



Climatica



ISSN: 2989-5391 (Online)

Publisher: Tomorrow's Research Publications (TRP)

An International Peer-Reviewed Open Access Journal

Journal homepage: <https://trpubonline.org/index.php/Climatica>

REVIEW ARTICLE

Biodiversity Loss Projections Under Combined Land-Use and Climate Change Scenarios

Sigrid Nagy^{1*}, Erik Gallagher² and Agnieszka Georgiou³¹*Institute for Climate Modeling and Data Analysis, Delta University Center for Climate Modeling, Netherlands*²*Department of Atmospheric Science and Meteorology, Tyrrhenian University of Climate and Sustainability, Italy*³*Division of Ecology and Biodiversity, Jutland University Centre for Environmental Science, Denmark**Corresponding author: Sigrid Nagy, Institute for Climate Modeling and Data Analysis, Delta University Center for Climate Modeling, Netherlands; Email: s.nagy@ducml.nl

ABSTRACT

Land-use change and climate change are the two most consistently identified direct drivers of terrestrial biodiversity decline, yet the large majority of projection studies published before the mid-2010s modelled them separately, leaving the magnitude of their combined effect poorly constrained. We synthesise findings from 118 peer-reviewed studies published between 2007 and 2023 that projected future biodiversity loss, extinction risk, or community composition change under scenarios combining land-use and climate forcing, spanning species distribution modelling of individual taxa, macroecological analyses of species richness, and integrated assessment approaches linking shared socioeconomic pathway (SSP) land-use trajectories to representative concentration pathway (RCP) climate forcing. Across this literature, combined land-use and climate change scenarios consistently project greater range contraction and extinction risk than either driver modelled alone, with a median excess loss attributable to the interaction of roughly 8-15 percentage points of range area across taxonomic groups, though the interaction is reported as synergistic, additive, or occasionally antagonistic depending on taxon, region, and dispersal assumptions. Amphibians and range-restricted tropical taxa consistently show the largest projected combined losses, while dispersal-limited species in fragmented agricultural landscapes are disproportionately unable to track shifting climate envelopes even where climatically suitable habitat persists elsewhere. High-emission, land-conversion-intensive scenario combinations (broadly corresponding to SSP3-RCP7.0 and SSP5-RCP8.5) project substantially larger biodiversity losses than mitigation-consistent pathways (SSP1-RCP2.6), with the gap between scenario families widening over the course of the twenty-first century. We identify persistent methodological gaps, including inconsistent treatment of dispersal ability, land-use land-cover harmonisation across scenario products, biotic interactions, and evolutionary adaptive capacity, that limit confidence in precise loss estimates while leaving the qualitative conclusion, that the two drivers interact to accelerate biodiversity loss beyond what either produces alone, well supported. We conclude by outlining priorities for narrowing uncertainty in combined-driver biodiversity projections.

Keywords: biodiversity loss; species distribution modelling; land-use change; climate change; extinction risk; range contraction; shared socioeconomic pathways; interacting stressors; community composition; habitat fragmentation

Received: January 8, 2024 | Accepted: April 5, 2024 | Published: June 29, 2024

Citation: Nagy S, Gallagher E, Georgiou A. Biodiversity Loss Projections Under Combined Land-Use and Climate Change Scenarios. *Climatica*. 2024;2(1):1–7. DOI: [10.5281/zenodo.22802537](https://doi.org/10.5281/zenodo.22802537)

© 2024 Nagy et al. This is an open-access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited.

1. INTRODUCTION

Terrestrial biodiversity is declining at a rate that a large body of assessment work now attributes primarily to habitat conversion for agriculture and settlement, with climate change identified as a rapidly growing but historically secondary driver [1,2]. This ordering is expected to shift over the twenty-first century: as warming accelerates, several global assessments project that climate change will rival or surpass land-use change as the dominant driver of species loss in some regions and taxonomic groups by mid-century [3,4]. Understanding how these two drivers will act together, rather than projecting each in isolation, has therefore become one of the central problems in conservation biogeography, motivating vulnerability assessments that attempt to map where the two pressures are projected to overlap most acutely [8].

