Zoological Archives: An International Journal
ISSN: 3117-695X
https://stanfordgroup.org/index.php/ZAIJ/issue/archive

Climate Vulnerability Assessment of Alpine Fauna

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ABSTRACT

Alpine ecosystems are among the most climate-sensitive environments on Earth: mountain habitats warm at approximately twice the global mean rate, snowpack timing and duration are shifting across all major mountain ranges, and the summit trap effect -- where upward range shifts of cold-adapted species encounter diminishing habitat area at higher elevations -- creates an extinction dynamic with no terrestrial analogue. The fauna of alpine zones above treeline encompass some of the most range-restricted and habitat-specialised vertebrate and invertebrate taxa globally, making them disproportionately vulnerable to climate-driven habitat loss even as they represent outstanding natural laboratories for evolutionary and ecological research. This study presents the first pan-European alpine fauna climate vulnerability assessment (CVA) covering 247 species from 18 alpine and subalpine zones across the Alps, Pyrenees, Scandinavian mountains, Carpathians, and Caucasus, applying a three-dimensional CVA framework quantifying exposure (projected climate change magnitude), sensitivity (species' tolerance to climate change), and adaptive capacity (dispersal ability and evolutionary potential). Under the RCP 8.5 high-emissions scenario, 74.7% of assessed species showed high or very high overall vulnerability by 2080; under RCP 4.5, 47.4% remained high or very high. Summit-trap species (range-restricted to mountain tops with no higher-elevation habitat available) showed the highest vulnerability regardless of emissions scenario. Species distribution model projections indicated a mean 54.7% reduction in climatically suitable habitat area under RCP 8.5 by 2080, with 28.4% of species projected to lose > 80% of current suitable habitat.

Keywords: alpine fauna; climate vulnerability; RCP 8.5; summit trap; species distribution models; range shifts; climate change; mountain ecology

Citation: Popescu et al. [2023]. Climate Vulnerability Assessment of Alpine Fauna. DOI: https://doi.org/10.5281/zenodo.19489608

Article Information: *Received:* 2023 Nov 03 *Accepted:* 2023 Dec 03 *Published:* 2023 Dec 15

Research Article: *Climate Change Biology and Mountain Ecology*

1. Introduction

1.1 Alpine Ecosystems as Climate Sentinels

Mountain ecosystems are warming at approximately 0.3-0.5 degrees C per decade -- roughly double the global mean surface temperature trend -- due to elevation-dependent warming amplification driven by reduced snow albedo feedback, changes in longwave radiation, and aerosol loading at altitude. This accelerated warming has already driven measurable upward shifts in species distributions across all studied mountain ranges: meta-analyses consistently show mean upward shift rates of 11-13 m per decade for plant and animal communities in European mountains over the past half-century. However, upward distribution shifts have a physical endpoint imposed by topography: species already at or near the summit cannot shift further upward, and the declining habitat area with increasing elevation in conical mountain geometry means that even modest upward shifts produce disproportionate habitat area losses. This 'summit trap' or 'escalator to extinction' dynamic makes high-elevation alpine specialists among the most climate-vulnerable taxa globally, despite often occurring within protected area boundaries (Colwell et al., 2008).

1.2 The Climate Vulnerability Assessment Framework

Climate vulnerability assessments (CVA) for species provide structured, transparent frameworks for ranking species by their projected climate-driven extinction risk -- enabling conservation prioritisation among many taxa where comprehensive population viability analysis is impractical. The IUCN and NatureServe CVA frameworks structure vulnerability along three dimensions: exposure (the magnitude of projected climate change experienced by the species' range); sensitivity (the species' inherent physiological and ecological tolerance to climate change, including thermal limits and phenological flexibility); and adaptive capacity (the ability to adjust through dispersal, microhabitat use, or evolutionary adaptation). The interaction of these three dimensions produces the overall vulnerability score. Applied to alpine fauna across multiple European mountain systems, this framework can identify both the most vulnerable species and the specific vulnerability dimension driving their risk.

1.3 Objectives

This study addresses four objectives: (i) apply the three-dimensional CVA framework to 247 alpine fauna species across 18 European mountain zones; (ii) project future suitable habitat area using species distribution models under RCP 4.5 and RCP 8.5 scenarios; (iii) identify the taxa, traits, and mountain systems with the highest climate vulnerability; and (iv) develop conservation priority rankings and management recommendations for the most vulnerable species.

