ENVIRONMENTAL STUDIES

Can we bend the curve: Trends in global biodiversity scenarios

Flavia Aschi[1,2]*, Stefan C. Dekker[1,3], David Leclère[4], Alexandra Marques[2], Christian Neumann[5], Geanderson Ambrosio[1], Detlef P. van Vuuren[1,2]

Internationally, it has been agreed to halt and reverse biodiversity loss, a commitment partly underpinned by model-based scenario analyses showing that bending the trend is possible. These scenarios provide insights into alternative future biodiversity trends and their drivers. Our meta-analysis differentiates scenarios that project biodiversity loss and that halt or reverse the trend based on their quantitative outcomes and explores their key characteristics such as scenario assumptions, drivers of loss, biodiversity indicators and models used. We found that bending-the-curve studies are scarce, and mostly do no account for climate change, which risks suggesting that the trend can be bent too easily. Our findings indicate that bending is only achievable with integrated efforts across different sectors, such as nature conservation, sustainable food production, diet change, and reduced food waste. To better support policymaking, scenarios should be based on model intercomparisons and use standardize indicators to allow comparisons across studies, account for additional drivers of loss to represent the real threats to biodiversity, and include more ambitious cross-sectoral actions to effectively bend the curve.

INTRODUCTION

As part of the Kunming-Montreal Global Biodiversity Framework (KMGBF) of the Convention on Biological Diversity (CBD), countries have agreed to take urgent action to halt and reverse biodiversity loss (*1*). However, despite these global commitments, under current policies global biodiversity is expected to further decline, largely as a result of human-induced climatic and environmental changes (*2*–*4*).

Model-based scenarios can be used for exploratory projections of biodiversity. They can provide insights into the consequences of current policies and trends, as well as alternative future pathways and policy choices that could affect biodiversity and achieve nature conservation objectives, such as the KMGBF goal (*5*–*8*). Scenario analysis often draws upon storylines of alternative future socioeconomic development (*8*). Models are then used to quantitatively assess future trajectories of biodiversity and its drivers under these plausible scenarios (*9*). Such biodiversity scenarios often form a major component of global biodiversity assessments [e.g., Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (*5*, *10*)]. Due to increasingly ambitious biodiversity goals and commitments [e.g., Global Biodiversity Framework (GBF)], over time, the focus of global biodiversity scenarios has shifted from exploratory projections of future biodiversity trends to developing pathways to achieve desirable futures by identifying policy options to reduce or halt the rate of biodiversity loss (*6*, *11*). Recently, scenarios have started to explore the type of actions needed to reverse biodiversity trends: This narrative of bending the curve of biodiversity loss has gained momentum over time (*3*, *12*, *13*).

Scenarios can inform policymakers about several key elements, including the most important drivers of biodiversity loss, actual progress in biodiversity using biodiversity indicators (BDIs) (*14*), the progress toward overall goals, and on the effective policy instruments. Important drivers of biodiversity loss include, for instance, climate and land-use changes, pollution, and invasive species (*5*, *15*), but not all drivers are equally accounted for in scenario studies (*16*). Regarding trends in biodiversity, a variety of different indicators have been used because of the multifaceted nature of biodiversity and differences across models. However, this complicates the comparison of different scenarios and their utility to assess progress toward biodiversity goals (*17*, *18*), and thus, there is a need to develop standardized indicators to measure progress toward global goals and allow comparisons across studies (*14*, *19*–*21*).

The last systematic review of global biodiversity scenarios was published over a decade ago (*18*) and did not compare scenarios in terms of their ability to "bend the curve." This means that we lack information on key determinants of biodiversity outcomes. In addition, no comprehensive review of scenario studies exists that investigates a number of key critical elements, such as the biodiversity indicator used, the drivers of biodiversity loss covered in the studies, the achievement of the scenarios, and their underlying policy assumptions. These elements have not been covered in earlier reviews (*16*, *18*). Understanding possible modeling limitations of these elements in global biodiversity scenarios is urgently important, given the recent commitment to new global goals, and the emergence of more policy-oriented global scenarios, including those consistent with the CBD goals.

