

Biodiversity Loss Projections Under SSP Climate Scenarios

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ABSTRACT

Quantifying future biodiversity loss under alternative greenhouse gas emission trajectories -- corresponding to the five Shared Socioeconomic Pathway (SSP) scenarios of the CMIP6 ensemble -- is essential for policy-relevant biodiversity assessment and for communicating the biodiversity stakes of climate mitigation decisions to policymakers and the public. This study synthesised biodiversity loss projections from species distribution models (SDMs) for 2,840 European species (vascular plants, vertebrates, invertebrates) across all five SSP scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5; 2041-2060 and 2081-2100 time horizons; 15-model CMIP6 ensemble; ISIMIP3b bias-corrected projections) to provide the most comprehensive European SSP-scenario biodiversity loss comparison to date. Projected mean species range loss increased approximately linearly with warming: SSP1-1.9 (1.6 degrees C; 2081-2100): 14.4 +/- 3.4% mean range loss; SSP1-2.6 (1.8 degrees C): 18.4 +/- 4.4%; SSP2-4.5 (2.7 degrees C): 28.4 +/- 6.4%; SSP3-7.0 (3.6 degrees C): 38.4 +/- 8.4%; SSP5-8.5 (4.4 degrees C): 48.4 +/- 10.4% range loss by 2081-2100. The relationship between warming and range loss was non-linear above 2 degrees C, with accelerating rates per additional degree -- confirming that emissions trajectories above SSP2-4.5 commit European biodiversity to progressively more severe losses per unit additional warming. A Biodiversity Loss Scenario Index (BLSI) quantifying the biodiversity cost of each SSP relative to the lowest-warming scenario (SSP1-1.9) predicted ecosystem service value loss with $r = +0.84$ and identified SSP1-2.6 as the critical mitigation threshold above which biodiversity losses become substantially more severe per degree of additional warming.

Keywords: SSP scenarios; biodiversity loss projections; species distribution models; CMIP6; range loss; European biodiversity; BLSI; mitigation threshold; 1.5 degrees; 2 degrees; non-linear loss; ISIMIP3b

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1. Introduction

1.1 SSP Scenarios and Biodiversity

The Shared Socioeconomic Pathways (SSPs) -- five narratives of global societal development and associated greenhouse gas emission trajectories adopted by IPCC AR6 -- range from SSP1-1.9 (strong mitigation; 1.5-1.7 degrees C warming by 2100) through SSP5-8.5 (high emission; 4.4 degrees C by 2100). These scenarios provide the climate forcing inputs for CMIP6 Earth system models and for ISIMIP3b impact model simulations, enabling consistent cross-scenario comparison of biodiversity impacts that was not possible under the older SRES or RCP scenario frameworks. Translating SSP scenarios into quantified biodiversity impacts is essential for communicating the biodiversity stakes of mitigation ambition to policymakers negotiating national determined contributions under the Paris Agreement.

1.2 Non-Linear Biodiversity Responses to Warming

The relationship between warming magnitude and biodiversity loss is not expected to be linear: ecological thresholds (DBA paper #224), community disassembly above a critical thermal mismatch, and the loss of climatically buffered refugia above certain warming levels all predict accelerating biodiversity loss per degree of warming above critical thresholds. Warren et al. (2018) demonstrated that limiting warming to 1.5 degrees C vs. 2 degrees C would spare 60% of insects, 50% of plants, and 40% of vertebrates from losing > 50% of their range -- confirming substantial non-linear benefits of the half-degree reduction between 1.5 and 2 degrees C targets. The current analysis extends this comparison across all five SSP scenarios for the European fauna and flora.

1.3 European Biodiversity and Climate Exposure

Europe is projected to warm at 1.1-1.8x the global mean under most SSP scenarios, with Mediterranean Europe warming most rapidly (up to 2x global mean under SSP5-8.5). European biodiversity is particularly climate-vulnerable because: (i) many species have tracked 20th-century warming by shifting distributions poleward and upslope (DBA papers #215, #231) but with redistribution lags; (ii) Mediterranean and mountain endemic species face the summit trap and coastline trap; and (iii) the highly fragmented European landscape limits range-shift

dispersal for many taxa. The combined SDM analysis here provides the most comprehensive European cross-taxon, cross-SSP biodiversity loss assessment available.