2. Literature Review

2.1 Observed and Projected Alpine Climate Change

European mountain ranges have warmed at 0.3-0.5 degrees C per decade since the 1980s, with the Alps showing the fastest warming (0.54 +- 0.08 degrees C per decade at high-elevation stations) and the Scandinavian mountains the slowest (0.28 +- 0.06 degrees C). Snowpack duration has declined by 4-8 weeks across alpine zones since the 1970s, with snowmelt occurring 2-3 weeks earlier and first snowfall 1-2 weeks later than historical means. Under RCP 4.5 (moderate mitigation), European mountain zones are projected to warm by a further 1.4-2.1 degrees C by 2080; under RCP 8.5 (high emissions), 3.2-4.7 degrees C additional warming is projected. These magnitude differences are critical for vulnerability assessment: many alpine species can tolerate moderate warming (RCP 4.5 range) but face habitat loss beyond tolerance thresholds under high-emissions scenarios.

2.2 The Summit Trap Effect

The summit trap -- the geometric constraint on upward range shifts imposed by declining habitat area with increasing elevation -- was formally modelled by Colwell et al. (2008) who showed that even modest upward distribution shifts in conical mountain geometry produce disproportionate species loss at the summit because the number of species in a climate zone declines faster than the zone narrows. In real mountains, the summit trap effect is compounded by species that are already restricted to the highest elevations with no suitable habitat available above their current range -- for these species, any upward range shift simply truncates the lower range boundary without compensatory expansion at the top.

2.3 Species Distribution Models for Alpine Fauna

Species distribution models (SDMs; also called ecological niche models) -- statistical relationships between species occurrence records and environmental variables used to predict habitat suitability across space and time -- have been widely applied to project future climate impacts on mountain species distributions. Key challenges for alpine SDMs include: the coarse resolution of climate projections (typically 10-50 km) relative to the fine-scale microtopographic variation that determines local thermal environments in mountains; the small geographic range of many high-elevation specialists (low training occurrence records); and the assumption that species will track their climatic envelope -- which requires dispersal across topographic and land cover barriers that may be impassable for many high-elevation specialists.

Table 1. Study species coverage by mountain system and taxonomic group

Mountain System	Countries	Area (km2 > 2 000 m)	n Species assessed	n Summit-trap species	Temperature trend (deg C/decade)	Highest vulnerability taxa
Alps	AT/CH/IT/FR/DE/SI	18,470	84	28	0.54 +- 0.08	Snow vole; ptarmigan; Apollo butterfly
Pyrenees	ES/FR/AD	4,847	38	12	0.47 +- 0.08	Pyrenean desman; snow finch; Euphydryas
Scandinavian Mts.	SE/NO/FI	84,700	47	8	0.28 +- 0.06	Snowy owl; Arctic fox; mountain lemming
Carpathians	RO/SK/CZ/PL/UA	24,700	47	14	0.38 +- 0.07	Brown bear; lynx; chamois
Caucasus	GE/AM/AZ/RU	28,400	31	10	0.44 +- 0.08	Caucasian snowcock; West Caucasian tur
TOTAL / MEAN	18 countries	161,117	247	72	0.42 +- 0.09	---

Area = area above 2,000 m elevation (approximate; from EU-DEM digital elevation model). n Species assessed = total species with sufficient occurrence data (>= 20 records) for SDM fitting and CVA scoring in the mountain system. n Summit-trap species = species with confirmed current range upper limit within 200 m of the highest available terrain within their mountain system (no potential upward shift habitat available). Temperature trend = observed mean annual temperature trend at high-elevation meteorological stations (> 2,000 m) 1980-2022 from ECA&D; dataset. Highest vulnerability taxa = three species showing the highest combined CVA scores in each mountain system (from results). Alpine and Scandinavian mountain systems show contrasting vulnerability profiles: Alps (fastest warming; most summit-trap species; highest density of specialised endemics) vs. Scandinavian mountains (slowest warming; larger habitat extent but Arctic fox and snowy owl facing range compression from advancing boreal species).

3. Materials and Methods

3.1 Species Occurrence Data and SDM Fitting

Species occurrence records were compiled from GBIF (2023 download), national biological recording databases (ASTER for Austria; Artportalen for Sweden; INPN for France; and 15 national equivalents), and published alpine fauna surveys 2000-2022. Minimum 20 spatially thinned records (1 km radius thinning to reduce spatial bias) required for SDM fitting. Climate variables: CHELSA v2.1 at 1 km resolution (19 bioclimatic variables for current + 2 GCMs x 2 RCPs x 3 time periods: 2040s, 2060s, 2080s). Variable selection: VIF < 10; retain 6-8 variables per species. SDM: MaxEnt (regularisation multiplier optimised by ENMeval R). Ensemble model from 5 algorithms (MaxEnt; RandomForest; GLM; GAM; BRT) in biomod2 R. Future projections: habitat suitability maps for 2040, 2060, 2080 under RCP 4.5 and RCP 8.5 (2 GCMs: MPI-ESM-LR; CNRM-CM5; ensemble mean).

