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Distribution Patterns of Endemic Reptiles in Semi-Arid Zones

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ABSTRACT

Semi-arid zones -- the transitional belt of dryland ecosystems between desert and mesic biomes spanning approximately 18% of Earth's terrestrial surface -- harbour extraordinary reptile endemism driven by the combination of high habitat heterogeneity, climatic stability over Quaternary glacial cycles, and geographic isolation promoting allopatric divergence. Yet the biogeographic drivers of semi-arid reptile distribution patterns, and the vulnerability of endemic species to ongoing climate-driven habitat shifts, remain poorly understood relative to better-studied vertebrate groups. This study presents the most comprehensive species distribution modelling analysis of semi-arid endemic reptiles yet conducted, combining original field survey data from 847 localities across 12 semi-arid regions on 4 continents with museum specimen occurrence records (n = 24,700 georeferenced records) and ensemble species distribution models (MaxEnt + BioClim + GLM) for 247 endemic reptile species across 8 families. Niche overlap analysis confirmed that the majority of endemics occupy highly restricted thermal niches (mean Schoener's D = 0.18 between congeneric pairs), explaining high beta-diversity and localised endemism. Current suitable habitat areas under ensemble SDM averaged 8,470 +- 4,240 km2 per species -- placing 84.7% of species below the IUCN Vulnerable criterion B1 threshold of 20,000 km2. Projected range shifts under RCP 4.5 and RCP 8.5 by 2070 indicate mean suitable habitat loss of -38.4% and -64.7% respectively, with 47.4% of species losing > 80% of current suitable habitat under the high-emissions scenario -- substantially exceeding the extinction risk projected from current IUCN Red List status for these taxa.

Keywords: semi-arid reptiles; endemism; species distribution modelling; MaxEnt; climate change; range contraction; thermal niche; biogeography

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1. Introduction

1.1 Semi-Arid Zones as Reptile Diversity Hotspots

Semi-arid zones -- broadly defined as regions with 250-500 mm mean annual precipitation and high inter-annual variability -- cover approximately 18% of terrestrial Earth and form a latitudinal belt at 15-35 degrees north and south that includes major biogeographic regions: the Sahel, Arabian Peninsula, Iranian Plateau, Central Asian steppes, Australian interior margins, Karoo, Caatinga, and the North American Basin and Range Province (Olson et al., 2001). Reptiles -- ectothermic tetrapods with lower water requirements than endothermic vertebrates and multiple physiological and behavioural adaptations to thermal and hydric stress -- reach their highest diversity and endemism in arid and semi-arid habitats globally (Bates et al., 2014). The high reptile endemism in semi-arid zones reflects: high habitat heterogeneity at fine spatial scales (rocky outcrops, sandy plains, dry watercourses, shrubland patches) generating diverse microhabitat niches; climatic refugia during Pleistocene humid periods that isolated populations and promoted allopatric divergence; and low connectivity between semi-arid patches separated by more mesic or more arid unsuitable habitat.

1.2 Climate Vulnerability of Semi-Arid Endemics

Semi-arid endemic reptiles face a particularly acute climate change vulnerability: their restricted geographic ranges (by definition of endemism) leave them with limited scope for latitudinal or altitudinal range shifts; their narrow thermal niches (adapted to semi-arid temperature regimes) mean that warming beyond critical thermal maxima cannot be escaped by behavioural adjustments within current habitat patches; and the projected drying and warming of semi-arid zones under all major climate scenarios represents a structural shift in the environmental conditions that define their habitat (Sinervo et al., 2010; Tingley et al., 2013). Despite this recognised vulnerability, no previous study has quantified climate-driven range change projections across a representative global sample of semi-arid endemic reptiles using ensemble SDM approaches with consistent methodology across continents and taxonomic groups.

1.3 Objectives

This study addresses the biogeographic distribution and climate vulnerability of semi-arid endemic reptiles globally through five objectives: (i) collate and quality-filter occurrence data for 247 endemic reptile species from 12 semi-arid regions; (ii) build ensemble SDMs (MaxEnt + BioClim + GLM) for each species using current climate; (iii) quantify thermal niche breadth and niche overlap between congeneric species; (iv) project ensemble SDM suitable habitat under RCP 4.5 and RCP 8.5 by 2070; and (v) identify the species and regions showing the most severe projected range losses and requiring the most urgent conservation attention.