Here, we aim to fill this knowledge gap by providing the most up-to-date quantitative systematic meta-analysis based on the complete set of existing global biodiversity scenarios. We do so by (i) differentiating between nonpolicy (baseline and worst-case) and policy scenarios, based on their level of ambition toward global targets (reduce-loss, net-zero, and bending-the-curve), by harmonizing outputs of all scenarios and compare their projected biodiversity changes. In addition, we review (ii) the full set of indicators used to describe biodiversity, given their importance to report progress toward global targets; and (iii) the drivers of loss considered, to identify gaps in modeling efforts. Last, we (iv) compare policy assumptions of the current set of ambitious scenarios, to suggest the dimensions

[1]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, Netherlands. [2]Netherlands Environmental Assessment Agency (PBL), The Hague, Netherlands. [3]NIOO-KNAW, The Netherlands Institute of Ecology, Wageningen, Netherlands. [4]Biodiversity and Natural Resources (BNR) Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. [5]Department Computational Landscape Ecology, Helmholtz-Centre for Environmental Research (UFZ), Leipzig, Germany.
*Corresponding author. Email: f.aschi@uu.nl

in which future global biodiversity studies should expand, if we are to reverse the declining trend of biodiversity.

RESULTS

Descriptive characteristics of global biodiversity scenarios: Scenario classification, BDIs, and drivers of loss

We retrieved metadata for the 57 papers that passed our screening procedure (see the "Search strategy and record screening" section). The number of papers presenting future biodiversity scenarios slowly increased in the 2006 to 2023 period (Fig. 1A). Also, the number of scenarios per paper rose in the same time period (Fig. 1B). We identified a total of 138 scenarios. These were categorized on the basis of quantitative information of model outputs for BDI projections. The majority were nonpolicy scenarios (63.4%, n scenarios = 85), baseline and worst-case, which, respectively, either assume the continuation of historical trends into the future projecting the effect of current policies on biodiversity (*8*) or describe a more pessimistic future than the baseline, with high values of drivers of biodiversity loss. The remaining scenarios (37.6%, n scenarios = 49) were classified as policy scenarios as they include biodiversity conservation polices and aim to improve biodiversity conditions. Among these, we found only nine scenarios in the category bending-the-curve, which involve policy actions that are projected to reverse biodiversity declines compared to the start of the projected period, and one scenario in the category net-zero loss, which leads to BDI levels comparable to the start of the projected period. In contrast, many more reduce-loss scenarios were found (n scenarios = 39), which lead to a reduction in rate of biodiversity loss compared to the relative baseline but do not reach higher level than that of the start of the projected period. Scenarios halting or reversing biodiversity loss first appeared in 2015 but became more frequently studied from 2018 onward. The reduce-loss scenarios were first published in 2006 but became more frequently studied from 2017. Worst-case was the most common scenario type (n scenarios = 45) studied across all years, followed by baseline (n scenarios = 40) (Fig. 1C). Scenarios of some papers (n papers = 19) could not be classified on the basis of our criteria because papers did not provide quantitative information on BDI projections.

The majority of quantitative global papers focused on terrestrial organisms (91%, n = 52), while paper focusing on aquatic organisms were rare (9%, n = 5). More than two-thirds of papers (66.7%, n = 38) used biodiversity models (BDMs) to describe the impacts of direct drivers of loss on biodiversity. Of the 19 BDMs identified in the selected literature, the GLOBIO model, Species Area Relationship, Systematic Conservation Planning, and Species Distribution Models were the most commonly used (n papers = 12, 8, 6, and 4, respectively) (Fig. 2A). We identified a total of 35 BDIs (Fig. 2B), which were classified into area-based indicators and species-based indicators. Area-based indicators were further categorized into species-distribution indicators, which describe changes in areas on the basis of the probability of occurrence of species; and habitat-transformation indicators, which describe changes in natural habitats without considering species distributions. Species-based indicators were categorized into species diversity, species abundance, and species risk of extinction (a list of the indicators per category is available in table S2).

More than half of all papers (63%, n = 36) used models describing pressures on biodiversity. In this category, 33 models were used. Here, Integrated Model to Assess the Global Environment was most used (n papers = 18), followed by Asia-Pacific Integrated Model (n papers = 3), CLUMondo (n papers = 3), and Global Biosphere Management Model (n papers = 2) (Fig. 2C and table S3).

Through the application of these models, the majority of papers examined the effect of land-use change on biodiversity (79%, n = 45), and a considerable number of papers accounted for climate change effects (37%, n = 21) (Fig. 3). Only a minority of papers (n = 14; 25%), accounted for additional drivers (such as pollution and agricultural