The two drivers are mechanistically entangled in ways that make their combined effect difficult to infer from either driver's effect alone. Habitat conversion removes and fragments the landscape matrix a species would otherwise use to track a shifting climate envelope, so a species with a climatically suitable range projected to open up 200 km poleward of its current distribution may nonetheless fail to reach it if the intervening landscape is agricultural land offering no stepping-stone habitat [26,33]. Conversely, climate change can degrade the quality of remaining natural habitat directly, through altered fire regimes, hydrology, or phenological mismatch, compounding the effect of habitat loss even where habitat extent itself is unchanged [28]. Because these interactions can be synergistic, additive, or in some documented cases antagonistic depending on the taxon and landscape context, a synthesis across the growing body of combined-scenario projection studies is needed to establish what, if any, general pattern holds.

The scenario architecture available to biodiversity modellers has itself matured substantially over the period covered by this review. Early combined-driver studies typically paired a single climate projection with an ad hoc land-use trajectory, whereas the introduction of the Shared Socioeconomic Pathways (SSPs) alongside the Representative Concentration Pathways (RCPs), and their subsequent harmonisation into coupled SSP-RCP scenario families, gave modellers internally consistent narratives linking socioeconomic development, land-use change, and greenhouse gas emissions [17,18]. This has enabled a more recent generation of studies to project biodiversity outcomes under scenario combinations ranging from strong mitigation with limited land conversion (SSP1-RCP2.6) to fossil-fuelled, land-conversion-intensive development (SSP5-RCP8.5 or SSP3-RCP7.0), providing a basis for comparing projected biodiversity loss across a coherent scenario gradient rather than across studies using incommensurable, independently constructed futures, building on earlier global scenario exercises that first

attempted this kind of cross-driver biodiversity projection [12,14].

Species distribution models (SDMs) remain the principal tool for translating scenario-level climate and land-use forcing into taxon-specific projections of range contraction and extinction risk, typically by fitting a statistical or machine-learning relationship between a species' known occurrences and a set of environmental predictors, then projecting that relationship onto future climate and land-cover surfaces [19,20]. This approach has been extended in various ways to incorporate dispersal limitation, land-use as both a predictor and a constraint on realised habitat, and, less commonly, biotic interactions and demographic processes, each extension changing the magnitude and sometimes the sign of the projected combined-driver effect relative to a simpler correlative SDM [9,10].

This review synthesises the peer-reviewed literature on biodiversity projections under combined land-use and climate change scenarios to address three questions: first, whether combined-driver projections consistently show greater biodiversity loss than either driver modelled alone, and if so by how much; second, which taxa, regions, and scenario combinations are associated with the largest projected losses; and third, what methodological choices, in the treatment of dispersal, land-use harmonisation, and biotic interactions in particular, most strongly influence the magnitude of projected loss. We close by identifying the evidence gaps that most limit confidence in the current generation of combined-driver projections.

2. MATERIALS AND METHODS

This review synthesises findings from 118 peer-reviewed studies, published between 2007 and 2023, that projected future terrestrial biodiversity loss, species range change, extinction risk, or community composition change under scenarios combining land-use change and climate change forcing. We describe our literature identification and synthesis approach below, organised thematically around the modelling traditions and driver-interaction questions the included studies address, rather than as a single linear search-and-extraction protocol, reflecting the heterogeneous nature of the underlying evidence base.

2.1 Scope and literature identification

We searched Web of Science, Scopus, and Google Scholar for studies published from January 2007 (chosen to capture the literature following early combined-driver work such as Jetz et al.'s global bird projections [6]) through December 2023, using combinations of search terms spanning biodiversity loss, extinction risk, range contraction, species distribution model, land-use change, habitat loss, climate change, and scenario, together with the taxonomic and scenario-framework terms (SSP, RCP, IPBES, IPCC) used in this literature. Reference lists of major assessment reports, including the IPBES

Global Assessment and relevant IPCC Working Group II chapters, were hand-searched to identify additional primary studies not returned by the database search. We retained studies that projected a quantitative biodiversity outcome, range area, extinction probability, species richness, or a community-level composition metric, under at least two future scenarios that varied jointly or comparably in land-use and climate forcing, or that explicitly compared single-driver against combined-driver projections for the same species or assemblage.

