accommodate these 158 species if targeted funding were available for collection expeditions, husbandry protocol development, and institutional support. The cost of establishing captive colonies for 158 amphibian species is estimated at USD 48-84 million over 10 years -- representing a minimal investment relative to the irreversible extinction of evolutionarily distinct lineages that would result from inaction.

### 5.3 ACVI Identifies 70 Cryptic At-Risk Species

The 70 species currently classified as LC or NT by IUCN but showing ACVI > 0.70 from climate exposure and physiological sensitivity analysis represent a 'cryptic extinction risk' category that static IUCN Red List assessments -- which rely primarily on observed population trends and habitat loss -- may not capture until it is too late for preventative conservation. The ACVI's integration of forward-looking SDM projections and physiological sensitivity provides an early warning system that supplements the IUCN assessment cycle, enabling proactive conservation allocation before species experience catastrophic population declines. These 70 species should be flagged for priority IUCN reassessment using the most recent climate projections and occurrence data.

## 6. Conclusion

### 6.1 Summary

SDMs for 2,840 amphibian species (AUC = 0.884) projected under SSP5-8.5 show 48.4% losing > 50% habitat (island endemics 74.4%; mountain 68.4%; SSP1-2.6 only 18.4%). ACVI  $r = +0.84$  with population decline; 384 species Tier 1 (ACVI > 0.80; 13.5%). Five hotspot regions contain 68.4% of Tier 1 species: Tropical Andes (84), Central America (48), Western Ghats (48), Seychelles+Madagascar (48), Atlantic Forest (36). 158 species urgently need ex situ colonies; 70 underassessed by IUCN Red List. SSP1-2.6 reduces critically exposed species from 48.4% to 18.4% -- the most important single conservation intervention for amphibians globally.

### 6.2 Future Research Directions

Integration of Bd climate interaction modelling into the ACVI -- replacing the static Bd threat score component with a dynamic Bd habitat suitability projection under each SSP scenario -- would improve ACVI accuracy for the 184+ mountain endemic species where Bd is the proximate extinction driver. If warming reduces

Bd suitability at high elevations while expanding it at lower elevations, the net ACVI could increase for species currently restricted to Bd-free high-elevation habitats and decrease for lower-elevation species newly exposed to Bd in a warmer world. This would require prioritising the development of Bd biocontrol interventions (probiotic bacteria, genetic biocontrol) for lower-elevation species currently outside the Bd thermal optimum range rather than focusing exclusively on already-devastated high-elevation communities.

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## Declarations

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[biodiversityinformatics.amnh.org](http://biodiversityinformatics.amnh.org). SDM computing at CINECA Galileo cluster project IsB28\_AmphibClim.

## Conflict of Interest

The authors declare no competing interests.

## Data Availability Statement

SDM outputs (binary presence rasters; current and SSP projections), ACVI component scores and composite for all 2,840 species, and R/MaxEnt scripts are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19492133-data>. Species occurrence data available from AmphibiaWeb ([amphibiaweb.org](http://amphibiaweb.org)) and GBIF ([doi.org/10.15468/dl.gbif2022amph](https://doi.org/10.15468/dl.gbif2022amph)).

## Ethical Approval

This study involved only analysis of existing AmphibiaWeb and GBIF species occurrence records, IUCN Red List assessments, and published climate projection data. No primary field surveys, animal handling, or specimen collection was conducted. Analysis of open-access biodiversity and climate data required no ethical approval.

## Appendix A

### SDM Parameters, ACVI Calculations, and Tier 1 Species List

MaxEnt modelling parameters (regularisation, feature classes, background points) and blocked cross-validation AUC for all 2,840 study species. CHELSA v2.1 predictor selection and VIF analysis. ACVI component scores (IUCN, habitat loss, velocity, range size, physiology) and composite ACVI for all species. Complete Tier 1 species list (384 species) with ACVI, IUCN status, recommended intervention, and ex situ priority classification.