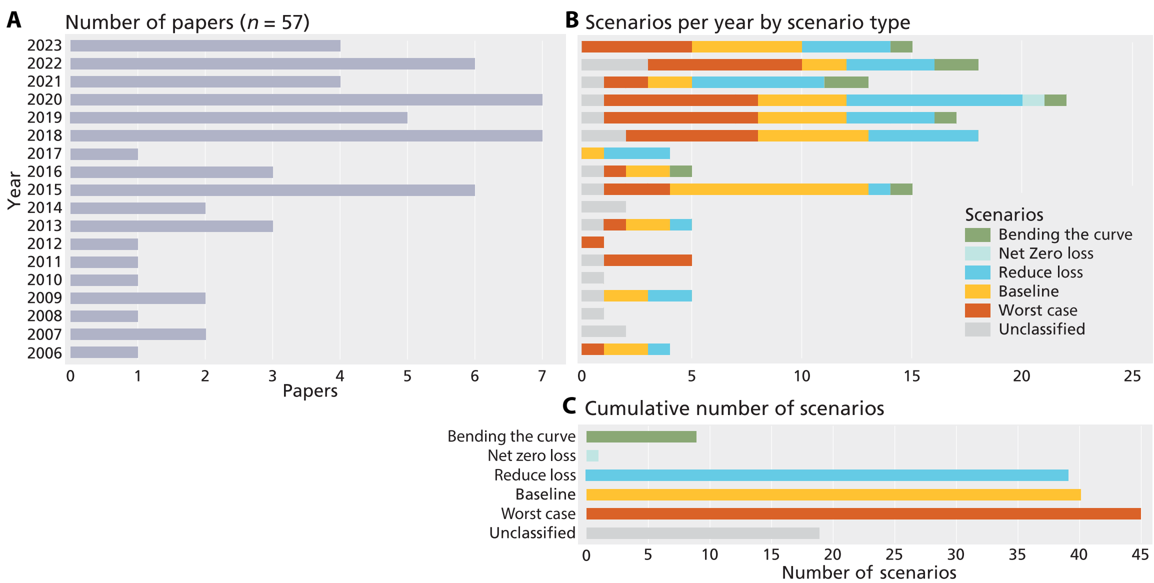

Fig. 1. Summary of paper and scenario publication trends and classification. (**A**) Number of papers by year of publication. (**B**) Number of scenarios by scenario type and year of publication. (**C**) Total number of scenarios per full period by scenario type. For additional information on scenario categorization, see the Supplementary Materials.