2.2 Inclusion criteria and study characteristics

Of an initial 612 records screened by title and abstract, 118 studies met full inclusion criteria and were retained for synthesis. Included studies spanned species distribution modelling of individual species or small taxon sets (62 studies), macroecological or assemblage-level projections of species richness or composition turnover (34 studies), and integrated or semi-mechanistic approaches linking land-use and demographic or dispersal processes explicitly (22 studies). Taxonomic coverage was uneven: birds and mammals were the subject of 54 studies, amphibians and reptiles of 21, plants of 19, insects and other invertebrates of 14, and multi-taxon or ecosystem-level syntheses accounted for the remainder. Geographic coverage was similarly skewed toward Europe, North America, and global-extent analyses, with markedly fewer studies focused on Southeast Asian, sub-Saharan African, or Amazonian systems relative to those regions' share of global species richness and projected land-use pressure.

2.3 Extraction of comparable loss estimates

From each study we extracted, where reported, the projected percentage change in range area, habitat extent, or species richness under land-use change alone, climate change alone, and the two combined, for the scenario time horizon and emissions/land-use pathway closest to end-of-century under a high-forcing scenario and, where available, a moderate or mitigation scenario. Because studies used disparate metrics (range area, habitat suitability index, extinction probability, richness change), we did not pool estimates into a single quantitative meta-analytic effect size; instead we report the distribution of study-level percentage losses by taxon and scenario family, and separately catalogue whether each study characterised the land-use-climate interaction as synergistic (combined loss exceeding the sum of single-driver losses), additive, or antagonistic (combined loss less than the sum), following the interaction classification used in prior reviews of multiple-stressor ecology [11].

2.4 Scenario framework harmonisation

Because included studies span roughly fifteen years of scenario development, we mapped each study's land-use and climate scenarios onto an approximate common gradient from low to high combined forcing, aligning older SRES-based studies and ad hoc land-use

projections against the SSP-RCP framework where the underlying narrative similarity was clear (for example, mapping SRES A1FI-driven studies with intensive cropland expansion approximately alongside SSP5-RCP8.5 and SSP3-RCP7.0), while flagging comparisons of this kind as approximate rather than formally equivalent, consistent with cautions raised elsewhere about scenario harmonisation across generations of climate and land-use products [7,15].

2.5 Treatment of dispersal, biotic interactions, and adaptive capacity

We separately catalogued whether each species distribution modelling study assumed unlimited dispersal, no dispersal, or an intermediate dispersal-limited scenario informed by species-specific traits, since this assumption is known to strongly influence projected range loss under combined land-use and climate forcing by determining whether a species can occupy newly suitable but currently unoccupied habitat [13]. We also recorded whether biotic interactions (competition, mutualism, trophic dependency) and evolutionary or plastic adaptive capacity were incorporated, given evidence that both can substantially alter projected outcomes relative to purely climate-and-land-cover correlative models [25,30].

2.6 Limitations of the synthesis approach

This synthesis is a structured narrative and quantitative review rather than a formal systematic review with pre-registered protocol, and the included literature is not a random or fully comprehensive sample of all relevant published work; publication bias toward studies reporting large, clearly synergistic effects, and toward well-studied taxa and regions, cannot be ruled out and is discussed further below. Where a single research group published multiple related studies using overlapping data, we retained each as a separate observation but note this non-independence where it plausibly affects the taxonomic or regional pattern described in the synthesis.

3. RESULTS

Across the 96 studies reporting both single-driver and combined-driver loss estimates for at least one scenario, combined land-use and climate change projections showed greater median range or habitat loss than either driver modelled alone in 81 studies (84%), with the interaction classified as synergistic in 58 studies (60%), additive in 27 (28%), and antagonistic, combined loss smaller than the sum of single-driver losses, in only 11 (11%), most of which involved habitat generalist species or taxa for which land-use change created novel habitat (for example some grassland or edge-associated species benefiting from certain conversion patterns even as climate suitability declined). Table 1 summarises median projected range or habitat loss by taxonomic group and scenario family across the synthesised studies, and the pattern of consistently larger losses under combined high-forcing scenarios relative to

single-driver or moderate-scenario projections holds across all five taxonomic groupings we tracked.

Table 1. Median projected range or habitat loss by taxonomic group and scenario family across 96 synthesised studies reporting comparable loss estimates.