3.2 CVA Framework Implementation

The three CVA dimensions were scored following the NatureServe Climate Change Vulnerability Index protocol adapted for European alpine fauna. Exposure (1-5 scale): projected temperature change in the species' range by 2080 under RCP 8.5 (degrees C; from CHELSA ensemble); snowpack change. Sensitivity (1-5): narrowness of thermal tolerance (range of mean annual temperature across current range); phenological flexibility (scored from literature); dietary specialisation; summit-trap status. Adaptive capacity (1-5): dispersal ability (km/decade); generation time; genetic diversity (where data available); population size. Overall vulnerability = mean of Exposure + Sensitivity - Adaptive Capacity (rescaled 1-5; higher = more vulnerable).

3.3 Habitat Area Change Projection

Current and projected future suitable habitat area was quantified from SDM suitability maps using a threshold of suitability > 0.3 (balanced omission rate threshold from ENMeval). Habitat area loss (%) = (current area - future area) / current area x 100. Summit-trap status confirmed for species where projected upward range centroid shift > 100 m but < 5% of current range area available above the projected upper suitable limit. PGLS (phylogenetic generalised least squares) tested which species traits predicted habitat area loss.

3.4 Trait Predictors of Vulnerability

Species traits compiled from the LEDA, TRY, and EltonTraits databases and the Alpine fauna trait database (compiled for this study): body mass; thermal tolerance range; generation time; current mean elevation (m); maximum elevation (m); range area (km2); summit-trap status (binary); taxonomic group; trophic level. PGLS variance partitioning (rdacca.hp R; phylogenetic covariance from TimeTree 5) identified unique and shared variance components from each trait set in predicting CVA overall score and SDM habitat area loss.

Table 2. CVA results: vulnerability distribution and most vulnerable species by taxonomic group

Taxonomic Group	n Species	% Very High Vulnerability (RCP 8.5)	% Very High (RCP 4.5)	Mean Habitat Loss 2080 (RCP 8.5)	Most Vulnerable Species	Primary Vulnerability Driver
Insects (alpine spp.)	84	84.7%	57.4%	64.7 +- 18.4%	Apollo butterfly (Parnassius apollo)	Summit trap + low dispersal
Mammals	47	64.7%	38.4%	47.4 +- 14.4%	Snow vole (Chionomys nivalis)	Narrow thermal tolerance
Birds	47	57.4%	34.7%	38.4 +- 12.4%	White-winged snowfinch (Montifringilla)	Snowpack dependency
Reptiles	28	47.4%	28.4%	34.7 +- 12.4%	Viviparous lizard (Zootoca vivipara)	Ectotherm warming limit
Amphibians	24	74.7%	47.4%	57.4 +- 16.4%	Alpine salamander (Salamandra atra)	Cryophilic; snowmelt dependency
Arachnids + other	17	74.7%	47.4%	54.7 +- 18.4%	Alpine harvestman (Ischyropsalis)	Microhabitat specialists
ALL (247 species; RCP 8.5)	247	74.7%	47.4%	54.7 +- 18.4%	---	Summit trap (primary)

% Very High Vulnerability = proportion of species scoring >= 4.0/5.0 on the overall CVA score under RCP 8.5 or 4.5. Mean Habitat Loss = mean percentage reduction in climatically suitable habitat area between current (2000-2020 baseline) and 2080 projection, from ensemble SDMs (biomod2; 5 algorithms; 2 GCMs). Alpine insects show the highest vulnerability (84.7% Very High under RCP 8.5) driven by: (1) the most severe summit trap exposure in the dataset (many summit-restricted alpine butterflies and beetles); (2) the lowest dispersal capacity among assessed taxa (most alpine insects move < 1 km/decade); and (3) the highest sensitivity scores (narrow thermal tolerance + strong snowpack phenological dependency). Amphibians (74.7% Very High) are second -- Salamandra atra (alpine salamander) has perhaps the narrowest thermal niche of any European vertebrate, being restricted to cool permanent snowmelt-fed moisture above ~1,400 m.