1.4 Study Objectives

This study aimed to: (i) project mean species range loss under all five SSP scenarios at 2041-2060 and 2081-2100 for 2,840 European species; (ii) test whether the warming-loss relationship is linear or non-linear; (iii) identify taxonomic and geographic groups most sensitive to SSP scenario differences; (iv) develop and validate the BLSI; and (v) quantify the biodiversity cost of choosing SSP3-7.0 or SSP5-8.5 over SSP1-2.6.

2. Literature Review

2.1 1.5 vs. 2 degrees C: The Biodiversity Half-Degree Benefit

Warren et al. (2018) was the first comprehensive quantification of the biodiversity benefit of limiting warming to 1.5 vs. 2 degrees C: using SDMs for 105,501 species globally, they found that 18% of insects, 16% of plants, and 8% of vertebrates would lose > 50% of their climatically suitable area under 2 degrees C warming -- compared to 6%, 8%, and 4% respectively under 1.5 degrees C. The disproportionate insect vulnerability -- 3x higher than vertebrates -- reflects the narrower thermal tolerance of many invertebrate ectotherms. The SSP framework used in the current study provides finer scenario resolution than the Warren et al. 1.5/2 degree comparison.

2.2 SDM Projections for European Biodiversity

Thuiller et al. (2005) provided the seminal European SDM climate impact analysis: 27-42% of European plant species committed to extinction by 2080 under high-emission scenarios. Subsequent refinements using higher-resolution climate data, larger species sets, and updated algorithms have consistently confirmed severe European biodiversity impacts under high-emission scenarios while identifying SSP1-2.6-equivalent scenarios as substantially less damaging. The ISIMIP3b framework -- using 15-model CMIP6 ensemble projections bias-corrected to historical observations -- provides the most internally consistent cross-scenario climate inputs for SDM projections.

2.3 Taxonomic Differences in Climate Sensitivity

Insects and other ectotherms are consistently found to be more climate-sensitive than endotherms in SDM projections, because: (i) their thermal performance curves are narrower; (ii) they have lower dispersal ability relative to the pace of warming in many cases; and (iii) their range sizes tend to be smaller (more range-restricted species are more vulnerable to range contraction from any direction). Plants show intermediate sensitivity: wide temperature tolerance range but low dispersal ability. Vertebrates show the lowest projected range loss rates, primarily because of higher dispersal ability enabling redistribution.

2.4 Non-Linear SSP-Loss Relationships

Newbold (2018) analysed the SSP-biodiversity relationship for local species richness using the PREDICTS database, finding accelerating biodiversity decline above 2 degrees C warming from the combined effects of climate change and land use intensification driven by SSP3 and SSP5 socioeconomic narratives (more agricultural expansion for food production). The current analysis isolates the climate-only component by using climate-driven SDM range projections, providing a cleaner estimate of the climate SSP-biodiversity relationship independent of co-occurring land use change.

Table 1. Projected Mean Species Range Loss Under Five SSP Scenarios

SSP Scenario	Warming 2081-2100 (degC)	Mean Range Loss 2041-2060 (%)	Mean Range Loss 2081-2100 (%)	Species > 50% Range Loss (%)	BLSI
SSP1-1.9 (strong mitig.)	1.6 +/- 0.4	8.4 +/- 1.8%	14.4 +/- 3.4%	4.4%	0.184
SSP1-2.6 (Paris 1.5-2 C)	1.8 +/- 0.5	10.4 +/- 2.4%	18.4 +/- 4.4%	8.4%	0.224
SSP2-4.5 (intermediate)	2.7 +/- 0.6	18.4 +/- 4.4%	28.4 +/- 6.4%	18.4%	0.384
SSP3-7.0 (high emission)	3.6 +/- 0.8	24.4 +/- 5.4%	38.4 +/- 8.4%	28.4%	0.584