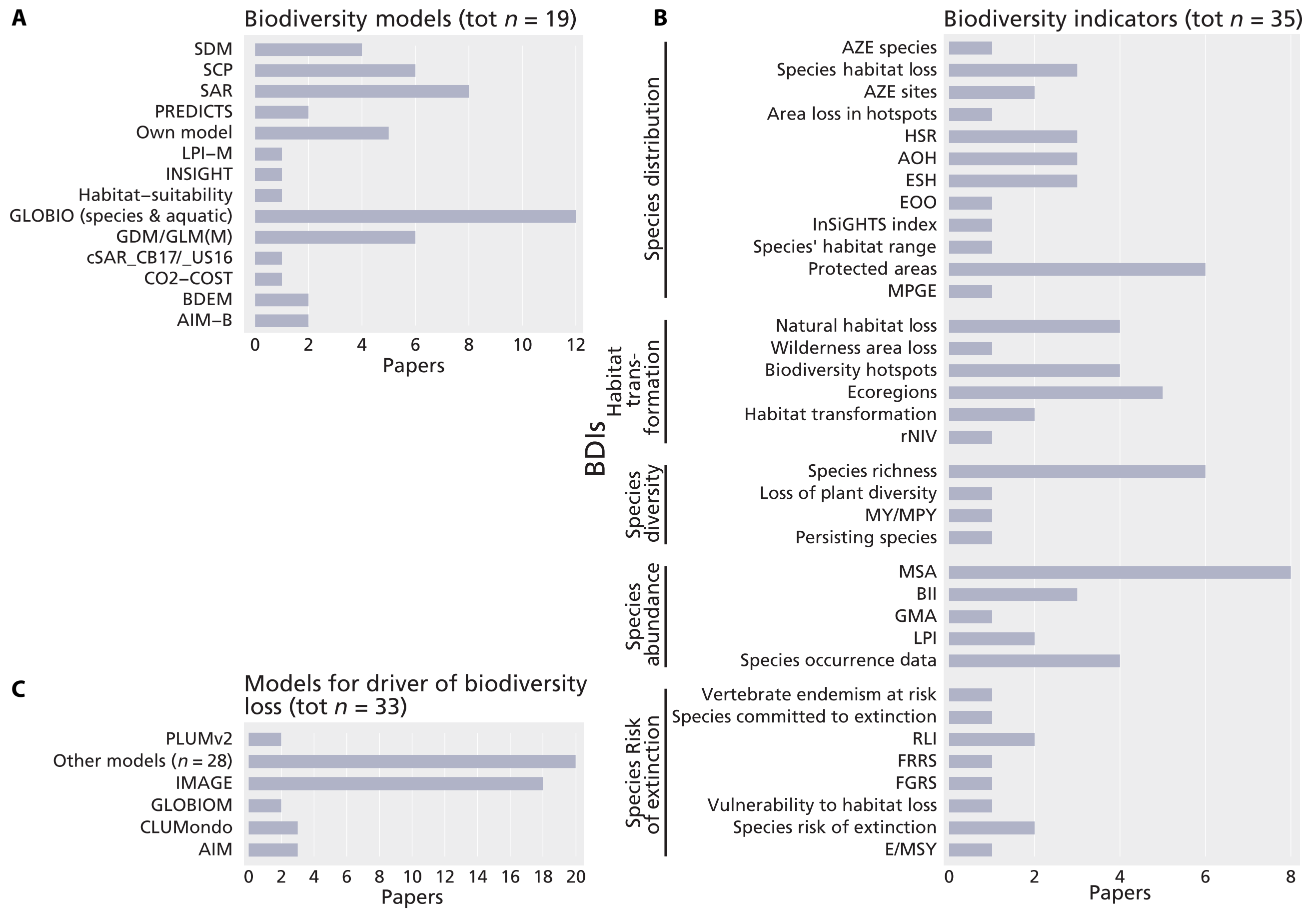

Fig. 2. Descriptive characteristics of selected literature. (**A**) Biodiversity models (BDMs) used to project changes in BDIs. (**B**) BDIs used to describe changes in biodiversity. (**C**) Top five models describing pressures on biodiversity. The list of acronyms for (A) to (C) is available in the Supplementary Materials.

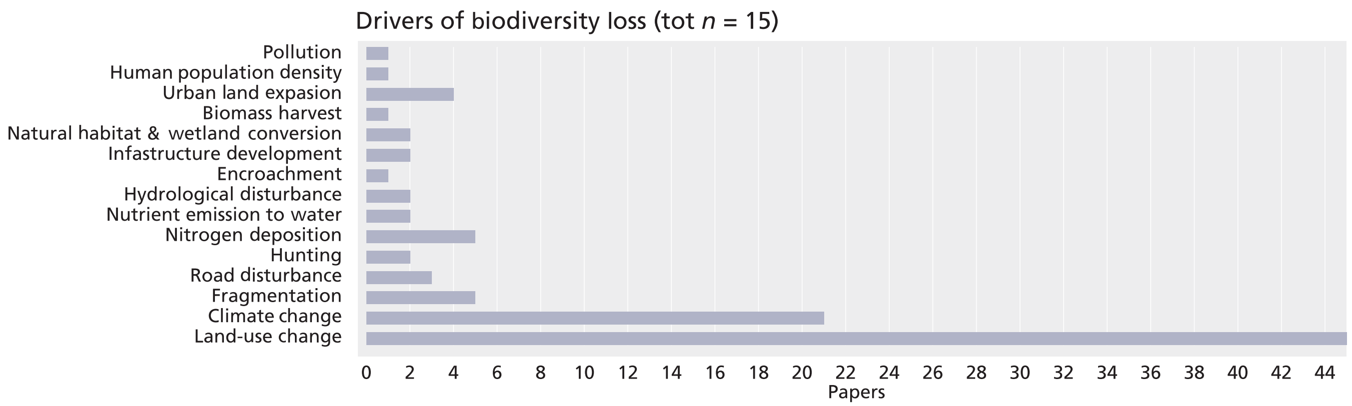

Fig. 3. Direct drivers of biodiversity loss found in the selected literature.

intensity), and none of the papers accounted for invasive species. Some of the listed drivers could belong to higher-level categories (e.g., urban land expansion to land-use change and nitrogen deposition to pollution). However, these were kept as separate drivers because papers reporting these drivers exclusively projected their specific impact on biodiversity.

Papers did not always provide complete data for all the BDIs modeled. As a result, we could not retrieve quantitative data in 19 of the 57 selected papers. Of the 35 papers from which we retrieved quantitative data, 22 (63%) focused on a single driver of loss, and 13 papers (37%) included multiple drivers. Eleven papers (31%) accounted for the additive effect of climate and land-use changes,