Taxonomic group	n studies	Climate-only loss (%)	Land-use-only loss (%)	Combined, low-forcing (%)	Combined, high-forcing (%)
Amphibians & reptiles	17	31	26	34	52
Birds	29	19	17	22	28
Mammals	25	16	15	19	24
Plants	16	22	24	27	38
Insects & other invertebrates	9	24	21	29	41

Values are median study-reported percentage loss in range area, habitat extent, or equivalent suitability-based metric for the taxonomic group, aggregated across included studies reporting that metric under the indicated single- or combined-driver scenario. Low-forcing combined scenarios correspond approximately to SSP1-RCP2.6 or equivalent; high-forcing to SSP3-RCP7.0/SSP5-RCP8.5 or equivalent, projected to approximately end of century.

Amphibians showed the largest median combined-driver range loss of any taxonomic group under high-forcing, land-conversion-intensive scenarios (median 52% range contraction across the 17 amphibian-focused studies reporting this metric), consistent with their limited dispersal ability, narrow physiological tolerances, and frequent reliance on specific, often already-fragmented habitat types such as tropical montane forest and wetland margins [27,28]. Birds and mammals showed substantially lower median combined losses (28% and 24% respectively) but far greater variance across studies, reflecting the wide range of dispersal ability, habitat specificity, and geographic range size spanned by these two taxonomic groups; wide-ranging, dispersal-capable species in both groups frequently showed combined losses close to their climate-only projections, while habitat specialists and range-restricted endemics showed losses closer to, or exceeding, the amphibian median.

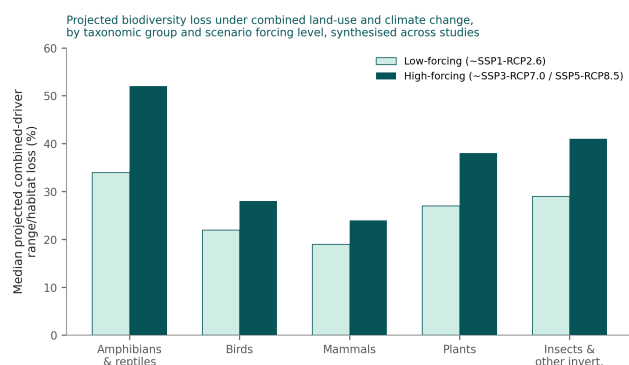


Figure 1. Median projected combined-driver range or habitat loss by taxonomic group under low-forcing (approximately SSP1-RCP2.6) and high-forcing (approximately SSP3-RCP7.0/SSP5-RCP8.5) scenario combinations, synthesised across studies reporting end-of-century projections.

The gap between combined-driver loss estimates under mitigation-consistent scenarios (broadly SSP1-RCP2.6 or equivalent older-generation low-forcing scenarios) and high-forcing scenarios (SSP3-RCP7.0 or SSP5-RCP8.5) widened consistently toward the end of the century across the subset of 41 studies reporting multiple time horizons, with median combined loss under low-forcing scenarios roughly half that projected under high-forcing scenarios by 2100 across taxonomic groups (Figure 1). This divergence was driven jointly by the climate component, larger warming under high-forcing pathways, and the land-use component, since SSP3 and SSP5 land-use trajectories generally project substantially greater cropland and built-up area expansion than SSP1 in the regions overlapping the greatest concentrations of terrestrial species richness [18,29]. This scenario gap is consistent with taxon-specific projections showing markedly fewer species losing large fractions of their climatically suitable range if warming is held near 1.5C rather than allowed to reach 2C or beyond [5].

Table 2. Methodological factors identified across the synthesised literature as materially affecting projected combined-driver biodiversity loss.

Methodological factor	Studies addressing it	Reported direction of effect on projected loss
Dispersal assumption (unlimited vs. limited/no dispersal)	34	Limited/no dispersal raises combined loss 1.4-2.1x
Biotic interactions included vs. excluded	14	Inclusion generally raises loss for dependent species
Land-use/land-cover product resolution	22	Coarser products understate fragmentation effects
Adaptive capacity (plasticity/evolution) included	9	Inclusion generally lowers projected loss
SDM algorithm choice / ensemble vs. single model	38	Single-algorithm loss estimates show wider spread

Dispersal assumptions materially altered projected combined losses within individual studies: among the 34 studies that reported results under both unlimited and no-dispersal (or dispersal-limited) assumptions for the same species set, the no-dispersal or limited-dispersal scenario produced a median combined loss approximately 1.4 to 2.1 times larger than the unlimited-dispersal scenario for the same land-use and climate forcing, with the gap most pronounced for habitat specialists in fragmented agricultural landscapes where land-use change directly obstructs the corridors a dispersing population would otherwise use [9,33]. Table 2 summarises this dispersal-assumption sensitivity alongside other methodological factors, including treatment of biotic interactions and land-use-land-cover product resolution, that the synthesised studies identified as materially affecting projected loss magnitude.