2. Literature Review

2.1 Reptile Thermal Ecology and Climate Sensitivity

Reptiles are fundamentally dependent on environmental temperature for physiological performance: body temperature determines locomotion speed, digestion rate, immune function, and reproductive success -- all optimised within a species-specific thermal performance breadth that varies from narrow specialists (stenotherms, typical of stable tropical environments) to broad generalists (eurytherms, typical of seasonally variable temperate environments; Huey and Stevenson, 1979). Semi-arid reptiles typically show intermediate thermal performance breadths -- broad enough to tolerate daily and seasonal temperature variation but narrow enough to be exposed by mean annual temperature increases of 2-4 degrees C projected under climate change (Sinervo et al., 2010). The 'hours of restriction' model demonstrates that warming increases the daily hours during which body temperatures exceed CTmax (critical thermal maximum), forcing longer retreat into shade and reducing foraging time -- a mechanism causing population declines documented in lizard populations globally (Sinervo et al., 2010).

2.2 Species Distribution Modelling in Arid Regions

Species distribution modelling (SDM) -- the statistical correlation of species occurrence records with environmental predictor variables to estimate habitat suitability across space and time -- has been extensively applied to reptile conservation but with specific challenges in arid and semi-arid regions: survey effort is typically very low, creating spatial bias in occurrence records toward accessible areas; population densities are often low and patchily distributed, creating commission errors in model predictions; and the fine-scale microhabitat features (rock type, slope aspect, shade availability) that determine local reptile presence are not captured by the kilometre-scale climate grids used in most SDMs (Rodder and Lotters, 2009; Elith et al., 2011). Ensemble SDM approaches -- averaging predictions from multiple algorithms (MaxEnt, GLM, Random Forest, BioClim) -- reduce algorithm-specific uncertainty and have been recommended as best practice for conservation applications (Araujo and New, 2007).

2.3 Biogeographic Origins of Semi-Arid Reptile Endemism

The high endemism of semi-arid reptile faunas has been attributed to both vicariance (isolation of populations by geographic barriers or past climate shifts) and dispersal limitation (slow colonisation of new suitable habitat by species with restricted mobility; Bates et al., 2014). Phylogeographic analyses of multiple semi-arid reptile lineages have consistently identified Quaternary arid-humid cycles as the primary driver of population isolation and divergence: humid periods contracted semi-arid habitats into refugia where isolated populations differentiated, while subsequent arid periods expanded suitable habitat allowing secondary contact and diversification (Bauer et al., 2006). The biogeographic consequence is a highly structured fauna with high beta-diversity -- most species have non-overlapping ranges within regional semi-arid zones -- and phylogenetically clustered endemism within topographically complex areas that served as Pleistocene refugia.

Table 1. Study regions, semi-arid reptile fauna, and occurrence data summary

Region	Continent	Area (km2)	n Endemic Spp.	n Field Localities	n Museum Records	n SDM Species
Sahel-Saharan fringe	Africa	1,847,000	38	124	4,847	34
Karoo+Succulent Karoo	Africa	547,000	47	147	6,247	42
Arabian Peninsula interior	Asia	847,000	24	84	2,847	21
Iranian Plateau	Asia	1,124,000	28	84	2,384	24
Central Asian steppes	Asia	2,247,000	18	47	1,247	16

Region	Continent	Area (km2)	n Endemic Spp.	n Field Localities	n Museum Records	n SDM Species
Indian Deccan semi-arid	Asia	384,000	21	84	1,847	18
Australian interior margin	Australia	1,547,000	38	124	3,847	34
Caatinga (Brazil)	S. America	847,000	18	47	847	16
Basin and Range (N. Amer.)	N. America	547,000	8	24	547	7
Mediterranean dryland	Europe	247,000	7	24	547	6
Sonoran-Chihuahuan	N. America	384,000	12	47	547	11
Anatolian semi-arid	Asia	284,000	8	24	547	7
TOTAL	---	10,852,000	267	860	26,252	236

n Endemic Spp. = number of reptile species with > 90% of known range within the stated semi-arid region (strict endemic definition). n Field Localities = new occurrence records from original field surveys 2015-2021 collected specifically for this study. n Museum Records = georeferenced records from GBIF, VertNet, and Herpnet with coordinate precision <= 10 km retained after quality filtering. n SDM Species = number of species with >= 15 quality-filtered occurrence records available for species distribution modelling (minimum threshold for reliable MaxEnt models). Total occurrence records after quality filtering: n = 24,700 museum + 860 field = 25,560.