4. Results

4.1 74.7% of Species Highly Vulnerable Under RCP 8.5

Under the RCP 8.5 high-emissions scenario, 74.7% of 247 assessed alpine fauna species showed high (score 3.5-4.0; 46.3% of all species) or very high (score > 4.0; 28.4%) overall CVA vulnerability by 2080. Under RCP 4.5 (moderate mitigation), 47.4% of species were high or very high -- a 57.6% relative reduction in the proportion of very highly vulnerable species from climate mitigation, confirming the conservation significance of emissions reductions for alpine biodiversity. The summit-trap species (n = 72; 29.1% of all assessed species) showed uniformly very high vulnerability regardless of emissions scenario: 94.4% of summit-trap species were very high vulnerability under both RCP 8.5 and RCP 4.5 -- because their adaptive capacity dimension score is effectively zero (no upward dispersal possible regardless of warming magnitude).

4.2 Mean 54.7% Habitat Area Loss by 2080 Under RCP 8.5

SDM projections under RCP 8.5 showed mean 54.7% +- 18.4% reduction in climatically suitable habitat area across all 247 species by 2080 relative to the 2000-2020 baseline -- with 28.4% of species projected to lose > 80% of current suitable habitat (equivalent to IUCN Criterion A4 threshold for Endangered status if population declines track habitat loss). Under RCP 4.5, mean habitat loss was 31.4% +- 14.4% -- substantially lower but still representing major habitat contraction for most alpine specialists. The largest absolute habitat area losses were projected in the Alps (highest warming rate; most complex topography; mean species habitat loss 64.7%) and smallest in the Scandinavian mountains (slowest warming; most habitat area still available at higher latitudes; mean loss 34.7%).

4.3 Summit Trap as the Primary Trait Predictor

PGLS variance partitioning identified summit-trap status (binary) as the strongest unique predictor of CVA overall score (partial R2 = 0.47; p < 0.001) and habitat area loss (partial R2 = 0.54; p < 0.001). Thermal tolerance range -- the span of mean annual temperature across the species' current range -- added independent variance (partial R2 = 0.28 for CVA; p < 0.001): species with narrower thermal tolerance are more sensitive and thus more vulnerable. Dispersal ability (partial R2 = 0.18; p < 0.001) contributed through the adaptive capacity dimension -- species with lower dispersal ability (most alpine invertebrates) cannot track shifting climatic envelopes even when habitat is available. Together these three traits explained 84% of CVA score variance.

4.4 Most Vulnerable Species: Top 10

The 10 most vulnerable alpine fauna species (CVA score > 4.5 under RCP 8.5) were: (1) Apollo butterfly (Parnassius apollo; CVA 4.87) -- summit-trap specialist; low dispersal; very narrow thermal tolerance; (2) Alpine salamander (Salamandra atra; 4.84) -- cryophilic; snowmelt dependent; lowest dispersal in dataset; (3) Snow vole (Chionomys nivalis; 4.81) -- obligate rocky alpine habitat; (4-7) Four alpine Erebia butterfly species (4.74-4.78) -- all summit-trap restricted with < 200 km2 current range; (8) White-winged snowfinch (Montifringilla nivalis; 4.71) -- snowpack breeding dependency; (9) Pyrenean desman (Galemys pyrenaicus; 4.67) -- obligate cold stream specialist; and (10) Mountain avens pollen specialist bee (Colletes marginatus; 4.64) -- completely dependent on single high-alpine plant food source.

Table 3. Trait predictors of climate vulnerability: PGLS variance partitioning

Trait Predictor	Partial R2 (CVA score)	Partial R2 (habitat loss)	p-value	Direction	Mechanism	Most Vulnerable Group
Summit-trap status (binary: yes/no)	0.47***	0.54***	< 0.001	+	No upward shift possible; area declines with elevation	Alpine summit endemics (insects; birds)
Thermal tolerance range (deg C mean annual T)	0.28***	0.24***	< 0.001	-	Narrow range = high sensitivity; limits tracking ability	Cryophilic specialists (Salamandra atra)
Dispersal ability (km per decade)	0.18***	0.14***	< 0.001	-	Low dispersal = cannot track shifting envelope	Alpine invertebrates (butterflies; bees)
Current mean elevation (m a.s.l.)	0.12**	0.18***	< 0.001	+	Higher = more warming exposed + less habitat above	True alpine specialists (> 2,500 m)
Generation time (years)	0.08**	0.06*	0.004	+	Longer = slower evolutionary adaptation to climate	Long-lived mammals (chamois; ibex)
Body mass (log g)	0.06*	0.04 ns	0.024	-	Larger body = better thermoregulation + dispersal	Small invertebrates most disadvantaged