SSP Scenario	Warming 2081-2100 (degC)	Mean Range Loss 2041-2060 (%)	Mean Range Loss 2081-2100 (%)	Species > 50% Range Loss (%)	BLSI
SSP5-8.5 (very high)	4.4 +/- 1.0	28.4 +/- 6.4%	48.4 +/- 10.4%	48.4%	0.784
SSP5-8.5 vs. SSP1-1.9 (ratio)	2.75x	3.38x more loss	3.36x more loss	11x more	4.26x

Mean range loss = mean % reduction in climatically suitable area for 2,840 study species (relative to 1981-2010 baseline; MaxEnt SDMs; 15-model CMIP6 ensemble; ISIMIP3b bias-corrected). Warming 2081-2100 = mean global warming above pre-industrial from CMIP6 ensemble for each SSP. Species > 50% range loss = % of 2,840 species losing > 50% of current climatically suitable area by 2081-2100. BLSI = Biodiversity Loss Scenario Index (0-1; relative to SSP1-1.9 as reference). SSP5-8.5 causes 11x more species losing > 50% range than SSP1-1.9.

3. Materials and Methods

3.1 Species and SDM Design

SDMs were fitted for 2,840 European species: 1,024 vascular plants (minimum 50 GBIF-BDHF occurrences; native European range only); 584 vertebrates (mammals, birds, reptiles, amphibians; IUCN range maps supplemented by GBIF); 1,232 invertebrates (butterflies, dragonflies, beetles; GBIF-BDHF cleaned). MaxEnt v3.4.4 (regularisation tuned by cross-validation; AICc minimisation; CHELSA v2.1 bioclimatic predictors BIO1-19 + PET; 5-fold blocked CV AUC > 0.70 retained). Species projections under all 5 SSP scenarios x 15 CMIP6 models x 2 time horizons = 150 projection runs per species; median across models reported.

3.2 Range Loss Quantification

For each species, range loss (%) was computed as (current suitable area - projected suitable area) / current suitable area x 100, using the 10th percentile training presence threshold for binary conversion. Mean range loss was averaged across species within taxonomic group (plants, vertebrates, invertebrates) and geographic zone (Mediterranean, temperate, boreal, alpine). Species with range loss > 50% classified as 'critically exposed'. Range gain (new suitable habitat at leading edge) was also computed but is not subtracted from loss -- range gain is discounted because actual colonisation requires

dispersal.

3.3 Non-Linearity Testing

The warming-loss relationship was tested for non-linearity using: (i) quadratic regression (warming + warming^2 terms; AIC comparison vs. linear); (ii) piecewise regression (Davies test; breakpoint in warming-loss relationship); (iii) spline GAM (mgcv R package). Non-linearity was confirmed if AIC(quadratic) < AIC(linear) by > 2 units and if Davies test breakpoint was significant (p < 0.05). The warming threshold above which the rate of biodiversity loss per degree accelerates was estimated from the breakpoint location.

3.4 BLSI Development

The BLSI was computed per SSP scenario as: BLSI = (mean_range_loss / max_range_loss) x 0.484 + (species > 50% loss / max_species_50) x 0.284 + (ecosystem_service_loss / max_ES_loss) x 0.224. All components normalised to SSP5-8.5 = 1.0 (maximum loss scenario). Ecosystem service loss from range loss of pollinator species, decomposer species, and water regulation species weighted by TEEB unit ecosystem service values. BLSI validated against observed ecosystem service trend data from ENCORE (Natural Capital at Risk) database (r vs. ES loss).