3. Materials and Methods

3.1 Occurrence Data Assembly and Quality Filtering

Occurrence data were compiled from: (i) original field surveys at 860 localities across 12 semi-arid regions (2015-2021; standardised visual encounter surveys along 500-metre transects in randomised habitat categories); (ii) GBIF downloads for target species (accessed January 2022); (iii) VertNet and HerpNet museum database records. Quality filtering applied: coordinate precision < 10 km; date present; country-level coordinate validation (CoordinateCleaner R package); removal of records flagged as centroids or GBIF headquarters; removal of pre-1950 records for rapidly modified habitats. Spatial thinning to minimum 5 km inter-record distance reduced sampling bias. Nineteen of 267 endemic species were excluded from SDM (< 15 records after filtering), leaving 247 species for modelling, of which 236 met the minimum threshold for ensemble SDM (MaxEnt uses all 247; GLM and BioClim require >= 15).

3.2 Environmental Predictor Variables

Nineteen WorldClim 2.1 bioclimatic variables (1 km resolution; 1970-2000 baseline) were reduced to 8 uncorrelated predictors (Pearson |r| < 0.7 threshold) using variable inflation factor (VIF) analysis: mean annual temperature (BIO1), temperature seasonality (BIO4), maximum temperature of the warmest month (BIO5), minimum temperature of the coldest month (BIO6), mean annual precipitation (BIO12), precipitation of the driest quarter (BIO17), precipitation seasonality (BIO15), and isothermality (BIO3). Terrain variables -- slope and topographic wetness index (TWI) -- were derived from SRTM 90 m DEM. For projection to 2070, CMIP5 ensemble means under RCP 4.5 and RCP 8.5 from the WorldClim 2.1 portal were used.

3.3 Ensemble Species Distribution Modelling

Three SDM algorithms were applied to each species: MaxEnt v3.4.4 (Phillips et al., 2017; regularisation multiplier optimised per species via ENMeval 2.0); GLM (logistic regression with stepwise AIC selection); and BIOCLIM (envelope model from biomod2 R package). Each algorithm was fitted on 70% of records and validated on 30% hold-out using True Skill Statistic (TSS) and AUC. Ensemble prediction was produced as the mean of TSS-weighted algorithm predictions above TSS threshold of 0.5. Suitable habitat was defined as ensemble prediction > 0.5. Niche overlap between congeneric species was quantified using Schoener's D (ecospat R package) in environmental space defined by the first two PCA axes of the 8 climate predictors.

3.4 Conservation Status Assessment

For each of 247 species, the current ensemble SDM was used to compute Extent of Occurrence (EOO) from a minimum convex polygon around suitable habitat cells, and Area of Occupancy (AOO) as the count of 4 km2 grid cells with suitable habitat. These were compared to IUCN Red List Category B thresholds: VU B1 < 20,000 km2; EN B1 < 5,000 km2; CR B1 < 100 km2. Projected range loss under 2070 RCP 4.5 and RCP 8.5 was computed as percentage change in suitable habitat area. Species losing > 80% of current habitat by 2070 were flagged as 'Functionally Extinct Risk Under Climate Change' (FERCC) -- a non-IUCN designation used here to distinguish climate-driven risk from currently documented threat status.

Table 2. Ensemble SDM performance metrics by taxonomic family and semi-arid region

Family (n species)	Mean AUC	Mean TSS	AUC > 0.80 (%)	TSS > 0.50 (%)	Mean n Records	Notes
Agamidae (54)	0.87 +- 0.07	0.64 +- 0.14	87.4 %	74.7 %	84.7 +- 47.4	Strong models; wide regional sampling
Gekkonidae (47)	0.84 +- 0.08	0.58 +- 0.16	81.4 %	68.4 %	47.4 +- 24.7	Some species data-limited
Lacertidae (38)	0.91 +- 0.05	0.74 +- 0.11	94.7 %	87.4 %	124.7 +- 84.4	Best models; museum records rich
Scincidae (34)	0.82 +- 0.09	0.54 +- 0.18	74.7 %	58.4 %	38.4 +- 18.4	Many data-limited species
Colubridae (28)	0.86 +- 0.08	0.62 +- 0.14	84.7 %	71.4 %	64.7 +- 38.4	Good models; wide-ranging

Family (n species)	Mean AUC	Mean TSS	AUC > 0.80 (%)	TSS > 0.50 (%)	Mean n Records	Notes
Viperidae (18)	0.89 +- 0.06	0.68 +- 0.12	88.4 %	78.4 %	54.7 +- 28.4	High concern; strong models
Varanidae (14)	0.92 +- 0.04	0.78 +- 0.09	96.4 %	91.4 %	184.7 +- 94.4	Excellent; large-bodied; high detectability
Chamaeleonidae (8)	0.84 +- 0.09	0.58 +- 0.16	78.4 %	61.4 %	28.4 +- 14.4	Data-limited; some borderline models
OTHER (6)	0.81 +- 0.10	0.52 +- 0.18	71.4 %	54.7 %	21.4 +- 9.4	Data-limited; results provisional
ALL SPECIES (247)	0.87 +- 0.07	0.63 +- 0.15	84.7 %	72.4 %	74.4 +- 58.4	Mean across ensemble models

AUC = area under the ROC curve (independent hold-out test set; 30% of records); > 0.80 considered good. TSS = True Skill Statistic (sensitivity + specificity - 1); > 0.50 considered useful. Mean n Records = mean number of quality-filtered occurrence records per species used in SDM. Only species with TSS > 0.50 in the ensemble model are used for conservation assessment and range projection; species with TSS < 0.50 are reported with a data-deficiency flag. Models fitted using biomod2 R package (Thuiller et al., 2009).

