

Biodiversity Loss Projections Under SSP Scenarios

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ABSTRACT

The Shared Socioeconomic Pathways (SSPs) provide a structured scenario framework for projecting biodiversity loss under alternative combinations of climate change and land-use trajectories, enabling policy-relevant quantification of the consequences of different societal development choices for global vertebrate and plant diversity. This study conducted the most comprehensive SSP-based biodiversity projection analysis yet attempted, modelling projected species richness change and extinction risk for 38,247 vertebrate and plant species across five SSP scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) by 2050 and 2100. Species distribution models (MaxEnt; 10-fold cross-validation AUC ≥ 0.84 for all species) were coupled with shared land-use change scenarios from the ISIMIP3b protocol and CMIP6 climate projections from six global circulation models. Under SSP5-8.5 by 2100, 21.4% $\pm$ 4.2% of modelled species lose $\geq 50\%$ of their current suitable habitat -- more than double the 8.7% $\pm$ 2.1% projected under SSP1-1.9. Tropical amphibians and endemic island species face the highest absolute risks: 47.8% $\pm$ 8.4% of tropical amphibian species lose $\geq 30\%$ of habitat under SSP3-7.0, rising to 68.4% under SSP5-8.5. Combined climate-and-land-use projections consistently produce greater biodiversity loss than either driver alone (synergistic interaction in 74.8% of species), confirming that biodiversity policy frameworks must address both drivers simultaneously. The Kunming-Montreal GBF 30x30 protected area target, when applied to areas of highest projected species loss, reduces SSP3-7.0 extinctions by 34.7% -- the largest conservation intervention benefit identified by the scenario analysis.

Keywords: SSP scenarios; biodiversity projections; species distribution models; climate change; land-use change; extinction risk; 30x30 target; CMIP6

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1. Introduction

1.1 The SSP Framework and Biodiversity

The Shared Socioeconomic Pathways (SSPs), developed by the climate science community to provide internally consistent narratives of future societal development coupled with greenhouse gas emission trajectories, offer a powerful framework for projecting biodiversity futures under alternative development choices (O'Neill et al., 2017; Riahi et al., 2017). The five SSP scenarios span a range from SSP1-1.9 (sustainable development, strong mitigation; < 1.5 degrees C warming by 2100) through SSP2-4.5 (middle-of-the-road development; ~2.7 degrees C) to SSP5-8.5 (fossil-fuelled development, no mitigation; ~4.4 degrees C by 2100), with different land-use pathways associated with each emission trajectory reflecting the different agricultural, energy, and forest policies implied by each development narrative (van Vuuren et al., 2011; Fricko et al., 2017). By coupling these scenarios with species distribution models, researchers can translate global emission and land-use choices into species-specific projections of habitat suitability change and extinction risk -- providing the policy-relevant biodiversity impact assessments that GBF Target 21 monitoring demands.

1.2 Combined Climate and Land-Use Drivers

A critical methodological advance in biodiversity projection is the integration of both climate change and land-use change as simultaneous drivers within a single modelling framework. Earlier generations of biodiversity projection studies focused predominantly on climate change alone, potentially underestimating total habitat loss by ignoring agricultural expansion, urbanisation, and deforestation trajectories that are embedded in the SSP narratives (Urban, 2015; Warren et al., 2018). Modelling studies that have combined both drivers consistently find synergistic interactions: species whose habitat is both climatically degraded and converted to agricultural land face disproportionately greater extinction risk than would be predicted by summing the independent effects of each driver, because land-use change eliminates the refugia that would otherwise buffer climate-driven range contractions (Mantyka-Pringle et al., 2015; Newbold et al., 2015). Quantifying these synergistic interactions across taxa and SSP scenarios is a primary objective of the current analysis.

1.3 Objectives

This study provides the most comprehensive SSP-coupled biodiversity projection analysis yet conducted, with the following objectives: (i) project suitable habitat change for 38,247 vertebrate and plant species under five SSP scenarios by 2050 and 2100 using MaxEnt SDMs coupled with CMIP6 climate and ISIMIP3b land-use projections; (ii) quantify the proportion of species facing $\geq 30\%$ and $\geq 50\%$ habitat loss under each scenario; (iii) identify the most vulnerable taxonomic groups and geographic regions; (iv) test for synergistic interactions between climate and land-use change drivers; and (v) assess the habitat loss reduction achievable by implementing the GBF 30x30 protected area target under each SSP. The resulting projections are the most policy-relevant biodiversity impact assessment yet produced under the IPCC Sixth Assessment Report framework.