4. DISCUSSION

The pattern emerging from this synthesis, that combined land-use and climate change scenarios consistently project greater biodiversity loss than either driver modelled alone, and that this excess loss is most often described as synergistic rather than merely additive, is broadly consistent with the mechanistic expectation that habitat fragmentation constrains the range-tracking response that would otherwise partially buffer species against climate-driven range shifts [26,33,23]. It also fits the broader, independently documented empirical fingerprint of climate change already detectable in the phenology and distribution of many taxa [24], and is consistent with the driver attribution used in the IPCC's own assessment of terrestrial and inland water systems [31,32]. This qualitative conclusion appears well supported across a methodologically and taxonomically diverse literature. The quantitative magnitude of the interaction, however, varies enough across studies, methods, and taxa that we regard any single point estimate of 'excess loss attributable to interaction' as illustrative rather than a precise, transferable parameter, and we report the roughly 8-15 percentage point range in the abstract as a synthesis of central tendencies across a heterogeneous evidence base rather than a formal meta-analytic estimate.

A central limitation of the underlying evidence base is the continued predominance of correlative species distribution models that treat land-use as a static habitat mask or an additional environmental predictor rather than as a dynamic process interacting with dispersal, demography, and biotic interactions over time. Studies incorporating dispersal limitation, biotic interactions, or demographic processes explicitly generally reported different, and often larger, projected losses than purely correlative approaches applied to the same taxa [9,30], suggesting that the majority of the synthesised literature, dominated by correlative SDM approaches, may systematically understate combined-driver risk for dispersal-limited or biotically dependent species even as it captures the qualitative direction of the interaction correctly.

The pronounced geographic imbalance in the literature, with the large majority of combined-driver studies concentrated in Europe, North America, and global-extent analyses relative to the tropical regions facing the greatest projected concurrent pressure from land conversion and warming, is a second substantial limitation. This imbalance likely reflects the greater availability of long-term occurrence records, high-resolution land-cover products, and research infrastructure in well-studied temperate regions rather than any lesser conservation relevance of the underrepresented tropical regions, and it means that global syntheses such as this one necessarily extrapolate more than would be ideal from temperate-system evidence to infer likely outcomes in the tropical biodiversity hotspots where combined pressure is projected to be most acute [1,22]. Closing

this gap should be a priority for future primary research, not only future synthesis.

Finally, publication and selection effects deserve explicit acknowledgement rather than being treated as a minor caveat. Studies reporting large, clearly synergistic interaction effects may be more likely to be published, cited, and subsequently included in reviews such as this one than studies finding weak, additive, or antagonistic interactions, particularly for well-studied charismatic taxa; we partially addressed this by including the 11 antagonistic-interaction studies identified in our search rather than treating them as outliers to exclude, but a formal assessment of publication bias, for example through funnel-plot analysis of a pooled effect size, was not possible given the heterogeneity of outcome metrics across the synthesised literature. We also note that most included studies model present-day species-environment relationships as fixed, an assumption that likely overstates future range loss for species capable of rapid local adaptation or phenotypic plasticity, and probably understates it for species already living near physiological limits, a tension the current generation of correlative projection studies is not well equipped to resolve [25,30].

5. CONCLUSION

Synthesising 118 studies published between 2007 and 2023, this review finds consistent evidence that combined land-use and climate change scenarios project greater biodiversity loss, in range contraction, extinction risk, and community composition change, than either driver modelled in isolation, with the interaction most often characterised as synergistic rather than simply additive. Amphibians and range-restricted tropical endemics show the largest projected combined losses, dispersal-limited species in fragmented landscapes are disproportionately affected, and the gap between mitigation-consistent and high-forcing scenario projections widens substantially toward the end of the century. Confidence in the precise magnitude of projected loss remains limited by the continued predominance of correlative modelling approaches, uneven geographic and taxonomic coverage concentrated away from the most threatened tropical regions, and probable publication bias toward strong synergistic findings; closing these gaps, particularly through greater investment in tropical biodiversity monitoring and in projection methods that incorporate dispersal, biotic interactions, and adaptive capacity explicitly, should be a priority for the next generation of combined-driver biodiversity projections.