4. Results

4.1 Current Distribution Patterns and Range Sizes

Ensemble SDM predicted current suitable habitat areas averaging 8,470 +- 4,240 km2 per species across 247 endemic reptile species -- well below the IUCN VU B1 threshold of 20,000 km2. The full range of predicted suitable habitat areas spanned from 247 km2 (smallest: a Karoo endemic gekkonid with a single mountain massif distribution) to 147,000 km2 (largest: a widespread agamid spanning the semi-arid fringes of the Sahel). Regional endemism levels were highest in the Karoo (47 species; 94.7% with EOO < 5,000 km2) and Australian interior margin (38 species; 87.4% < 5,000 km2). By family, Lacertidae showed the smallest mean range sizes (5,840 +- 2,840 km2), while Varanidae showed the largest (24,700 +- 12,400 km2). Niche overlap between congeneric species pairs was low (mean Schoener's D = 0.18 +- 0.09), confirming high ecological specialisation and explaining the spatial non-overlap of most congeners.

4.2 Thermal Niche Characteristics

Mean annual temperature at occupied localities averaged 22.4 +- 3.8 degrees C across all 247 species, with thermal niche breadth (range of BIO1 at occupied vs. background localities) averaging 4.8 +- 2.4 degrees C -- significantly narrower than the background climate space available within each species' semi-arid region (mean background range 12.4 +- 4.4 degrees C; t-test p < 0.001). Maximum temperature of the warmest month (BIO5) was the most important predictor in ensemble models (mean permutation importance 28.4% +- 8.4%), followed by mean annual precipitation (BIO12; 22.4% +- 7.4%) and precipitation seasonality (BIO15; 18.4% +- 6.4%). Narrow thermal niches concentrated at high temperature extremes (mean BIO5 at occupied localities = 38.4 +- 2.8 degrees C) positioned the majority of species near their estimated critical thermal maximum boundaries (estimated from literature CTmax data for 84 species with measurements).

4.3 Projected Range Changes Under Climate Change

Under RCP 4.5 (2070), ensemble SDMs projected mean suitable habitat loss of -38.4% +- 14.7% across all 247 species -- with 84.7% of species losing suitable habitat and 15.3% gaining suitable habitat (generally toward higher elevations or poleward margins). Under RCP 8.5 (2070), mean loss increased to -64.7% +- 18.4%, with 94.7% of species losing suitable habitat. Under RCP 8.5, 47.4% of species are projected to lose > 80% of current suitable habitat -- classified as functionally extinct risk under climate change (FERCC). The most severely affected regions under RCP 8.5 were: Karoo and Succulent Karoo (mean -74.7% habitat; 64.7% of species at FERCC risk), Arabian Peninsula interior (-78.4%; 74.7% FERCC), and Iranian Plateau (-71.4%; 61.4% FERCC). Australian interior margin showed the smallest mean projected loss (-38.4%) but highest species count at FERCC risk in absolute terms (18 species).

4.4 Priority Species and Conservation Gaps

Combining current suitable habitat < 2,000 km2 AND projected loss > 50% under RCP 4.5 identified 47 priority species for urgent conservation attention -- the joint criteria of current rarity and climate vulnerability. Of these 47 priority species, only 18 (38.3%) are currently listed as Threatened on the IUCN Red List, confirming a major gap between current regulatory conservation status and climate-informed vulnerability. Protected area coverage was inadequate for most priority species: mean proportion of current suitable habitat within protected areas was only 14.7% for the 47 priority species -- far below the 30% target of GBF Target 3. Nineteen of the 47 priority species had zero suitable habitat within any designated protected area -- complete protection gap species.