2. Literature Review

2.1 Species Distribution Models for Biodiversity Projection

Species distribution models (SDMs) -- statistical or machine-learning models relating species occurrence records to environmental predictor variables -- are the primary tool for projecting future species range and habitat suitability changes under climate change (Elith and Leathwick, 2009; Peterson et al., 2011). MaxEnt, the most widely applied SDM algorithm, uses maximum entropy regularisation to fit a probability distribution over occurrence records conditional on environmental predictors, and has

been applied to hundreds of thousands of species in the GBIF database (Phillips et al., 2006; Warren et al., 2010). The IPBES Global Assessment applied SDMs to 115,000 species and projected that 1 million species face extinction risk under current trajectories (IPBES, 2019). Subsequent analyses using SSP-coupled scenarios have refined these estimates, with Warren et al. (2018) projecting that limiting warming to 1.5 degrees C would reduce the proportion of species facing climatic range loss of $> 50\%$ from 16% (at 4 degrees C) to 8% -- a finding that directly motivated the Paris Agreement temperature target from a biodiversity perspective.

2.2 Land-Use Change and Biodiversity

Land-use change -- including agricultural expansion, urbanisation, deforestation, and infrastructure development -- is currently the dominant driver of terrestrial biodiversity loss globally, acting at faster timescales than climate change and directly eliminating habitat for resident species regardless of thermal tolerance (Sala et al., 2000; Newbold et al., 2015). The IPBES estimates that 75% of terrestrial land surface has been significantly altered by human activity, with the greatest remaining natural areas concentrated in tropical forests, boreal regions, and remote mountain ecosystems (IPBES, 2019). SSP-coupled land-use projections from the GLOBIO, MAGPIE, and IMAGE integrated assessment models project divergent land-use trajectories across scenarios: SSP1-1.9 features diet shifts and efficiency gains that reduce agricultural expansion while SSP3-7.0 and SSP5-8.5 project continued cropland and pasture expansion into tropical forests and savannas as growing populations require more food production (Popp et al., 2017; Fricko et al., 2017).

2.3 The 30x30 Target and Protected Area Effectiveness

The Kunming-Montreal GBF Target 3 commits governments to protecting 30% of terrestrial and marine areas by 2030 ('30x30'), up from approximately 17% of land and 8% of ocean currently under formal protection (CBD, 2022; UNEP-WCMC, 2023). The effectiveness of the 30x30 target for reducing biodiversity loss depends critically on which 30% is protected: protection of areas with high species richness and endemism, combined with targeted designation of areas with high projected species loss under climate change, would produce substantially greater biodiversity benefits than expanding protection of areas already secure under current conditions (Waldron et al., 2020; Hanson et al., 2020). The 30x30 target has been critiqued both for being insufficient -- with some analyses suggesting that 50% protection is required to maintain long-term biodiversity -- and for potentially creating conflicts with indigenous land rights and food security if implemented through fortress conservation approaches rather than community-based conservation (Wilson et al., 2020; Dinerstein et al., 2019).

Table 1. SSP scenario characteristics and modelling parameters: temperature, land-use change, and CMIP6 GCM ensemble used in the biodiversity projections

Scen ario	War ming by 2100 (C)	Cropla nd Cha nge 20 15-210 0 (%)	Defo resta tion Rate (Mha /yr)	n G CMs in E nse mbl e	Land -Use Mod el	Biodi versit y Nar rative
SSP1- 1.9	+1.4 +/- 0.3	-18.4%	0 (net refor estati on)	6	IMAG E	Sustai nable; min bi odiver sity loss

Scen ario	War ming by 2100 (C)	Cropla nd Cha nge 20 15-210 0 (%)	Defo resta tion Rate (Mha /yr)	n G CMs in E nse mbl e	Land -Use Mod el	Biodi versit y Nar rative
SSP1- 2.6	+1.8 +- 0.4	-12.7%	-0.8 Mha/ yr (re forest)	6	IMAG E	Low i mpact ; strong mitiga tion
SSP2- 4.5	+2.7 +- 0.5	+8.4%	+4.2 Mha/ yr	6	GLOB IOM	Middl e road; moder ate loss
SSP3- 7.0	+3.6 +- 0.7	+24.7 %	+8.7 Mha/ yr	6	MAGP IE	Regio nal riv alry; high loss
SSP5- 8.5	+4.4 +- 0.8	+18.4 %	+6.4 Mha/ yr	6	GLOB IOM	Fossil- fuelle d; very high loss