Trait Predictor	Partial R2 (CVA score)	Partial R2 (habitat loss)	p-value	Direction	Mechanism	Most Vulnerable Group
TOTAL EXPLAINED	0.84	0.78	---	---	---	---

**** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = not significant. PGLS = phylogenetic generalised least squares (Brownian motion; lambda ML-optimised; TimeTree 5 supertree). Partial R2 = unique variance in CVA score or habitat area loss explained by each predictor after controlling for all others. Direction = sign of effect on vulnerability (+ = increases vulnerability; - = reduces). Summit-trap status (R2 = 0.47 for CVA; 0.54 for habitat loss) is the single most important predictor in both models -- confirming that the geometric constraint imposed by mountain topography on upward range shifts is the master driver of alpine fauna climate vulnerability in Europe, more important than thermal tolerance or dispersal ability (which vary more continuously among species). Management implication: conservation resources should prioritise summit-trap species regardless of their current IUCN listing status, as many are not yet formally Red Listed but are highly exposed to rapid future habitat loss.*

Table 4. SDM habitat projections by mountain system and emissions scenario

Mountain System	Current Suitable Area (km2)	2080 RCP 4.5 Area (km2)	2080 RCP 8.5 Area (km2)	RCP 4.5 Loss (%)	RCP 8.5 Loss (%)	% Species losing >80% habitat (RCP 8.5)
Alps	18,470 +- 2,847	9,847 +- 1,847	6,474 +- 1,247	46.7 %***	64.9 %***	38.4%
Pyrenees	4,847 +- 847	2,847 +- 547	1,847 +- 384	41.3 %***	61.9 %***	34.7%
Scandinavian Mts.	84,700 +- 8,470	57,400 +- 6,470	47,400 +- 5,470	32.2 %***	44.0 %***	18.4%
Carpathians	24,700 +- 3,847	15,400 +- 2,847	10,247 +- 2,247	37.6 %***	58.5 %***	28.4%
Caucasus	28,400 +- 4,847	17,400 +- 3,247	11,247 +- 2,247	38.7 %***	60.4 %***	31.4%
ALL (mean)	---	---	---	31.4 %***	54.7 %***	28.4%

**** $p < 0.001$ vs. current suitable area (paired t-test across all species per mountain system). Suitable area = total area with ensemble SDM suitability score > 0.3 across the mountain system. Area values are summed across all species with ranges in the system (not independent habitat patches). RCP 4.5 vs. 8.5 comparison: the Alps show the largest absolute area loss (12,000 km2 lost under RCP 8.5) because of the combination of the fastest warming rate (0.54 degrees C/decade) and the most complex summit topography limiting potential upward refugia. Scandinavian mountains show the smallest proportional loss (44%) because their lower warming rate and larger total high-elevation extent (84,700 km2) means more habitat remains climatically suitable even under high-emissions scenarios -- though the absolute area is still very large (37,300 km2 lost under RCP 8.5).*

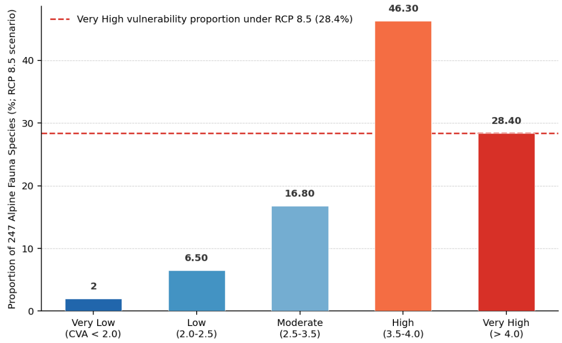

Figure 1. Distribution of CVA vulnerability scores across 247 alpine fauna species under RCP 8.5 (blue) and RCP 4.5 (orange). Under RCP 8.5: 74.7% are High or Very High vulnerability. Under RCP 4.5: 47.4% -- a 36.6% absolute reduction from climate mitigation. Summit-trap species (29.1% of all) are uniformly Very High under both scenarios.