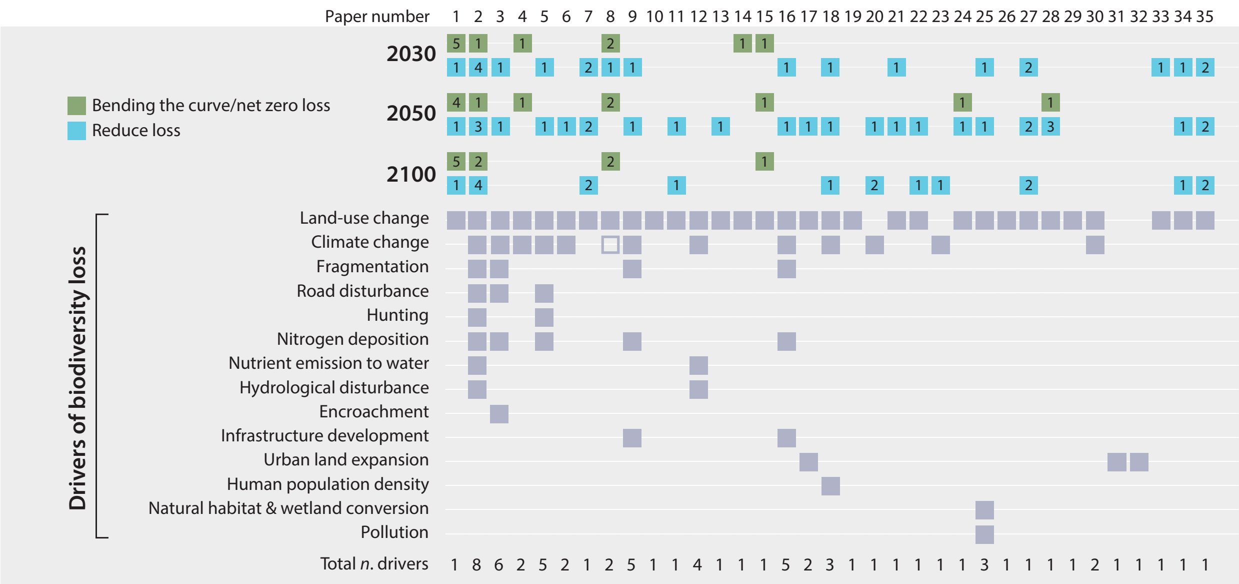

Fig. 4. Drivers of biodiversity loss in bending-the-curve and reduce-loss scenarios. Top: Policy scenarios (bending-the-curve/net-zero-loss scenarios in green and reduce-loss scenarios in blue) per paper (columns) and projected year 2030, 2050, and 2100 (rows). Colors represent scenarios, and value within the cell the number of BDIs used in that scenario. Bottom: Direct drivers of biodiversity loss included per paper, indicated by the purple cells. The one hollow cell for paper number 8 indicates that the driver climate change is not included in the bending-the-curve scenario.

one of which accounted also for their synergetic interaction (Fig. 4, paper number 8). Only two of the papers that account for climate change are categorized as bending-the-curve scenario (Fig. 4, paper numbers 2 and 4) (*13*, *22*); all other papers that include climate change, at best, produced reduce-loss scenarios (34%, *n* papers = 12). Other papers (31%, *n* papers = 11) included additional drivers of loss, other than land-use and climate change, such as fragmentation and nitrogen deposition (Fig. 4). Of the 35 papers from which we retrieved quantitative data, 13 papers (37%) modeled multiple BDIs (*n* BDIs = 2 to 5), and the rest (*n* papers = 22; 63%) modeled single indicators (Fig. 4). The collected quantitative data on BDI projections was used for further analysis (see the next section).

Comparison of BDI projections

We used quantitative data collected for the 35 studies to plot projections of BDIs by class and scenario type. The BDI projections were harmonized for the years 2030, 2050, and 2100 as a proportional change compared to a base year, which we chose to be 2015. We plotted projected trends per BDI class by scenario type (Fig. 5).

Overall, the projections of BDIs show that the rate of biodiversity loss is expected to increase further in future years under current policies (worst-case and baseline scenarios) and to reduce and even reverse under increasingly ambitious scenarios (reduce-loss and bending-the-curve scenarios) (Table 1).

For BDI classes of terrestrial species abundance and risk of extinction, the scenario categories—worst-case, baseline, reduce-loss, and bending-the-curve—exhibit more distinct future trends (Fig. 5, A and C). For the other BDI classes, species distributions, species diversity, and habitat transformation (Fig. 5, B, D, and E), there is a stronger overlap between the scenario categories. We found that a higher uncertainty range of all scenarios is generally associated with a higher number of BDIs compared (≥4), while scenarios with a lower uncertainty range are generally resulting from comparing fewer BDIs (≤3), with the exception of scenarios that compare similar BDIs (e.g., extinctions per million species years and extinctions per million species years) (*23*).

For all BDI classes, the worst-case and baseline scenarios show a negative relative change in BDI projections in 2050 compared to that in base year value 2015 (−12.7 and −5.9%, respectively). Among the policy scenarios, reduce-loss scenarios project an average relative negative change of BDIs of −4.5%. and bending-the-curve scenarios (*n* scenarios = 11) project an average positive relative change of 3.6%, with the exception of one study that project up to 92% of recovery of arable areas of natural intact vegetation (*24*).