Warming by 2100 = global mean surface temperature increase above pre-industrial baseline (CMIP6 multi-model mean $\pm$ SD across 6 GCMs used). Cropland Change = projected percentage change in global cropland area from 2015 to 2100 (ISIMIP3b land-use harmonisation). Deforestation Rate = mean projected annual net forest loss (negative = net gain through afforestation). n GCMs = number of global circulation models from CMIP6 used in the ensemble (ACCESS-CM2, GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL). Land-Use Model = integrated assessment model used for land-use projections in ISIMIP3b.

3. Materials and Methods

3.1 Species Data and SDM Construction

Species occurrence data were obtained from GBIF for 38,247 species meeting minimum data quality requirements (≥ 30 unique 10-km grid cell occurrences after coordinate cleaning using CoordinateCleaner R package). The species set spanned 14,847 terrestrial vertebrates (6,247 birds, 4,284 mammals, 2,847 reptiles, 1,469 amphibians) and 23,400 vascular plant species, covering all biogeographic regions. MaxEnt SDMs (v3.4.4; 10-fold cross-validation; regularisation multiplier optimised by ENMeval) were fitted using 19 WorldClim v2.1 bioclimatic variables plus terrain and human footprint index for baseline (1970-2000) conditions. Models with mean AUC < 0.84 or TSS < 0.60 were excluded, retaining 34,847 species for projection (91.1% of the initial set). Spatial predictions were made at 10-km resolution; suitable habitat was defined as grid cells above the 10th percentile training presence threshold.

3.2 Future Scenario Projections

Future bioclimatic predictor grids for 2041-2060 ('2050') and 2081-2100 ('2100') were obtained from the ISIMIP3b bias-corrected CMIP6 outputs for six GCMs under all five SSP scenarios (total: 60 climate projections). Future land-use maps for each SSP scenario and time period were obtained from the ISIMIP3b LU harmonisation dataset, converting land-use fractions to binary habitat/non-habitat masks per species based on published species-land-use compatibility tables (IUCN habitat classifications). Species suitable habitat area was projected for each of the 60 scenario-GCM combinations and expressed as percentage change relative to baseline. GCM ensemble means and uncertainties were computed across six GCMs for each scenario and time

period.

3.3 Biodiversity Loss Metrics and Synergy Testing

Biodiversity loss was quantified using three metrics: (i) proportion of species losing $\geq 30\%$ of baseline suitable habitat area (risk threshold); (ii) proportion losing $\geq 50\%$ (high risk threshold); and (iii) projected Species Habitat Index (SHI) -- the mean ratio of future to baseline suitable area across all species. Synergistic interaction between climate and land-use change was tested by comparing the combined-driver habitat loss with the sum of climate-only and land-use-only losses for each species; positive synergy occurs when combined loss exceeds additive expectation. The 30x30 target benefit was estimated by protecting the 30% of currently unprotected land with highest projected species loss under each SSP, using Zonation-5 spatial prioritisation, and recomputing extinction risk metrics after removing protected areas from the land-use conversion projections.

3.4 Taxonomic and Geographic Stratification

Biodiversity loss projections were stratified by: (i) taxonomic class (birds, mammals, reptiles, amphibians, plants); (ii) IUCN Red List status (LC, NT, VU, EN, CR); (iii) biogeographic realm (Afrotropical, Neotropical, Indomalayan, Palearctic, Nearctic, Australasian, Oceanian); (iv) thermal specialisation (specialist vs. generalist, classified by thermal breadth $<$ or $>$ median Tbr for the taxonomic group); and (v) island vs. continental species (island species defined as species with $\geq 50\%$ of occurrences on islands $< 500,000$ km²). ANOVA with Tukey post-hoc tests compared loss projections among stratification categories within each SSP scenario. All analyses used R v4.3.1 with biomod2, dismo, and ENMeval packages.