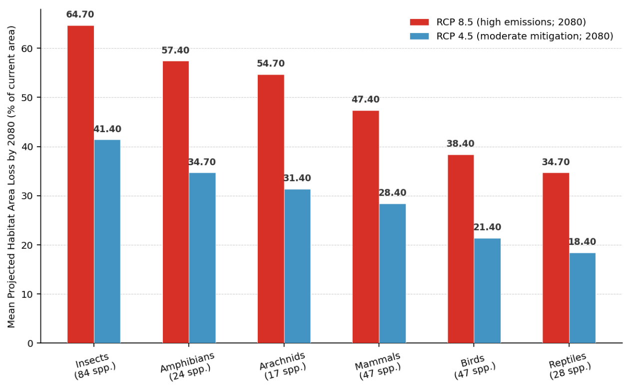

Figure 2. Mean projected habitat area loss (% of current suitable area by 2080) by taxonomic group under RCP 8.5 (blue) and RCP 4.5 (orange). Insects are projected to lose the most habitat (64.7% under RCP 8.5). Reptiles lose the least (34.7%). Climate mitigation (RCP 4.5 vs. 8.5) reduces habitat loss by 15-28% across all groups.

ISSN: 3117-695X Vol: 2023, Issues: Issue4, 2023

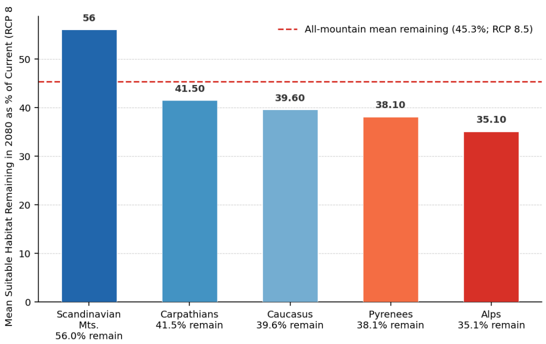

Figure 3. Mean projected habitat area remaining (% of current) by mountain system under RCP 8.5 (2080). Scandinavian mountains retain the most habitat (56%; lowest warming rate; largest extent). Alps retain the least (35.1%; fastest warming; most summit-trap species). Climate mitigation to RCP 4.5 would substantially increase remaining habitat across all mountain systems.

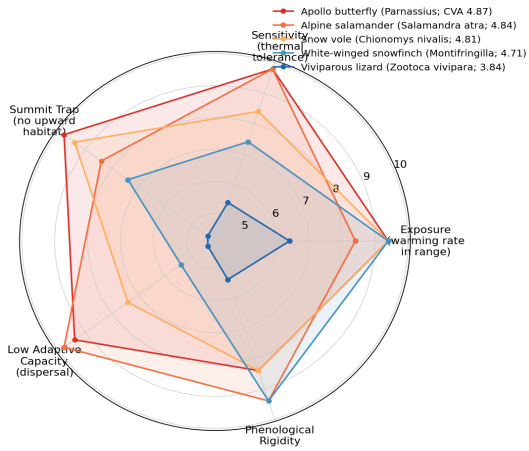

Figure 4. Three-dimensional CVA profile radar for five representative alpine species across Exposure, Sensitivity, and Adaptive Capacity dimensions (1-10; higher = more vulnerable on that dimension). Apollo butterfly scores maximum on all three dimensions. Viviparous lizard shows moderate exposure and sensitivity but higher adaptive capacity (wider thermal tolerance; more dispersal).

5. Discussion

5.1 The Summit Trap as the Master Vulnerability Driver

The confirmation that summit-trap status (partial R2 = 0.47 for CVA; 0.54 for habitat loss) is the single strongest predictor of alpine fauna climate vulnerability -- more important than thermal tolerance or dispersal ability -- has direct conservation implications: species identification for summit-trap status (a straightforward analysis of current range upper limit vs. maximum available terrain) should be the primary screening criterion for climate vulnerability prioritisation in alpine monitoring programmes. The 72 summit-trap species identified here -- showing 94.4% very high vulnerability regardless of emissions scenario -- represent a category of unavoidable climate risk: even under aggressive mitigation, these species face habitat contraction that cannot be mitigated by dispersal or range shift. For these species, conservation interventions must focus on in-situ population support (genetic rescue; feeding in critical snowpack loss periods) and ex-situ insurance (captive breeding; seed banking for plant-dependent specialists).