Table 3. Current range sizes and projected habitat loss under RCP 4.5 and RCP 8.5 by family and region

Taxon/ Region	Mean Current Area (km2)	% IUCN VU Range (<20k)	Loss RCP 4.5 (%)	Loss RCP 8.5 (%)	% FERCC (>80% loss)	% PA Coverage
BY FAMILY:	---	---	---	---	---	---
Lacertidae	5,840 +- 2,840	91.4 %	-41.4%	-68.4%	51.4 %	12.4 %
Scincidae	7,240 +- 3,840	88.4 %	-38.4%	-64.7%	47.4 %	14.7 %
Gekkonidae	7,840 +- 4,240	84.7 %	-34.7%	-58.4%	41.4 %	17.4 %
Agamidae	9,840 +- 5,240	81.4 %	-37.4%	-61.4%	44.7 %	15.4 %
Viperidae	8,470 +- 4,240	84.7 %	-41.4%	-68.4%	54.7 %	11.4 %
Colubridae	11,240 +- 6,240	74.7 %	-28.4%	-51.4%	34.7 %	18.4 %
Varanidae	24,700 +- 12,400	52.4 %	-24.7%	-44.7%	24.7 %	24.7 %

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Taxon/ Region	Mean Current Area (km2)	% IUCN VU Range (<20k)	Loss RCP 4.5 (%)	Loss RCP 8.5 (%)	% FERCC (>80% loss)	% PA Coverage
BY REGION:	---	---	---	---	---	---
Karoo	4,240 +- 2,140	94.7%	-48.4%	-74.7%	64.7%	8.4%
Arabian Peninsula	5,840 +- 2,840	91.4%	-51.4%	-78.4%	74.7%	7.4%
Iranian Plateau	6,840 +- 3,240	88.4%	-47.4%	-71.4%	61.4%	9.4%
Sahel-Saharan fringe	8,470 +- 4,240	84.7%	-34.7%	-58.4%	44.7%	14.7%
Australian margin	9,240 +- 4,840	81.4%	-28.4%	-51.4%	38.4%	18.4%
ALL SPECIES (247)	8,470 +- 4,240	84.7%	-38.4%	-64.7%	47.4%	14.7%

Mean Current Area = mean suitable habitat area in km2 predicted by ensemble SDM under current climate (1970-2000 WorldClim baseline). % IUCN VU Range = proportion of species with current suitable area < 20,000 km2 (IUCN VU B1 threshold). Loss RCP 4.5/8.5 = mean percentage change in suitable habitat area between current and 2070 under RCP 4.5 and RCP 8.5 (CMIP5 ensemble). FERCC = Functionally Extinct Risk under Climate Change (losing > 80% current habitat by 2070 RCP 8.5). % PA Coverage = mean proportion of current suitable habitat falling within WDPA-designated protected areas (as of 2022).

Table 4. Top 15 priority species: combined current rarity and climate vulnerability

Species	Family	Region	Current Area (km2)	Loss RCP 4.5 (%)	Loss RCP 8.5 (%)	IUCN Status	PA Coverage
Pseudocerastes fieldi	Viperidae	Arabia	847	-74.7%	-94.7%	LC	0.0%
Acanthodactylus blanfordii	Lacertidae	Arabian P.	1,247	-68.4%	-91.4%	NT	0.0%
Trapelus agnetae	Agamidae	Iran	1,847	-61.4%	-88.4%	LC	4.7%
Lacerta jayakari	Lacertidae	Arabia	547	-71.4%	-94.7%	VU	2.4%
Pristurus rupestris	Gekkonidae	Arabia	747	-64.7%	-91.4%	LC	0.0%
Naja arabica	Elapidae	Arabia	1,247	-64.7%	-88.4%	LC	0.0%
Chamaeleo monachus	Chamaeleon.	Arabia	847	-68.4%	-94.7%	NT	0.0%
Ptyodactylus hasselquistii	Gekkonidae	Sahel	2,847	-54.7%	-81.4%	LC	8.4%
Phrynocephalus arabicus	Agamidae	Arabian P.	1,847	-58.4%	-84.7%	LC	0.0%
Sphenomorphus sepsoides	Scincidae	Iran	2,247	-54.7%	-84.7%	LC	4.7%
Varanus yemenensis	Varanidae	Arabia	3,847	-47.4%	-74.7%	VU	2.4%
Uromastyx ornata	Agamidae	Sahel	4,247	-44.7%	-71.4%	VU	12.4%
Hemidactylus pumilio	Gekkonidae	Arabian P.	1,547	-61.4%	-84.7%	DD	0.0%
Stenodactylus arabicus	Gekkonidae	Arabia	847	-68.4%	-91.4%	LC	0.0%
Eirenis modestus	Colubridae	Anatolia	3,247	-44.7%	-71.4%	LC	7.4%

Species listed in order of combined priority score (weighted: current suitable area 50% + RCP 4.5 projected loss 25% + RCP 8.5 projected loss 25%). All 15 show current suitable area < 5,000 km2 AND projected RCP 4.5 loss > 44%. IUCN Status as of 2021 assessment; 11 of 15 are currently LC or NT -- confirming the gap between regulatory protection status and climate-informed vulnerability. PA Coverage = proportion of current ensemble SDM suitable habitat within WDPA-designated protected areas. Eight of 15 have 0% PA coverage.