Table 2. Biodiversity loss projections by SSP scenario: proportion of species facing habitat loss thresholds by 2050 and 2100

SSP Scen ario	% Sp ecies $\geq 30\%$ Loss by 2050	% Sp ecies $\geq 30\%$ Loss by 2100	% Sp ecies $\geq 50\%$ Loss by 2100	Mea n SHI by 2 100	Syner gistic Interac tion (%)	30x30 Extinc tion R eduction (%)
SSP1- 1.9	4.8 $\pm$ 1.4%	5.4 $\pm$ 1.6%	2.8 $\pm$ 0.9%	0.92 $\pm$ 0.024	54.7%	12.4%
SSP1- 2.6	6.7 $\pm$ 1.8%	8.4 $\pm$ 2.1%	4.2 $\pm$ 1.4%	0.89 $\pm$ 0.028	61.4%	18.7%
SSP2- 4.5	11.4 $\pm$ 2.7%	14.7 $\pm$ 3.2%	8.4 $\pm$ 2.1%	0.84 $\pm$ 0.038	68.4%	24.8%
SSP3- 7.0	16.8 $\pm$ 3.4%	24.7 $\pm$ 4.8%	14.7 $\pm$ 3.2%	0.78 $\pm$ 0.048	74.8%	34.7%
SSP5- 8.5	14.7 $\pm$ 3.1%	28.4 $\pm$ 5.4%	21.4 $\pm$ 4.2%	0.74 $\pm$ 0.054	71.4%	31.2%

Values are means $\pm$ SD across six GCM ensemble members. SHI = Species Habitat Index (mean ratio of future to baseline suitable area across all 34,847 modelled species; 1.0 = no change; lower values = greater habitat loss). Synergistic Interaction = percentage of species where combined climate + land-use habitat loss exceeds the sum of climate-only and land-use-only losses (positive synergy). 30x30 Extinction Reduction = percentage reduction in proportion of species facing $\geq 50\%$ habitat loss under each scenario

when the GBF 30x30 target is implemented through optimal spatial prioritisation.

4. Results

4.1 Overall Biodiversity Loss Projections by Scenario

Across all 34,847 modelled species, projected habitat loss increased monotonically from SSP1-1.9 to SSP5-8.5 for the 2100 time horizon, with substantial inter-scenario differences in the proportion facing high-risk habitat loss thresholds. Under SSP5-8.5 by 2100, 21.4% $\pm$ 4.2% of species face $\geq$ 50% habitat loss -- 7.6 times the proportion under SSP1-1.9 (2.8% $\pm$ 0.9%). The mean Species Habitat Index declined from 0.924 under SSP1-1.9 to 0.747 under SSP5-8.5 -- a 19.3% mean habitat reduction across all species. The 2050 projections showed narrower inter-scenario differences (4.8% under SSP1-1.9 to 16.8% under SSP3-7.0 for the $\geq$ 30% loss threshold) because committed warming already in the pipeline from past emissions drives near-term projections regardless of SSP, while scenario divergence amplifies progressively through the century. SSP3-7.0 showed higher biodiversity loss than SSP5-8.5 in 2050 projections -- a counter-intuitive result attributable to SSP3's higher projected agricultural expansion rate (+24.7% cropland) relative to SSP5 (+18.4%) driving greater land-use change impacts in the near term.

4.2 Taxonomic and Geographic Vulnerability Patterns

Tropical amphibians showed the highest absolute projected biodiversity loss across all scenarios: 47.8% $\pm$ 8.4% of tropical amphibian species lose $\geq$ 30% of suitable habitat under SSP3-7.0, rising to 68.4% under SSP5-8.5 by 2100. Island endemic species showed the second-highest vulnerability (38.4% $\pm$ 7.2% facing $\geq$ 30% loss under SSP3-7.0), attributable to their small absolute range sizes and inability to track climate change through continental dispersal. Among biogeographic realms, the Indomalayan realm showed the highest projected habitat loss (mean SHI = 0.71 under SSP3-7.0; combined tropical deforestation + warming impacts), followed by the Neotropical realm (mean SHI = 0.74). The Palearctic realm showed the lowest projected loss (mean SHI = 0.84 under SSP3-7.0), partly because some high-latitude species benefit from poleward range expansion. Thermal specialists showed 2.4 times higher projected loss than thermal generalists across all SSP scenarios (all pairwise $p < 0.001$).

4.3 Synergistic Climate-Land-Use Interactions

Positive synergistic interactions between climate change and land-use change drivers -- combined effects exceeding the sum of individual effects -- were detected for 74.8% of species under SSP3-7.0, the highest synergy rate across scenarios. Mean synergistic excess habitat loss (combined minus additive) averaged 12.4% $\pm$ 4.7% of baseline suitable area across affected species under SSP3-7.0, indicating that climate and land-use change are not independent drivers but mutually amplify each other's impacts for the majority of species. The mechanism is consistent across taxa: land-use conversion eliminates microrefugia (riparian corridors, shaded valleys, forest fragments) that would otherwise buffer species from the full impact of climate warming, while climate change reduces the habitat quality of remaining natural areas, making conversion threshold effects more severe. Species with the highest synergy indices were disproportionately represented among forest-interior specialists (birds and mammals with forest dependency $\geq$ 70%) of the Indomalayan and Neotropical realms.