Policy assumptions of the current set of ambitious scenarios: Bending the curve and reduce loss

We also examined the policy measures in the bending-the-curve and reduce-loss scenarios. A total of 18 measures were identified and were classified in five action bundles: increased conservation, agriculture and forestry supply, food demand, mitigation measures, and other (the full list of single measures included in each bundle is available in table S4). Bending-the-curve scenarios include more policy measures (>5) and from more different action bundles (>3) than the set of reduce-loss scenarios (Fig. 6, A and B). The majority (66%) of bending-the-curve scenarios used measures across all five action bundles, in contrast to 10% in the reduce-loss scenarios. Half (48%) of reduce-loss scenarios include five or more measures. These either are based on less ambitious measures directly addressing biodiversity loss (36%) (e.g., SSP1xRCP2.6), account for multiple drivers of loss (29%), focus on policies spanning fewer action bundles (13%), or project less sensitive BDIs (4.5%).

Diet change, reduced food waste, and sustainable intensification are policy measures that are included in all bending-the-curve

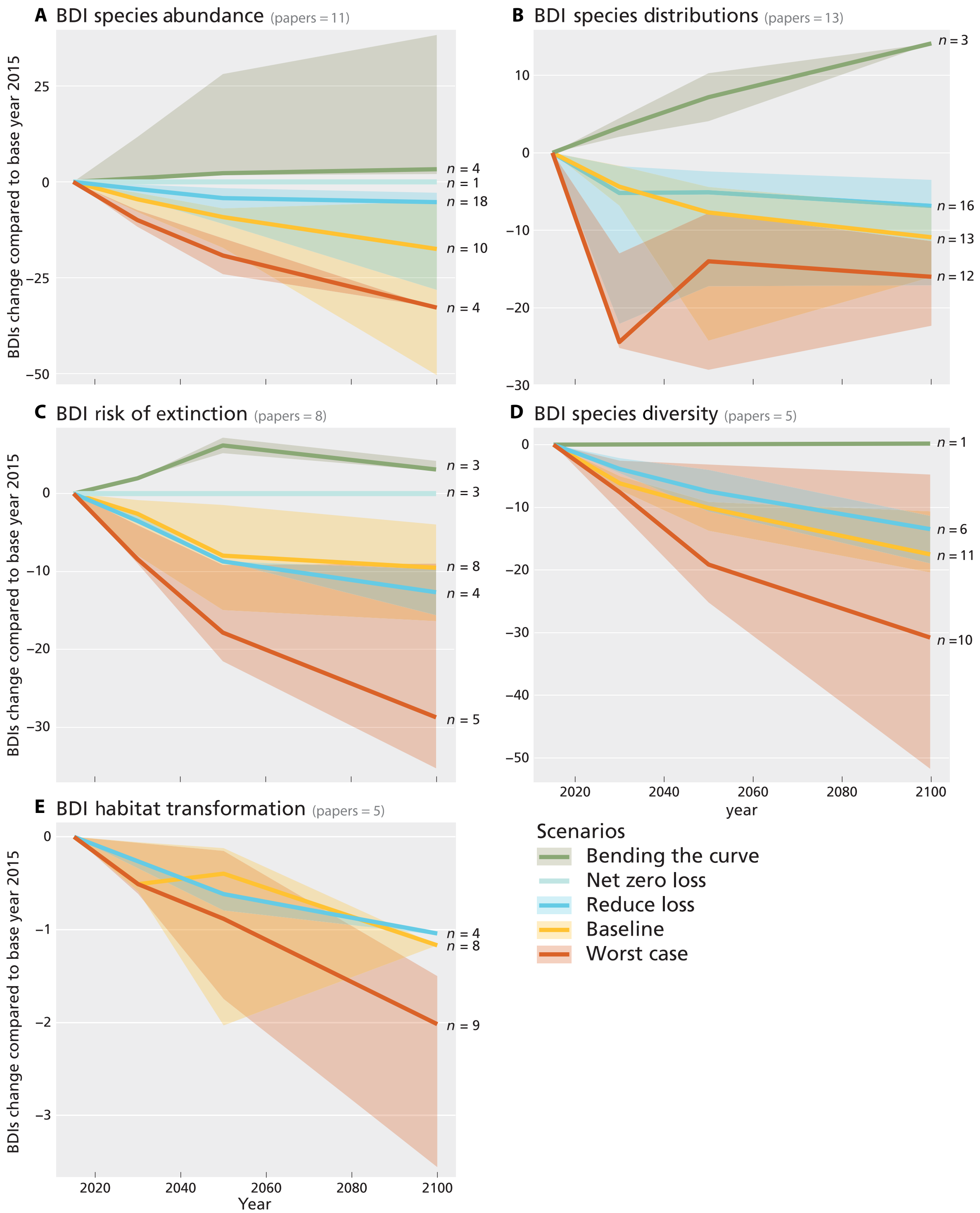

Fig. 5. Relative change of five BDI classes harmonized to a common base year (2015) and for the projected years 2030, 2050, and 2100. Trends are shown across five BDI classes: species abundance (**A**), species distributions (**B**), risk of extinction (**C**), species diversity (**D**), and habitat transformation (**E**). In each panel [(A) to (E)], the solid line indicates the median, and the shaded areas represent the 16th and 84th percentiles. The number of scenarios contributing to the trend is shown next to the trend line for each scenario. A list of BDIs for each class is available in table S2.

Table 1. Relative change of BDIs by class, scenario type, and projected year (2030 and 2050). The change is relative to the base year 2015. The values represent the median. "*X*" denotes missing values.

	Worst case		Baseline		Reduce loss		Bending the curve	
	2030	2050	2030	2050	2030	2050	2030	2050
Species abundance	−9.9	−19	−4.5	−9.1	−1.9	−4.2	0.9	2.3
Species distributions	−24.4	−14	−4.3	−7.7	−5.2	−5.1	3.2	7.2
Risk of extinction	−8.4	−18	−2.6	−8	−3.5	−8.7	2	6.2
Species diversity	−7.6	−19	−6.2	−10	−3.9	−7.5	*X*	*X*
Habitat transformation	−0.5	−0.9	−0.5	0	*X*	−0.6	*X*	*X*

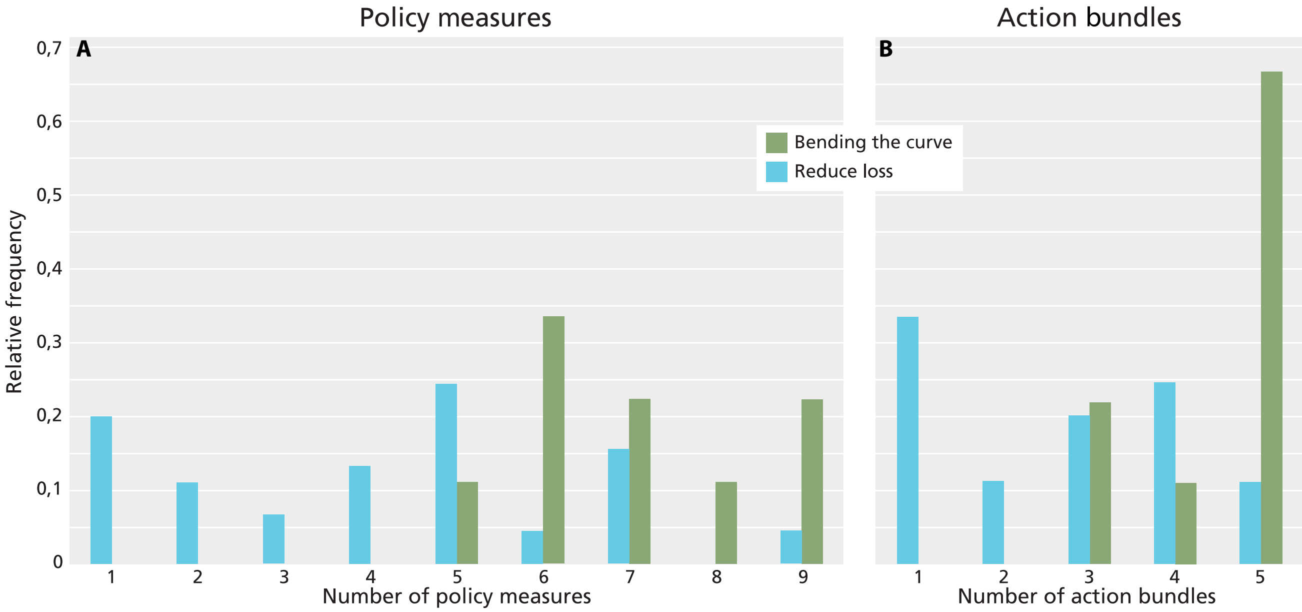

Fig. 6. Summary of policy assumptions in bending-the-curve and reduce-loss scenarios. Relative frequency of (**A**) policy measures included in bending-the-curve (green) and reduce-loss (blue) scenarios, and (**B**) the number of action bundles from which the policy measures are taken.

scenarios. Expanded protected areas and reduced use of bioenergy are often included, while restoration, land planning, increased trade, crop mix change, forestry plantation, reforestation, and lifestyle changes are less frequently included.