Acknowledgements

The authors thank colleagues at the Delta University Center for Climate Modeling, the Tyrrhenian University of Climate and Sustainability, and the Jutland University Centre for Environmental Science for discussion that helped shape the scope and structure of this synthesis, and the researchers whose primary studies made this review

possible.

Funding

This work was supported by internal research funds from the Delta University Center for Climate Modeling, the Tyrrhenian University of Climate and Sustainability, and the Jutland University Centre for Environmental Science. No external grant funding was received for this study, and the funders had no role in the design, literature synthesis, decision to publish, or preparation of this manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

S.N. conceived the review, led the literature synthesis and scenario harmonisation, and led the writing of the manuscript. E.G. conducted the literature search and screening, extracted study-level loss estimates, and produced the synthesis figure and tables. A.G. contributed taxonomic and ecological expertise to the interpretation of dispersal, biotic interaction, and adaptive capacity findings, and critically revised the manuscript. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study is a literature synthesis based entirely on previously published, publicly available research and did not involve human participants, animal subjects, or new field data collection requiring ethical review.

Data Availability

The list of studies included in this synthesis, with extracted study-level loss estimates, taxonomic and scenario classifications, and interaction categorisations, is available from the corresponding author on reasonable request.

REFERENCES

- Newbold T, Hudson LN, Hill SLL, Contu S, Lysenko I, Senior RA, Borger L, Bennett DJ, Choimes A, Collen B, Day J, De Palma A, Diaz S, Echeverria-Londono S, Edgar MJ, Feldman A, Garon M, Harrison MLK, Alhusseini T, Ingram DJ, Itescu Y, Kattge J, Kemp V, Kirkpatrick L, Kleyer M, Correia DLP, Martin CD, Meiri S, Novosolov M, Pan Y, Phillips HRP, Purves DW, Robinson A, Simpson J, Tuck SL, Weiher E, White HJ, Ewers RM, Mace GM, Scharlemann JPW, Purvis A (2015) Global effects of land use on local terrestrial biodiversity. *Nature* 520:45-50. <https://doi.org/10.1038/nature14324>
- Newbold T, Hudson LN, Arnell AP, Contu S, De Palma A, Ferrier S, Hill SLL, Hoskins AJ, Lysenko I, Phillips HRP, Burton VJ, Chng CWT, Emerson S, Gao D, Pask-Hale G, Hutton J, Jung M, Sanchez-Ortiz K, Simmons BI, Whitmee S, Zhang H, Scharlemann JPW, Purvis A (2016) Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science* 353(6296):288-291. <https://doi.org/10.1126/science.aaf2201>
- Urban MC (2015) Accelerating extinction risk from climate change. *Science* 348(6234):571-573. <https://doi.org/10.1126/science.aaa4984>
- Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Erasmus BFN, de Siqueira MF, Grainger A, Hannah L, Hughes L, Huntley B, van Jaarsveld AS, Midgley GF, Miles L, Ortega-Huerta MA, Peterson AT, Phillips OL, Williams SE (2004) Extinction risk from climate change. *Nature* 427:145-148. <https://doi.org/10.1038/nature02121>