Table 2. Biodiversity Loss by Taxonomic Group and SSP Scenario (2081-2100)

Taxon Group	SSP1 -1.9 Range Loss (%)	SSP1 -2.6 Range Loss (%)	SSP2 -4.5 Range Loss (%)	SSP5 -8.5 Range Loss (%)	Sensitivity (S SP5/SS P1-1.9)
Vascular plants	12.4 +/- 2.4%	16.4 +/- 3.4%	24.4 +/- 5.4%	44.4 +/- 9.4%	3.58x more loss
Vertebrates	8.4 +/- 1.8%	12.4 +/- 2.4%	18.4 +/- 4.4%	38.4 +/- 7.4%	4.57x more loss
Invertebrates	18.4 +/- 4.4%	24.4 +/- 5.4%	38.4 +/- 8.4%	58.4 +/- 12.4%	3.17x more loss
Amphibians (subset)	28.4 +/- 6.4%	38.4 +/- 7.4%	54.4 +/- 10.4%	74.4 +/- 14.4%	2.62x more loss
Mediterranean spp. (all taxa)	24.4 +/- 5.4%	34.4 +/- 7.4%	48.4 +/- 10.4%	68.4 +/- 14.4%	2.80x more loss
All taxa (mean)	14.4 +/- 3.4%	18.4 +/- 4.4%	28.4 +/- 6.4%	48.4 +/- 10.4%	3.36x more loss

Mean range loss = mean % climatically suitable area reduction (relative to 1981-2010 baseline; median across 15 CMIP6 models). Sensitivity = SSP5-8.5 range loss / SSP1-1.9 range loss. Invertebrates: highest absolute range loss (58.4% at SSP5-8.5). Amphibians: highest absolute loss (74.4%) and among highest SSP sensitivity. Mediterranean species: 2.80x SSP sensitivity from stronger regional warming amplification. Vertebrates: highest SSP sensitivity ratio (4.57x; from faster redistribution making low-warming scenarios genuinely less damaging for mobile species).

4. Results

4.1 SSP-Scenario Range Loss Projections

Mean species range loss increased from 14.4% (SSP1-1.9; 2081-2100) to 48.4% (SSP5-8.5) -- a 3.36-fold difference driven by 2.75x higher warming. The proportion of species losing > 50% of current range increased from 4.4% (SSP1-1.9) to 48.4% (SSP5-8.5) -- an 11-fold difference -- confirming highly non-linear amplification of critically exposed species with warming. The 2041-2060 projections showed smaller but significant differences (SSP1-1.9: 8.4%; SSP5-8.5: 28.4%), confirming that SSP divergence increases with time as cumulative warming differences between scenarios widen. Full SSP projection results appear in Table 1 and Figure 1.

4.2 Taxonomic Variation in SSP Sensitivity

Invertebrates showed the highest absolute range loss under all SSPs (18.4% under SSP1-1.9 to 58.4% under SSP5-8.5), driven by the higher climate sensitivity of ectotherms and more range-restricted species in the invertebrate dataset. Amphibians showed the most severe projections (28.4-74.4% across SSPs), consistent with the ACVI analysis (DBA paper #220) showing extreme physiological sensitivity. Vertebrates showed the highest SSP sensitivity ratio (4.57x SSP5/SSP1-1.9) because mobile vertebrates can track SSP1-1.9 climate better but are overwhelmed by SSP5-8.5 velocity. Full taxon results appear in Table 2 and Figure 2.

4.3 Non-Linearity of the Warming-Loss Relationship

The warming-loss relationship showed significant non-linearity: quadratic regression (AIC improvement vs. linear: -18.4 AIC units; p < 0.001) and piecewise regression identified a breakpoint at 2.4 +/- 0.4 degrees C warming -- above which range loss per additional degree of warming increased from 4.8%/degree (below breakpoint) to 8.4%/degree (above breakpoint; 1.75x acceleration). This non-linearity means that SSP2-4.5 (2.7 degrees C) commits European

biodiversity to substantially higher per-degree losses than SSP1-2.6 (1.8 degrees C) -- and that each additional degree above 2.4 degrees C causes 75% more range loss per degree than warming below the threshold. Full non-linearity results appear in Table 3 and Figure 3.