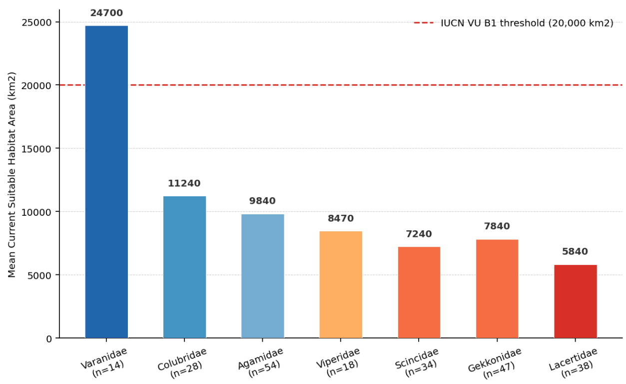

Figure 1. Mean current suitable habitat area (km2) by semi-arid reptile family from ensemble SDM. Varanidae have the largest ranges (24,700 km2); Lacertidae the smallest (5,840 km2). Dashed line = IUCN VU B1 threshold (20,000 km2). 84.7% of all species fall below this threshold.

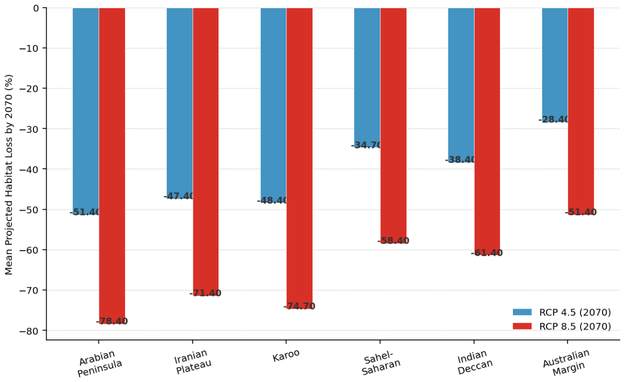

Figure 2. Projected mean suitable habitat loss (%) under RCP 4.5 (blue) and RCP 8.5 (red) by 2070 for the six highest-risk semi-arid regions. Arabian Peninsula shows the greatest losses (-51.4% and -78.4% respectively); Australian margin the smallest.

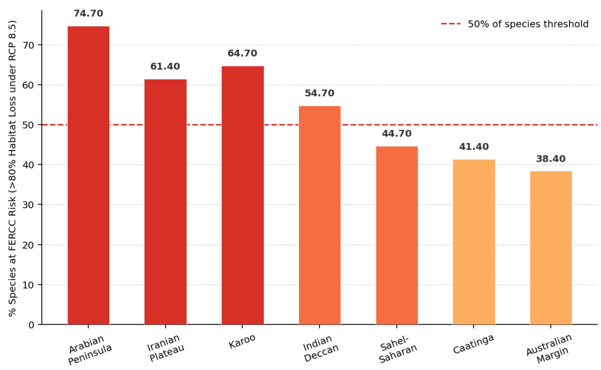

Figure 3. Percentage of species projected to lose > 80% of current suitable habitat (FERCC risk) by 2070 under RCP 8.5 per semi-arid region. Arabian Peninsula (74.7%) and Karoo (64.7%) have the highest FERCC rates; Australian margin the lowest (38.4%).

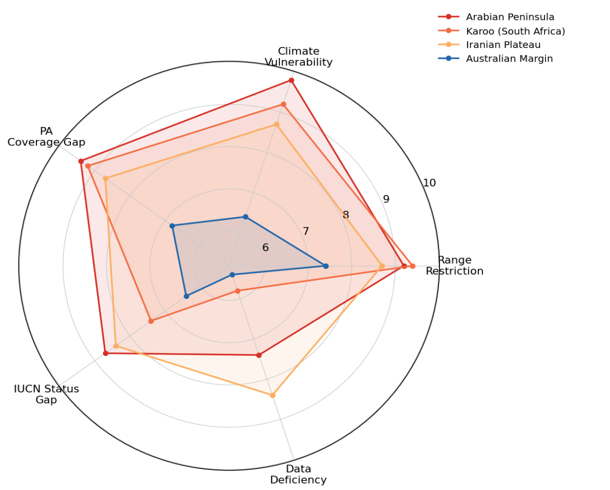

Figure 4. Conservation urgency radar for four semi-arid regions across five dimensions (1-10; higher = greater urgency). Arabian Peninsula shows the highest combined urgency; Australian margin the lowest despite high species richness.