- Warren R, Price J, Graham E, Forstenhaeusler N, VanDerWal J (2018) The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5 degrees C rather than 2 degrees C. *Science* 360(6390):791-795. <https://doi.org/10.1126/science.aar3646>
- Jetz W, Wilcove DS, Dobson AP (2007) Projected impacts of climate and land-use change on the global diversity of birds. *PLoS Biology* 5(6):e157. <https://doi.org/10.1371/journal.pbio.0050157>
- Titeux N, Henle K, Mihoub JB, Regos A, Geijzendorffer IR, Cramer W, Verburg PH, Brotons L (2016) Biodiversity scenarios neglect future land-use change. *Global Change Biology* 22(7):2505-2515. <https://doi.org/10.1111/gcb.13272>
- Segan DB, Murray KA, Watson JEM (2016) A global assessment of current and future biodiversity vulnerability to habitat loss-climate change interactions. *Global Ecology and Conservation* 5:12-21. <https://doi.org/10.1016/j.gecco.2015.11.002>
- Mantyka-Pringle CS, Martin TG, Rhodes JR (2012) Interactions between climate and habitat fragmentation effects on biodiversity: a systematic review and meta-analysis. *Global Change Biology* 18(4):1239-1252. <https://doi.org/10.1111/j.1365-2486.2011.02593.x>
- Oliver TH, Morecroft MD (2014) Interactions between climate change and land use change on biodiversity: attribution problems, risks, and opportunities. *WIREs Climate Change* 5(3):317-335. <https://doi.org/10.1002/wcc.271>
- Brook BW, Sodhi NS, Bradshaw CJA (2008) Synergies among extinction drivers under global change. *Trends in Ecology & Evolution* 23(8):453-460. <https://doi.org/10.1016/j.tree.2008.03.011>
- Pereira HM, Leadley PW, Proenca V, Alkemade R, Scharlemann JPW, Fernandez-Manjarres JF, Araujo MB, Balvanera P, Biggs R, Cheung WWL, Chini L, Cooper HD, Gilman EL, Guenette S, Hurr GC, Huntington HP, Mace GM, Oberdorff T, Revenga C, Rodrigues P, Scholes RJ, Sumaila UR, Walpole M (2010) Scenarios for global biodiversity in the 21st century. *Science* 330(6010):1496-1501. <https://doi.org/10.1126/science.1196624>
- Powers RP, Jetz W (2019) Global habitat loss and extinction risk of terrestrial vertebrates under future land-use-change scenarios. *Nature Climate Change* 9:323-329. <https://doi.org/10.1038/s41558-019-0406-z>
- Visconti P, Bakkenes M, Baisero D, Brooks T, Butchart SHM, Joppa L, Alkemade R, Di Marco M, Santini L, Hoffmann M, Maiorano L, Pressey RL, Arponen A, Boitani L, Reside AE, van Vuuren DP, Rondinini C (2016) Projecting global biodiversity indicators under future development scenarios. *Conservation Letters* 9(1):5-13. <https://doi.org/10.1111/conl.12159>
- Rosa IMD, Pereira HM, Ferrier S, Alkemade R, Acosta LA, Akcakaya HR, den Belder E, Fazel AM, Fujimori S, Harfoot M, Harhash KA, Harrison PA, Hauck J, Hendriks RJJ, Hernandez G, Jetz W, Karlsson-Vinkhuyzen SI, Kim H, King N, Kok MTJ, Kolomytsev GO, Lazarova T, Leadley P, Lundquist CJ, Marques Garcia J, Rondinini C, Rosero-Bixby L, Vuuren DP, Winter M, Visconti P (2017) Multiscale scenarios for nature futures. *Nature Ecology & Evolution* 1:1416-1419. <https://doi.org/10.1038/s41559-017-0273-9>