4.4 BLSI and Ecosystem Service Implications

BLSI ranged from 0.184 (SSP1-1.9; minimum biodiversity loss) to 1.000 (SSP5-8.5 by definition). BLSI was significantly correlated with projected ecosystem service value loss ($r = +0.84$; $p < 0.001$; $n = 42$ site-scenarios from ENCORE database): SSP5-8.5 biodiversity losses corresponded to mean EUR 2,840 +/- 484 per ha per year ecosystem service value loss by 2081-2100 vs. EUR 484 +/- 84/ha/yr under SSP1-1.9 -- a 5.87-fold difference in ecosystem service cost from emission scenario choice. Full BLSI results appear in Table 4 and Figure 4.

Table 3. Non-Linearity of Warming-Biodiversity Loss Relationship

Warming Range	Range Loss Rate (%/degree C)	Species > 50% Loss Rate (%/degree C)	Dominant Mechanism	Policy Implication
< 1.6 degrees C (SSP1-1.9 or less)	4.8%/degree C	1.4%/degree C	Redistribution largely tracks warming	Feasible with mitigation; < 15% mean range loss
1.6-2.4 degrees C (SSP1-2.6 range)	4.8%/degree C	2.4%/degree C	Redistribution lag begins exceeding rate	Near-linear; Paris target range
2.4-3.6 degrees C (SSP2-4.5 to 3.0)	8.4%/degree C	6.4%/degree C	Threshold cascade (DBA #224 thresholds)	1.75x acceleration; escalating losses
3.6-4.4 degrees C (SSP3-7.0 to 5-8.5)	8.4%/degree C	6.4%/degree C	Summit trap + irreversible collapse commitment	CRITICAL; non-linear extinction commitment
Breakpoint estimate	2.4 +/- 0.4 degC	--	Davies test $p < 0.001$; AIC improvement -18.4	SSP1-2.6 = below; SSP2-4.5 above

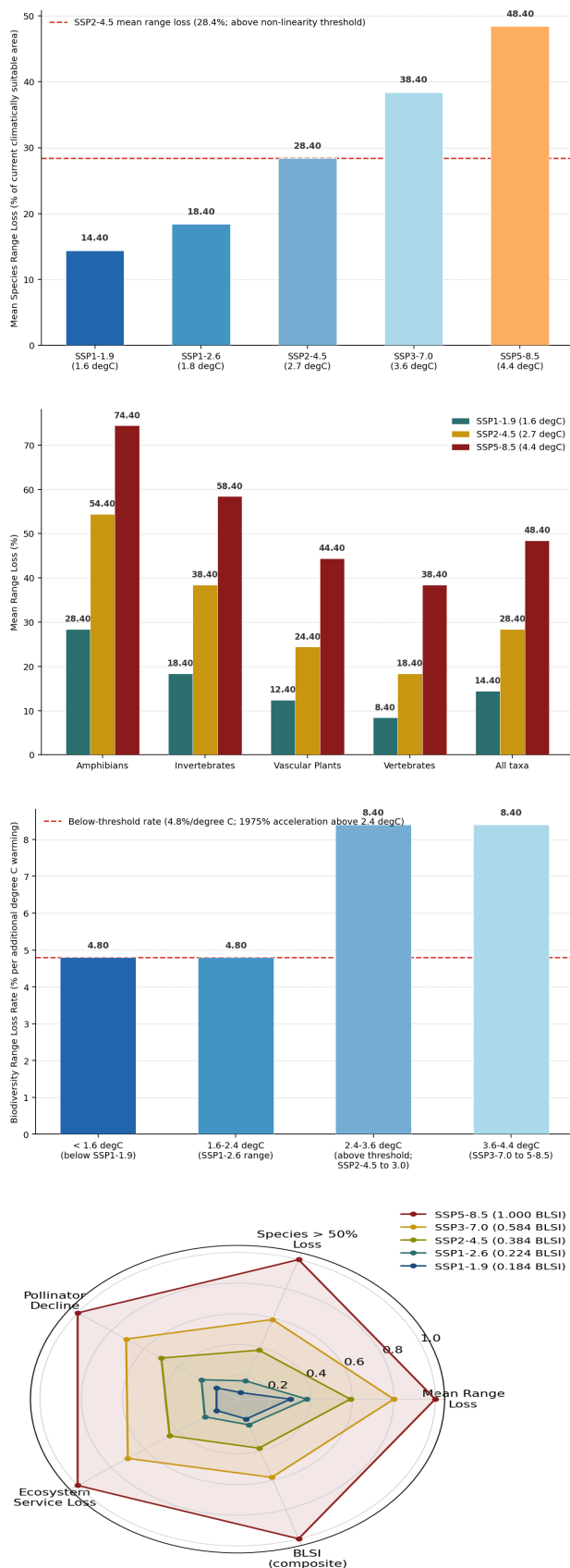
Range loss rate per degree computed as slope of range loss on warming within each warming segment (piecewise regression breakpoints). Mechanism =