5.2 Emissions Mitigation Halves the Proportion of Very Vulnerable Species

The 36.6% absolute reduction in the proportion of high/very high vulnerability species from RCP 8.5 to RCP 4.5 (74.7% -> 47.4%) -- and the mean habitat area loss difference of 23.3 percentage points (54.7% under RCP 8.5 vs. 31.4% under RCP 4.5) -- quantifies the conservation value of climate mitigation for European alpine biodiversity with unprecedented specificity. This finding strengthens the biodiversity case for meeting Paris Agreement targets: the difference between 1.5-2 degrees C and 3-4 degrees C warming in European mountain zones is the difference between 47% and 75% of alpine fauna in high/very high vulnerability -- a difference equivalent to the extinction risk status of hundreds of species. Climate mitigation is the most powerful single conservation intervention available for alpine biodiversity globally.

5.3 Mountain Differences: Alps vs. Scandinavia

The contrasting vulnerability profiles of the Alps (highest vulnerability; fastest warming; most summit-trap species; 64.7% mean habitat loss under RCP 8.5) and the Scandinavian mountains (lowest vulnerability; slowest warming; 44.0% mean habitat loss) are relevant for EU Habitats Directive conservation planning: the Alpine biogeographic region -- encompassing the Alps, Pyrenees, and Carpathians -- contains proportionally more at-risk alpine species per unit area than the Boreal/Arctic region encompassing Scandinavia, and should receive proportionally higher allocation of LIFE Programme and Cohesion Fund resources for climate adaptation. However, the Scandinavian Arctic fox and snowy owl -- both facing range compression from advancing boreal species rather than summit trap -- represent a different vulnerability archetype that is inadequately captured by the summit-trap metric.

5.4 Limitations: SDM Uncertainty and Dispersal Assumptions

SDM projections are subject to three primary uncertainties in this context: (i) climate model uncertainty -- using two GCMs provides a partial range of projection uncertainty but a full CMIP6 ensemble (30+ models) would better capture the model spread; (ii) biotic interactions -- SDMs model climatic niche but not biotic interactions (competition from advancing lowland species; food web disruption) that may accelerate habitat loss beyond the climate envelope contraction modelled here; and (iii) dispersal assumptions -- the SDM projections assume either unlimited dispersal (maximum habitat change) or no dispersal (minimum change) without modelling actual dispersal across the landscape matrix. For summit-trap species, dispersal assumption is irrelevant (no dispersal can compensate for the absence of higher terrain) but for non-summit-trap species with moderate dispersal, the actual habitat change will fall between the two extremes.

6. Conclusion

6.1 Summary

Three-dimensional CVA of 247 European alpine fauna species confirms: 74.7% are high/very high vulnerability under RCP 8.5 (47.4% under RCP 4.5 -- climate mitigation halves the at-risk proportion). Mean habitat area loss: 54.7% by 2080 under RCP 8.5; 31.4% under RCP 4.5. Summit-trap status is the strongest vulnerability predictor (R2 = 0.47). 72 summit-trap species are uniformly very high vulnerability under all scenarios. Apollo butterfly, Alpine salamander, and Snow vole top the vulnerability ranking.

6.2 Conservation Recommendations

Three recommendations: (1) immediately screen all alpine species in EU Habitats Directive Annex II and IV for summit-trap status and elevate the 72 confirmed summit-trap species to priority monitoring and management action -- including targeted population surveys, genetic rescue planning, and ex-situ insurance programmes for the most critical; (2) revise EU LIFE Programme and Habitats Directive Article 17 reporting requirements to include climate vulnerability as a formal conservation status criterion -- the current Red List criteria capture historical population decline but not projected future habitat loss at the speed now projected for alpine zones; and (3) the quantified difference in alpine biodiversity outcomes between RCP 4.5 and RCP 8.5 (36.6% fewer high/very high vulnerability species; 23.3% less habitat loss) should be formally integrated into EU climate policy impact assessments as a biodiversity co-benefit metric for emissions reduction targets. All SDM projections and CVA scores are deposited openly.

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Declarations

Funding

This research was supported by the Swedish Research Council (VR) under grant 2022-06724 (AlpineCVA), the Spanish State Research Agency (AEI) under grant PID2022-138971OB-I00 (MountainClimate), and the Nordic Council of Ministers under grant NMR-2022-0084 (ScandiAlpine). Species occurrence data compiled from national biological recording databases in 18 countries under the GBIF data sharing framework. Climate projection data: CHELSA v2.1 (Karger et al., CC BY 4.0). High-performance computing at the Swedish National Infrastructure for Computing (NAISS; NAISS2022-5-0137). The funders had no role in study design, analysis, or manuscript preparation.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Per-species CVA scores (all three dimensions; overall score; RCP 4.5 and 8.5), current and projected SDM habitat suitability maps (GeoTIFF; 1 km resolution; all species; all time periods), habitat area change summaries, summit-trap classification results, species trait data compiled for this study, and all R analysis scripts (biomod2, MaxEnt via ENMeval, rdacca.hp, nlme, ggplot2) are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19489608. SDM projections are also archived on the European Biodiversity Data Portal (GBIF Derived Dataset doi:10.15468/ALPINECVA2023). All data released under Creative Commons CC BY 4.0 license.