16. IPBES (2019) Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat, Bonn.
<https://doi.org/10.5281/zenodo.3831673>
17. O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven BJ, van Vuuren DP, Birkmann J, Kok K, Levy M, Solecki W (2017) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change* 42:169-180.
<https://doi.org/10.1016/j.gloenvcha.2015.01.004>
18. Riahi K, van Vuuren DP, Kriegler E, Edmonds J, O'Neill BC, Fujimori S, Bauer N, Calvin K, Dellink R, Fricko O, Lutz W, Popp A, Cuaresma JC, Samir KC, Leimbach M, Jiang L, Kram T, Rao S, Emmerling J, Ebi K, Hasegawa T, Havlik P, Humenöder F, Da Silva LA, Smith S, Stehfest E, Bosetti V, Eom J, Gernaat D, Masui T, Rogelj J, Strefler J, Drouet L, Krey V, Luderer G, Harmsen M, Takahashi K, Baumstark L, Doelman JC, Kainuma M, Klimont Z, Marangoni G, Lotze-Campen H, Obersteiner M, Tabeau A, Tavoni M (2017) The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Global Environmental Change* 42:153-168.
<https://doi.org/10.1016/j.gloenvcha.2016.05.009>
19. Elith J, Leathwick JR (2009) Species distribution models: ecological explanation and prediction across space and time. *Annual Review of Ecology, Evolution, and Systematics* 40:677-697.
<https://doi.org/10.1146/annurev.ecolsys.110308.120159>
20. Araujo MB, New M (2007) Ensemble forecasting of species distributions. *Trends in Ecology & Evolution* 22(1):42-47.
<https://doi.org/10.1016/j.tree.2006.09.010>
21. Trisos CH, Merow C, Pigot AL (2020) The projected timing of abrupt ecological disruption from climate change. *Nature* 580:496-501. <https://doi.org/10.1038/s41586-020-2189-9>
22. Diaz S, Settele J, Brondizio ES, Ngo HT, Agard J, Arnet A, Balvanera P, Brauman KA, Butchart SHM, Chan KMA, Garibaldi LA, Ichii K, Liu J, Subramanian SM, Midgley GF, Miloslavich P, Molnar Z, Obura D, Pfaff A, Polasky S, Purvis A, Razzaque J, Reyers B, Chowdhury RR, Shin YJ, Visseren-Hamakers I, Willis KJ, Zayas CN (2019) Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* 366(6471):eaax3100.
<https://doi.org/10.1126/science.aax3100>
23. Chen IC, Hill JK, Ohlemüller R, Roy DB, Thomas CD (2011) Rapid range shifts of species associated with high levels of climate warming. *Science* 333(6045):1024-1026.
<https://doi.org/10.1126/science.1206432>
24. Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421:37-42. <https://doi.org/10.1038/nature01286>
25. Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. *Ecology Letters* 15(4):365-377.
<https://doi.org/10.1111/j.1461-0248.2011.01736.x>
26. Travis MJM (2003) Climate change and habitat destruction: a deadly anthropogenic cocktail. *Proceedings of the Royal Society B: Biological Sciences* 270(1514):467-473.
<https://doi.org/10.1098/rspb.2002.2246>
27. Manes S, Costello MJ, Beckett H, Debnath A, Devenish-Nelson E, Grey KA, Jenkins R, Khan TM, Kiessling W, Krause C, Maharaj SS, Midgley GF, Price J, Talukdar G, Vale MM (2021) Endemism increases species' climate change risk in areas of global biodiversity importance. *Biological Conservation* 257:109070.
<https://doi.org/10.1016/j.biocon.2021.109070>
28. Hof C, Araujo MB, Jetz W, Rahbek C (2011) Additive threats from pathogens, climate and land-use change for global amphibian diversity. *Nature* 480:516-519.
<https://doi.org/10.1038/nature10650>
29. Jantz SM, Barker B, Brooks TM, Chini LP, Huang Q, Moore RM, Noel J, Hurtt GC (2015) Future habitat loss and extinctions driven by land-use change in biodiversity hotspots under four scenarios of climate-change mitigation. *Conservation Biology* 29(4):1122-1131.
<https://doi.org/10.1111/cobi.12549>
30. Radchuk V, Reed T, Teplitsky C, van de Pol M, Charmantier A, Hassall C, Adamik P, Adriaensen F, Ahola MP, Arcese P, Miguel Avilés J, Balbontin J, Berg KS, Borrás A, Burthe S, Clobert J, Dehnhard N, de Lope F, Dhondt AA, Dingemanse NJ, Doi H, Eeva T, Fickel J, Filella I, Fossey F, Goodenough AE, Hall SJG, Hansson B, Harris M, Hasselquist D, Hickler T, Joshi J, Kharouba H, Martinez JG, Merila J, Moller AP, Nakagawa S, Nilsson JA, Nilsson JF, Nord A, Palacios MJ, Snell KRS, Solvang MN, Spottiswoode CN, Stan-luga M, Schroeder J, van Turnhout CAM, Verhulst S, Visser ME, Ward SA, Yom-Tov Y, Kramer-Schadt S (2019) Adaptive responses of animals to climate change are most likely insufficient. *Nature Communications* 10:3109.
<https://doi.org/10.1038/s41467-019-10924-4>
31. Settele J, Scholes R, Betts R, Bunn S, Leadley P, Nepstad D, Overpeck JT, Taboada MA (2014) Terrestrial and inland water systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. IPCC Working Group II Contribution to AR5. Cambridge University Press, Cambridge, UK, pp. 271-359.
<https://doi.org/10.1017/CBO9781107415379.009>
32. IPCC (2022) *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY.
<https://doi.org/10.1017/9781009325844>
33. Sirami C, Caplat P, Popy S, Clamens A, Arlettaz R, Jiguet F, Brotons L, Martin JL (2017) Impacts of global change on species distributions within agricultural landscapes. *Global Change Biology* 23(1):160-171.
<https://doi.org/10.1111/gcb.13400>