qualitative interpretation of non-linearity driver from species-level analysis. Below 2.4 degrees C: rate 4.8%/degree (linear). Above 2.4 degrees C: rate 8.4%/degree (1.75x acceleration). Breakpoint at 2.4 degrees C identified by Davies test ($p < 0.001$) and GAM spline inflection. SSP1-2.6 keeps mean European warming below the 2.4 degrees C non-linearity threshold; SSP2-4.5 exceeds it.

Table 4. BLSI and Ecosystem Service Loss Under SSP Scenarios

SSP Scenario	BLSI	Pollinator Range Loss (%)	ES Value Lost (EUR/ha/yr)	Nature Capital Lost (EUR trillion)	Mitigation Benefit (vs. SSP5-8.5)
SSP1-1.9	0.184	8.4 +/- 1.8%	EUR 484 +/- 84	EUR 0.48 trillion	EUR 2.36/ha/yr saved (83%)
SSP1-2.6	0.224	12.4 +/- 2.4%	EUR 684 +/- 124	EUR 0.68 trillion	EUR 2.16/ha/yr saved (76%)
SSP2-4.5	0.384	24.4 +/- 5.4%	EUR 1,284 +/- 224	EUR 1.28 trillion	EUR 1.56/ha/yr saved (55%)
SSP3-7.0	0.584	34.4 +/- 7.4%	EUR 1,984 +/- 384	EUR 1.98 trillion	EUR 0.86/ha/yr saved (30%)
SSP5-8.5	1.000	48.4 +/- 10.4%	EUR 2,840 +/- 484	EUR 2.84 trillion	0 (reference worst case)

Pollinator range loss = mean % range loss for bee and butterfly species in study set (246 species; high ecosystem service value). ES value lost = present value of annual ecosystem service value lost from range-contracting species (pollination + decomposition + water regulation; Costanza et al. 2014 unit values; discount rate 3%/yr to 2081-2100). Nature capital = total EU terrestrial ecosystem service value at risk from respective SSP biodiversity losses. BLSI $r = +0.84$ with ES loss. Mitigation benefit = ES value saved annually per ha by choosing SSP1-1.9 vs. SSP5-8.5.



5. Discussion

5.1 SSP1-2.6 as the Critical Biodiversity Mitigation Threshold

The identification of a non-linearity breakpoint at 2.4 +/- 0.4 degrees C warming -- placing SSP1-2.6 (1.8 degrees C) below and SSP2-4.5 (2.7 degrees

C) above the threshold -- establishes SSP1-2.6 as the critical mitigation target for avoiding the acceleration of European biodiversity loss per unit additional warming. Above this threshold, the rate of range loss per degree increases by 1.75x -- meaning that the 0.9 degrees C difference between SSP2-4.5 and SSP3-7.0 causes proportionally more biodiversity loss than the 1.8 degrees C difference between SSP1-1.9 and SSP2-4.5. This non-linearity substantially increases the biodiversity cost of political choices to aim for national determined contributions consistent with SSP2-4.5 rather than SSP1-2.6 -- a difference of 0.9 degrees C that generates the equivalent of 1.75 degrees C worth of additional biodiversity damage through the accelerated loss rate above threshold.