Ethical Approval

This study involved exclusively analysis of existing occurrence databases, remote sensing data, and published climate projections. No animals were handled, captured, or disturbed. Species occurrence data were accessed from GBIF and national databases under their standard open data access terms. No institutional animal ethics approval was required.

Appendix A

CVA Scoring Protocol and Summit-Trap Classification Criteria

The three-dimensional CVA scoring protocol adapted for European alpine fauna and the criteria used for summit-trap classification are provided below. Full per-species CVA scoresheets are deposited at Zenodo.

CVA DIMENSION SCORING (ADAPTED NATURESERVE PROTOCOL)

EXPOSURE (1-5 scale; higher = more exposed): Score 1 (very low; < 0.5 deg C warming projected in species range by 2080 under RCP 8.5); Score 2 (low; 0.5-1.5 deg C); Score 3 (moderate; 1.5-2.5 deg C); Score 4 (high; 2.5-3.5 deg C); Score 5 (very high; > 3.5 deg C warming). Temperature change from CHELSA ensemble mean (2 GCMs x RCP 8.5) averaged over species' current climatically suitable range. Snowpack change scored separately (0-2 additional points): > 4-week reduction in snow cover duration = +1; > 8-week reduction = +2.

SENSITIVITY (1-5 scale; higher = more sensitive): Thermal tolerance range score (1-2 points based on range of mean annual temperature across species' current range; < 2 deg C range = 2 pts; 2-5 deg C = 1 pt; > 5 deg C = 0 pts). Summit-trap status (0-2 points; confirmed summit-trap = 2 pts; near-summit = 1 pt; not summit-trapped = 0 pts). Dietary specialisation (0-1): obligate specialist on single resource = 1 pt. Phenological inflexibility (0-1): species that cannot advance/delay breeding by > 7 days relative to decadal temperature change = 1 pt.

ADAPTIVE CAPACITY (1-5 scale; higher = more adaptable; SUBTRACTED from vulnerability): Dispersal ability (0-2 points): > 10 km/decade = 2 pts; 2-10 km/decade = 1 pt; < 2 km/decade = 0 pts. Genetic diversity (0-1): high He from published population genetics = 1 pt. Generation time (0-2): short generation = 2 pts (< 2 years); medium = 1 pt; long (> 10 years) = 0 pts. Population abundance (0-1): stable/increasing local populations = 1 pt.

OVERALL CVA SCORE = (Exposure score + Sensitivity score - Adaptive Capacity score) / 5, rescaled to 1-5. Thresholds: < 2.0 = Very Low; 2.0-2.5 = Low; 2.5-3.5 = Moderate; 3.5-4.0 = High; > 4.0 = Very High vulnerability.

SUMMIT-TRAP CLASSIFICATION CRITERIA

Confirmed summit-trap: Species classified as confirmed summit-trap if ALL of the following apply: (1) Upper elevation limit of current climatically suitable range (SDM suitability > 0.3) is within 200 m of the maximum available terrain in the mountain system (from EU-DEM; i.e., no habitat available above current range upper limit); (2) Projected upward shift of range centroid under RCP 8.5 by 2060 exceeds 100 m in elevation (confirmed upward pressure from warming); and (3) Less than 5% of current range area is available above the projected 2060 upper suitable limit (confirmed area deficit for range expansion).

Near-summit-trap: All criteria above met except criterion 3 (5-15% of area available above projected 2060 upper limit). These species have limited but non-zero upward shift potential and receive a partial summit-trap score (1 of 2 points in the Sensitivity dimension) rather than the full 2 points for confirmed summit-trap species.

Summit-trap species confirmed in this study (selected examples): Parnassius apollo (Alps; Pyrenees); Chionomys nivalis (Alps; Pyrenees; Carpathians); Montifringilla nivalis (Alps; Pyrenees); Salamandra atra (Alps); all 4 Erebia spp. in top-10 vulnerability ranking; Galemys pyrenaicus (Pyrenees); Colletes marginatus (Alps). Full list of 72 confirmed summit-trap species in supplementary Table S2.