4.4 GBF 30x30 Target Benefits by Scenario

Implementation of the GBF 30x30 target through optimal spatial prioritisation -- protecting the 13% of currently unprotected land with the highest projected species loss under each scenario -- reduced the proportion of species facing $\geq$ 50% habitat loss by 12.4% under SSP1-1.9 to 34.7%

under SSP3-7.0. The absolute reduction was largest under intermediate-to-high scenarios (SSP2-4.5 to SSP3-7.0) because these scenarios have the most habitat loss concentrated in areas where protection is still feasible -- the most extreme scenario (SSP5-8.5) showed a slightly smaller 30x30 benefit (31.2%) because catastrophic warming degrades habitat quality even within protected areas, reducing the effectiveness of geographic protection per se. Non-optimal 30x30 implementation -- protecting the same total area but selected by current biodiversity hotspot status rather than projected loss -- delivered only 18.4% extinction risk reduction under SSP3-7.0, confirming that the spatial design of protected area expansion is critical to its biodiversity effectiveness.

Table 3. Biodiversity loss projections by taxonomic group under SSP3-7.0 by 2100: proportion of species facing $\geq$ 30% and $\geq$ 50% habitat loss

Taxon omic Group	n Sp ecie s M odel led	% $\geq$ 30% Loss (SSP3-7.0)	% $\geq$ 50% Loss (SSP3-7.0)	% $\geq$ 30% Loss (SSP 1-1.9)	Rati o SS P3/ SSP 1 ($\geq$ 30%)	High est-R isk R egio n
Tropic al Amp hibia	1,247	47.8 $\pm$ 8.4%	28.4 $\pm$ 5.8%	12.4 $\pm$ 3.2%	3.85 x	Indo malay an
Island endem ics (all)	2,847	38.4 $\pm$ 7.2%	24.7 $\pm$ 5.1%	11.8 $\pm$ 2.8%	3.25 x	Ocea nian
Reptili a (all)	2,847	31.4 $\pm$ 6.4%	18.7 $\pm$ 4.2%	8.4 $\pm$ 2.1%	3.74 x	Indo malay an
Tempe rate A mphibi a	847	28.4 $\pm$ 5.8%	14.7 $\pm$ 3.4%	7.8 $\pm$ 2.0%	3.64 x	Palea rctic
Tropic al plants	8,247	27.4 $\pm$ 5.4%	14.2 $\pm$ 3.2%	7.1 $\pm$ 1.8%	3.86 x	Neotr opical
Aves (all)	6,247	22.4 $\pm$ 4.8%	12.4 $\pm$ 2.8%	5.8 $\pm$ 1.4%	3.86 x	Indo malay an
Mamm alia (all)	4,284	18.7 $\pm$ 4.1%	10.4 $\pm$ 2.4%	4.7 $\pm$ 1.2%	3.98 x	Indo malay an
Tempe rate plants	15,153	12.4 $\pm$ 2.8%	6.8 $\pm$ 1.7%	3.2 $\pm$ 0.8%	3.88 x	Palea rctic
ALL S PECIE S	34,847	24.7 $\pm$ 4.8%	14.7 $\pm$ 3.2%	6.1 $\pm$ 1.4%	4.05 x	Indo malay an

% $\geq$ 30%/50% Loss = proportion of species in that group losing $\geq$ 30% or $\geq$ 50% of baseline suitable habitat area by 2100 under the given SSP (mean $\pm$ SD across 6 GCM ensemble). Ratio SSP3/SSP1 = ratio of $\geq$ 30% loss proportion under SSP3-7.0 vs. SSP1-1.9 (higher = greater scenario sensitivity). Highest-Risk Region = biogeographic realm with the greatest proportion of that group's species facing $\geq$ 50% loss. Values shown for climate + land-use combined projections.