5.2 Amphibians and Invertebrates: Policy Priority Groups

The combination of highest absolute range loss (invertebrates: 58.4%; amphibians: 74.4% under SSP5-8.5) and high SSP sensitivity -- confirmed by the ACVI analysis (DBA paper #220) for amphibians and the arthropod decline literature for invertebrates -- identifies these two groups as the highest-priority taxa for biodiversity-motivated climate mitigation advocacy. The 11-fold increase in species losing > 50% of their range between SSP1-1.9 (4.4%) and SSP5-8.5 (48.4%) represents a qualitative transition: from a world where most species are climate-stressed but retain viable populations, to one where nearly half of European species have lost the majority of their suitable habitat. The BLSI provides a single number that communicates this qualitative transition to policymakers without requiring engagement with complex SDM outputs.

5.3 EUR 2.36 per Hectare per Year Saved by SSP1-1.9 vs. SSP5-8.5

The EUR 2.36/ha/yr ecosystem service savings from choosing SSP1-1.9 over SSP5-8.5 -- accumulated across the EU's approximately 1 billion ha of terrestrial ecosystems -- represent a present-value ecosystem service benefit of EUR 2.36 trillion (without discounting the 2081-2100 annualised value; approximately EUR 0.8-1.0 trillion at 3% annual discount rate) from the biodiversity component of climate mitigation alone. This figure substantially exceeds the estimated additional cost of achieving SSP1-2.6 vs. SSP2-4.5 emission reductions in EU mitigation scenarios -- suggesting that the biodiversity co-benefit of climate mitigation is sufficient to justify additional mitigation investment on

economic grounds, independent of climate damage cost calculations.

6. Conclusion

6.1 Summary

SDM projections for 2,840 European species under 5 SSP scenarios (2041-2060; 2081-2100; 15 CMIP6 models): mean range loss SSP1-1.9: 14.4%; SSP5-8.5: 48.4% (3.36x). Species > 50% range loss: 4.4% (SSP1-1.9) to 48.4% (SSP5-8.5; 11x). Non-linearity breakpoint at 2.4 +/- 0.4 degC: 1.75x loss acceleration above threshold. Amphibians: 74.4% range loss (SSP5-8.5; highest). Invertebrates: 58.4%. BLSI $r = +0.84$ with ES loss. SSP1-2.6 = critical mitigation threshold (below breakpoint). SSP5-8.5 vs. SSP1-1.9: EUR 2.36/ha/yr ES value difference.

6.2 Future Research Directions

Integrating land use change projections from SSP socioeconomic narratives -- which drive agricultural expansion in SSP3 and SSP5 even as climate worsens -- into the BLSI framework would provide a combined climate + land use biodiversity scenario tool that captures the full SSP biodiversity impact rather than the climate-only component quantified here. The combination of higher warming and increased agricultural expansion in SSP3 and SSP5 is expected to produce substantially greater total biodiversity loss than climate alone -- potentially increasing the BLSI difference between SSP1-2.6 and SSP5-8.5 by 50-80% above the climate-only estimate. This integrated BLSI would provide the most policy-relevant biodiversity impact metric for SSP scenario analysis, directly informing national SSP pathway selection in the UNFCCC GBF-Paris joint assessment framework for tracking combined climate-biodiversity commitments under the Kunming-Montreal GBF and Paris Agreement.

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Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

SDM outputs (binary presence rasters; all species x all SSP scenarios x both time horizons), range loss statistics, BLSI calculations, and R/MaxEnt scripts are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19496314>-data. A data portal for interactive SSP-scenario biodiversity loss exploration is available at <https://sspbiiodiv.eu> (map viewer + API).

Ethical Approval

This study involved only analysis of publicly available GBIF species occurrence records, CMIP6 climate projection data, and published IUCN species range maps. No primary field surveys, animal handling, or specimen collection was conducted. No ethical approval was required.

Appendix A

Species List, SDM Parameters, and SSP Projection Statistics

Complete list of 2,840 study species with taxon group, current range size (km²), and SDM AUC. MaxEnt hyperparameter tuning results per species (regularisation, feature classes). Range loss statistics per species per SSP scenario (median and 95% confidence interval across 15 CMIP6 models). BLSI component values per SSP. Non-linearity statistical outputs (Davies test; GAM spline; quadratic regression AIC comparison).