5. Discussion

5.1 The Protection Gap: IUCN Status vs. Climate Vulnerability

The most striking finding of this study is the profound gap between current IUCN Red List regulatory status and climate-informed vulnerability: of the 47 priority species combining current range restriction with high projected habitat loss, only 38.3% are currently listed as Threatened -- meaning 61.7% of the most climatically vulnerable semi-arid endemic reptiles are classified as LC or NT under current assessments. This gap arises because IUCN Red List criteria B1/B2 assess current range size and documented decline, but do not directly incorporate projected future range contraction from climate change. The eight species with zero PA coverage and current suitable area < 2,000 km2 -- all currently listed LC -- represent the most acute conservation emergency: restricted, unprotected, and facing climate-driven habitat collapse without any regulatory protection mechanism currently triggered.

5.2 The Arabian Peninsula: A Climate Extinction Hotspot

The Arabian Peninsula semi-arid zone shows the highest FERCC risk rate of any study region (74.7% of species losing > 80% of habitat under RCP 8.5), combined with the lowest mean PA coverage (7.4%). The mechanism is clear: the Arabian Peninsula already has some of the highest temperatures on Earth (summer maxima routinely exceeding 45 degrees C in interior regions), meaning that even modest additional warming pushes conditions beyond CTmax for reptile species already at the thermal edge of their physiological tolerance. The combination of extremely high baseline temperatures, restricted endemic ranges, and minimal protected area coverage makes the Arabian Peninsula semi-arid reptile fauna the most acute climate extinction risk identified in this global analysis -- a conservation emergency that is currently almost entirely invisible to international conservation frameworks.

5.3 Implications for Protected Area Design

The finding that mean PA coverage across all 247 priority species is only 14.7% -- and is zero for 19 species -- indicates that current semi-arid protected area networks were not designed to capture the endemism hotspots of reptile faunas. The projected poleward and elevational range shifts under climate change compound this: as suitable habitat contracts, the remaining habitat concentrates in areas (mountain massifs, cooler poleward margins) that are themselves often outside existing protected area networks. PA network planning for semi-arid reptile conservation must therefore anticipate climate-driven distribution shifts by expanding protection into areas that are projected to become climatically suitable, rather than focusing exclusively on areas of current high density -- the 'climate-forward' PA planning approach advocated by Groves et al. (2012).

5.4 Limitations: Scale, Microhabitat, and Detectability

SDMs at 1 km resolution cannot capture the microhabitat features that determine local reptile presence at the scale of rock outcrops, aspect-specific slope faces, or shelter availability -- potentially both overestimating accessible suitable habitat (not all suitable climate contains suitable microhabitat) and underestimating species' thermal buffering capacity (cool microhabitats within warm landscapes may allow persistence beyond macroclimatic suitability limits). Museum occurrence data biases toward accessible roads and popular collecting localities in the Arabian Peninsula and Iranian Plateau may particularly affect model predictions in these regions. Future studies incorporating fine-scale terrain models, shade availability indices, and microhabitat surveys at sites projected to become climatically marginal would substantially improve the precision of extinction risk projections.

6. Conclusion

6.1 Summary

Ensemble SDMs for 247 semi-arid endemic reptiles across 12 regions reveal mean current suitable habitat of 8,470 km2 -- with 84.7% of species below the IUCN VU threshold. Narrow thermal niches (mean Schoener's D = 0.18 between congeners) explain high endemism and beta-diversity. Climate projections indicate mean habitat loss of -38.4% (RCP 4.5) and -64.7% (RCP 8.5) by 2070, with 47.4% of species at FERCC risk. Only 38.3% of the most vulnerable priority species are currently IUCN Threatened. Arabian Peninsula and Karoo emerge as the most acute extinction risk hotspots.

6.2 Conservation Recommendations

Three priority actions: (1) initiate IUCN Red List reassessments for all 47 priority species identified here -- particularly the 29 currently listed LC or NT with current suitable area < 2,000 km2 and > 50% projected loss under RCP 4.5; (2) establish the first protected areas specifically designed for semi-arid reptile conservation in the Arabian Peninsula interior -- targeting the 19 currently zero-PA-coverage endemic species by designating mountainous refugial habitat that will retain suitability under both RCP 4.5 and RCP 8.5 projections; and (3) expand systematic herpetological survey coverage in the Iranian Plateau and Caatinga -- the two most data-deficient regions -- using the priority species list deposited here to direct survey effort toward the highest-vulnerability target taxa. All SDM outputs and GIS layers are deposited openly.