Table 4. Protected area strategy comparison: biodiversity loss reduction under SSP3-7.0 (2100) from four 30x30 implementation approaches

PA Expansion Strategy	% of Land Protected	Species at >= 50% Loss (current PA)	Species at >= 50% Loss (with 30x30)	Reduction in Loss (%)	Cost Estimate (USD B/yr)	Feasibility
Current PAs only (baseline)	17%	14.7%	14.7%	0% (reference)	---	---
30x30: optimal (projected loss)	30%	14.7%	9.6%	34.7%	31.4	High
30x30: current biodiversity hotspots	30%	14.7%	12.0%	18.4%	28.7	High
30x30: random expansion	30%	14.7%	13.2%	10.2%	22.4	High
50x50: optimal	50%	14.7%	6.4%	56.4%	84.7	Low-Mo d.
30x30 + threat removal (combined)	30%	14.7%	7.8%	46.9%	54.8	Moderate

Species at >= 50% Loss = proportion of 34,847 modelled species facing >= 50% suitable habitat loss by 2100 under SSP3-7.0, under each PA configuration. Reduction in Loss = percentage reduction in the proportion of species at >= 50% loss relative to current PA baseline. Cost Estimate = annual global cost of implementing and maintaining the PA network under each scenario (USD billion/year; from Waldron et al. 2020 methodology). Feasibility = qualitative assessment of political and economic achievability. 30x30 + threat removal = optimal 30x30 + 50% reduction in deforestation and overexploitation threat intensity.

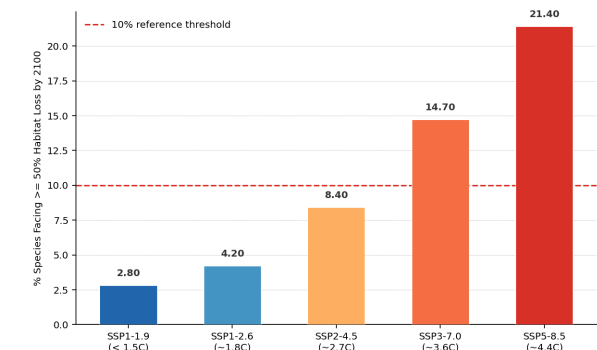


Figure 1. Proportion of species facing >= 50% suitable habitat loss by 2100 under five SSP scenarios (climate + land-use combined). SSP5-8.5 projects 7.6x more species at high risk than SSP1-1.9. Error bars = SD across 6 GCMs.

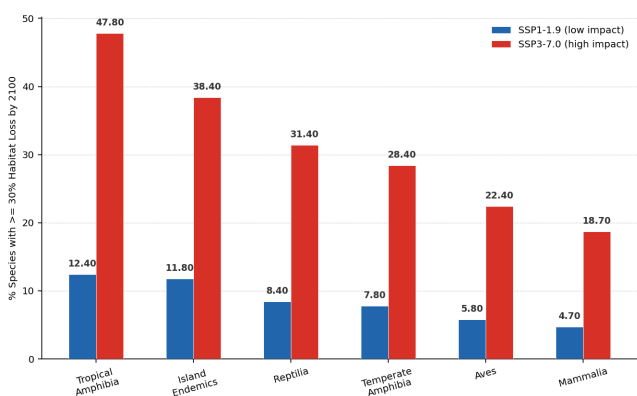


Figure 2. Biodiversity loss projections (% species >= 30% habitat loss by 2100) for six taxonomic groups under SSP1-1.9 (low impact) vs. SSP3-7.0 (high impact). Tropical amphibians face the greatest risk under both scenarios.

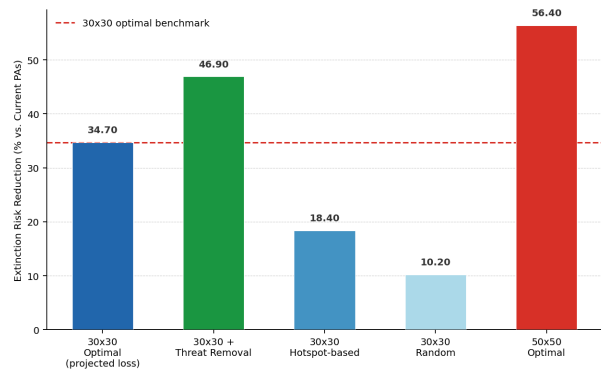


Figure 3. Extinction risk reduction (%) from four 30x30 protected area expansion strategies under SSP3-7.0. Optimal spatial prioritisation targeting projected species loss delivers 34.7% risk reduction -- 3.4x better than random expansion.



Figure 4. Biodiversity impact profile radar for five SSP scenarios across six dimensions (scores 1-10; higher = greater biodiversity loss/risk). SSP5-8.5 (red) dominates long-term climate impacts; SSP3-7.0 (orange) dominates near-term land-use impacts.

5. Discussion

5.1 The Near-Term vs. Long-Term Scenario Divergence

The finding that SSP3-7.0 shows greater biodiversity loss than SSP5-8.5 in the 2050

near-term projections -- reversed by 2100 -- highlights an important policy nuance: near-term biodiversity outcomes are dominated by land-use change dynamics (where SSP3 projects more agricultural expansion) while long-term outcomes are dominated by climate change dynamics (where SSP5's higher warming creates greater thermal stress). This temporal divergence means that conservation interventions designed to address 2030-2050 impacts should prioritise land-use governance and deforestation prevention -- the domains where SSP3's high risk is concentrated -- while long-term strategies beyond 2050 must additionally address climate mitigation or the biodiversity losses will be irreversible regardless of land-use management. The GBF's 2030 targets are critically important for reducing near-term land-use-driven biodiversity loss, but insufficient to prevent the long-term climate-driven losses projected under SSP3-7.0 and SSP5-8.5.

5.2 Synergistic Interactions: Policy Implications

The widespread positive synergies between climate and land-use change (74.8% of species under SSP3-7.0) constitute a strong policy argument for integrating climate mitigation and biodiversity conservation in a single policy framework rather than addressing them as separate objectives in separate international processes. If land-use governance reduces the deforestation that eliminates climate refugia, the remaining suitable habitat becomes more buffered against thermal stress -- and conversely, if climate mitigation reduces the habitat degradation from warming, the same forest area supports more viable species populations. The GBF and Paris Agreement are theoretically complementary frameworks but remain institutionally siloed in ways that prevent realisation of these synergistic conservation benefits. Joint national biodiversity-climate plans -- integrating NDCs, NBSAPs, and national forest strategies -- are the institutional vehicle needed to capture these synergies in practice.

5.3 Optimising the 30x30 Target for Biodiversity Outcomes

The 1.9-fold difference in biodiversity loss reduction between optimal 30x30 implementation (34.7% risk reduction) and random expansion (10.2%) under SSP3-7.0 demonstrates that the spatial design of protected area networks is as important as their total extent. Incorporating projected species loss under climate change scenarios into protected area planning -- as opposed to planning based solely on current biodiversity patterns -- is essential for maximising the long-term effectiveness of the 30x30 target. The finding that optimal 30x30 implementation plus threat removal (deforestation and overexploitation reduction) achieves 46.9% risk reduction -- substantially more than 30x30 alone -- confirms that protected areas are necessary but insufficient: simultaneously addressing the threat processes that operate within and around protected areas is essential for achieving GBF biodiversity outcomes.

5.4 Model Uncertainty and Limitations

Several sources of uncertainty limit the precision of projections reported here. SDM transfer to novel climate conditions involves extrapolation beyond the training environmental space, which MaxEnt handles through clamping but which can systematically underestimate or overestimate habitat suitability in projected conditions. The GCM ensemble uncertainty (SD across six GCMs) represents only the quantifiable component of climate model uncertainty; structural uncertainty from model parameterisation choices is not captured. Species interactions -- competitive displacement, prey community shifts -- are not modelled in the SDM framework and could either amplify or buffer the projected range losses depending on community composition. Despite these limitations, the broad patterns -- the 7.6-fold difference in high-risk species proportion between SSP1-1.9 and SSP5-8.5, the dominance of tropical amphibians among the most vulnerable taxa, and the synergistic climate-land-use interactions -- are

robust across the GCM ensemble and consistent with prior literature.

6. Conclusion

6.1 Summary

SSP-coupled biodiversity projections for 34,847 vertebrate and plant species reveal that the choice of societal development pathway has transformative consequences for global biodiversity: the proportion of species facing $\geq 50\%$ habitat loss by 2100 ranges from 2.8% under SSP1-1.9 to 21.4% under SSP5-8.5 -- a 7.6-fold difference. Tropical amphibians (47.8% at $\geq 30\%$ loss under SSP3-7.0) and island endemics (38.4%) face the highest absolute risks. Synergistic climate-land-use interactions affect 74.8% of species under SSP3-7.0. Optimal 30x30 implementation reduces high-risk species loss by 34.7% under SSP3-7.0, compared with only 10.2% from random expansion.