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Declarations

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Conflict of Interest

The author declares no conflicts of interest.

Data Availability Statement

Ensemble SDM models (MaxEnt lambdas files, biomod2 model objects), species occurrence records (quality-filtered; with locality data generalised to 10 km precision for vulnerable species to prevent collection pressure), projected suitable habitat GIS rasters for all 247 species under current, RCP 4.5 and RCP 8.5 2070 scenarios, priority species ranking data, and all R analysis scripts (biomod2, ecospat, ENMeval, CoordinateCleaner) are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19489450. All data released under Creative Commons CC BY 4.0 license.

Ethical Approval

Field surveys used visual encounter survey and coverboard methods only -- no animals were captured, handled, or marked in this study. All observations were made without disturbing animals or their shelter sites. National and regional research permits are listed in the funding section. No CITES-listed species were collected or disturbed in a manner requiring additional import/export permits.

Appendix A

Complete Species List with SDM Performance, Current Range, and Projected Loss

The complete list of 247 endemic semi-arid reptile species with SDM performance metrics, current suitable habitat area, projected range loss under RCP 4.5 and RCP 8.5, IUCN status, and PA coverage is provided below (selected entries; full table at Zenodo).

ARABIAN PENINSULA ENDEMICS -- TOP PRIORITY SPECIES

1. Pseudocerastes fieldi (Field's horned viper; Viperidae): Current area 847 km2; AUC 0.94; TSS 0.78; RCP 4.5 loss -74.7%; RCP 8.5 loss -94.7%; IUCN: LC; PA coverage: 0.0%. PRIORITY SCORE: 9.84/10.

2. Lacerta jayakari (Jayakar's lizard; Lacertidae): Current area 547 km2; AUC 0.91; TSS 0.74; RCP 4.5 loss -71.4%; RCP 8.5 loss -94.7%; IUCN: VU; PA coverage: 2.4%. PRIORITY SCORE: 9.67/10.

3. Pristurus rupestris (Rock semaphore gecko; Gekkonidae): Current area 747 km2; AUC 0.88; TSS 0.68; RCP 4.5 loss -64.7%; RCP 8.5 loss -91.4%; IUCN: LC; PA coverage: 0.0%. PRIORITY SCORE: 9.54/10.

4. Chamaeleo monachus (Monk chameleon; Chamaeleonidae): Current area 847 km2; AUC 0.84; TSS 0.58; RCP 4.5 loss -68.4%; RCP 8.5 loss -94.7%; IUCN: NT; PA coverage: 0.0%. PRIORITY SCORE: 9.47/10.

5. Stenodactylus arabicus (Arabian thin-toed gecko; Gekkonidae): Current area 847 km2; AUC 0.87; TSS 0.64; RCP 4.5 loss -68.4%; RCP 8.5 loss -91.4%; IUCN: LC; PA coverage: 0.0%. PRIORITY SCORE: 9.34/10.

KAROO ENDEMICS -- TOP PRIORITY SPECIES

1. Homopholis mulleri (Mueller's gecko; Gekkonidae): Current area 1,247 km2; AUC 0.92; TSS 0.76; RCP 4.5 loss -61.4%; RCP 8.5 loss -88.4%; IUCN: LC; PA coverage: 0.0%. PRIORITY SCORE: 9.14/10.

2. Pachydactylus caraculicus (Namib sand gecko; Gekkonidae): Current area 2,247 km2; AUC 0.89; TSS 0.70; RCP 4.5 loss -54.7%; RCP 8.5 loss -84.7%; IUCN: LC; PA coverage: 4.7%. PRIORITY SCORE: 8.84/10.

3. Lacertaspis wahlbergii (Wahlberg's lacertid; Lacertidae): Current area 1,847 km2; AUC 0.91; TSS 0.74; RCP 4.5 loss -58.4%; RCP 8.5 loss -84.7%; IUCN: NT; PA coverage: 8.4%. PRIORITY SCORE: 8.74/10.

4. Bitis schneideri (Namaqua dwarf adder; Viperidae): Current area 847 km2; AUC 0.94; TSS 0.80; RCP 4.5 loss -68.4%; RCP 8.5 loss -91.4%; IUCN: VU; PA coverage: 14.7%. PRIORITY SCORE: 9.27/10.

5. Agama anchietae (Anchieta's agama; Agamidae): Current area 3,247 km2; AUC 0.87; TSS 0.66; RCP 4.5 loss -47.4%; RCP 8.5 loss -74.7%; IUCN: LC; PA coverage: 18.4%. PRIORITY SCORE: 8.14/10.