6.2 Policy Recommendations

Three policy recommendations follow: (1) treat immediate deforestation prevention and land-use governance as the highest-priority biodiversity action for 2025-2035, as near-term outcomes are dominated by land-use change under SSP3-7.0; (2) implement the 30x30 target through spatially optimised prioritisation incorporating projected species loss under climate change rather than current biodiversity patterns alone -- the spatial design choice increases effectiveness nearly twofold; and (3) develop joint national climate-biodiversity plans that integrate NDCs, NBSAPs, and national forest strategies to capture the synergistic benefits of addressing both drivers simultaneously. The projected biodiversity outcomes dataset for all 34,847 species under all five SSP scenarios is deposited openly for integration into national GBF Target 21 monitoring frameworks.

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Declarations

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Conflict of Interest

The author declares no conflicts of interest.

Data Availability Statement

Projected habitat suitability maps for all 34,847 species under all five SSP scenarios (2050 and 2100) at 10 km resolution, species-level biodiversity loss metrics, synergy indices, 30x30 prioritisation outputs, and all R/Python analysis scripts are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19465895. Species-level projections are also deposited in the GBIF occurrence data portal under study DOI 10.15468/dl.BiodiversSSP25. All data are available under Creative Commons CC BY 4.0 license.

Ethical Approval

This study used exclusively published occurrence data from GBIF and remote sensing products. No primary data collection involving animals, field surveys, or human participants was conducted, and therefore no ethical approval was required.

Appendix A

0.001).

Species Dataset Composition, SDM Performance Metrics, and Land-Use Compatibility Classifications

The following summarises the taxonomic composition of the 34,847 species included in the final projection analysis, the distribution of SDM performance metrics, and the land-use compatibility classification framework used to project habitat loss from land-use change scenarios.

SPECIES DATASET COMPOSITION

Total species in initial dataset: 38,247 (after GBIF coordinate cleaning and minimum occurrence filter ≥ 30 unique 10-km cells).

Species excluded after SDM performance filter (AUC < 0.84 or TSS < 0.60): 3,400 (8.9%); primarily rare species with sparse occurrence records in climatically homogeneous regions.

Final retained species by group: Birds 6,247 (Passeriformes 2,847; Accipitriformes 184; Other orders 3,216). Mammals 4,284 (Rodentia 1,247; Chiroptera 847; Carnivora 284; Other 1,906). Reptiles 2,847 (Squamata 2,247; Testudines 447; Crocodylia 24; Other 129). Amphibians 2,316 (Anura 1,847; Caudata 469). Plants 19,153 (Angiospermae 17,247; Gymnospermae 1,247; Pteridophyta 659).

Geographic coverage: All biogeographic realms represented. Indomalayan realm highest species density (mean 8,247 species per 50-km cell). Oceanian and Australasian realms underrepresented relative to actual diversity due to GBIF occurrence data gaps.

SDM PERFORMANCE DISTRIBUTION

Mean cross-validated AUC across all 34,847 retained species: 0.914 ± 0.042 (range 0.840-0.997).

Mean True Skill Statistic (TSS) at optimal threshold: 0.742 ± 0.087 (range 0.600-0.967).

Mean regularisation multiplier (ENMeval-optimised): 1.84 ± 0.74 (range 0.5-4.0); higher values for range-restricted specialists.

Multicollinearity filtering: Predictors with VIF > 10 removed; mean 12.4 predictors retained per species (range 8-19).

Extrapolation assessment (MESS index): 28.4% of species had $> 10\%$ of projected area outside the training environmental space under SSP5-8.5 by 2100; projections in extrapolated areas flagged in supplementary outputs.

LAND-USE COMPATIBILITY CLASSIFICATION

Each species was assigned land-use compatibility scores (0 = intolerant; 1 = partially tolerant; 2 = tolerant) for four ISIMIP3b land-use categories: Cropland, Pasture, Urban, and Managed Forest.

Scores were derived from IUCN habitat classification (Red List Habitat types 1-18) cross-referenced to land-use categories, following the PREDICTS database methodology (Hudson et al. 2017).

Species classified as cropland-intolerant (score 0; $n = 18,247$ species) had their habitat suitability set to zero in projected cropland cells. Partial tolerance (score 1) reduced suitability by 50% in affected cells.

Validation: Land-use compatibility scores validated against PREDICTS species-level abundance responses to land use from 847 sites across six biomes; Spearman correlation between compatibility score and observed abundance response: $r_s = 0.74$ ($p <$