DISCUSSION

Main findings and research gaps in existing scenario studies

In this meta-analysis, we examined how scenarios have been used in the past two decades to explore projections of future biodiversity trends. By systematically screening literature, we identified 138 modeled global scenarios (covered by 57 papers) that project, reduce, stop, or reverse biodiversity loss. This allows us to identify three major research gaps and derive conclusions regarding the content of the scenarios. For each conclusion, we outline critical research recommendations.

Bending-the-curve scenarios are scarce

We found that the majority of scenarios (>60%) project future biodiversity losses under current trends or worst-case policies. Scenarios that aim to reduce, stop, or reverse biodiversity loss are less frequent within the screened literature (<40%). Within the latter group, scenarios that halt the loss of biodiversity represent the bigger share (80%), and the more ambitious scenarios that aim at bending are less common (only nine in total).

The narrative of bending the curve was first introduced in 2018 to describe a new generation of ambitious scenarios (*20*, *25*). The recent effort to develop scenarios that fully reverse the loss of biodiversity based on this narrative is concomitant to the recent increase in ambition in policy objectives at global scale (GBF). Bending-the-curve–like scenarios first appeared in 2015 (*22*, *26*) and have been increasingly modeled since 2019 (*3*, *4*, *13*, *24*, *27*–*29*). However, because the GBF goal is relatively recent (*1*), these scenarios are still scarce in literature. Effort to increase knowledge about bending-the-curve model and scenario application, as well as policy options to fully reverse biodiversity loss, is crucial if we are to meet current global biodiversity targets.

The use of many different indicators makes comparison challenging

Despite earlier calls for a defined set of quantitative, global, and standardized indicators to measure progress toward biodiversity goals and allow comparisons across studies (*14*, *19*–*21*), we found large varieties of BDIs (*n* BDIs = 35), BDMs, and models that describe pressures on biodiversity (Fig. 2, A to C). Inspired by the Essential Climate Variables from the climate science community, the Essential Biodiversity Variables (EBVs) were proposed, a minimum set that capture different components and dimensions of biodiversity change (*14*, *30*–*32*). The BDIs found in the screened literature are aligned with mainly one of the six EBV classes (namely, species populations). The reason for this is because the studies here reviewed use indicators that are meaningful at a global scale [e.g., Mean Species Abundance (MSA), biodiversity intactness index (BII), and living planet index (LPI)] but are unable to model local-scale–dependent biodiversity measures (e.g., within-species diversity, functional traits, and local adaptations). Nonetheless, the diversity of BDIs found represents a critical research gap in global biodiversity scenarios. Not only it complicates a direct comparison of scenario outcomes (*4*, *5*, *18*), but also it has been identified as a factor contributing to the failure of meeting any of the CBD Aichi Targets and seriously slows down international policy making (*33*–*35*).

At the moment, a direct comparison of scenario studies is only possible after harmonizing scenarios and input data, and it is likely that is also needed in the future (*5*). Multimodel comparisons typically are a catalyst for such harmonization efforts (*36*, *37*). However, model intercomparison studies for global biodiversity scenarios are limited (*3*, *4*), and scenarios reviewed in this study are based on single or small number of models, with the exception of one study (*3*). In contrast, climate research benefits from extensive community scenarios (e.g., Shared Socioeconomic Pathways (SSPs) and current policy scenarios) and regular model comparisons, which provide insight into the role of different models. The scarcity of such modeling approaches in global biodiversity studies, as well as challenges of comparing outputs from different indicators, emphasizes the need for joint efforts in scenario development and quantification (including bending-the-curve scenarios), as well as standardized reporting to facilitate the comparison of single-model studies and an increase in multimodel analyses.

Although modeling global biodiversity provides meaningful insights into the opportunity space for reversing biodiversity loss, scenarios are unlikely to be fully implemented in their current form. Because policy needs to be implemented at a local scale and drivers of loss have different impacts at different scales, changes in biodiversity are required to be assessed with more detailed indicators at a local scale [e.g., Gérard *et al.* (*38*)] (*39*, *40*).

It is difficult to link biodiversity outcomes to specific scenario types. Despite the multitude of BDIs identified, we attempted a comparison of scenario outputs. To enable comparison across models and BDIs, we calculated the relative change over time and analyzed the direction of the change compared to the present across indicators (Fig. 5).

Overall, the magnitude of projected losses in nonpolicy scenarios for all BDIs is greater than gains in policy scenarios; see also (*3*, *4*). The high variation in projected future changes for different BDIs classes could be a result of different modeling approaches of studies, the high sensitivity of models that describe pressures on biodiversity, or differences in how BDMs capture the impacts of drivers of loss and biodiversity responses (*4*).

In addition, we see that, for several BDI classes (e.g., species abundance and risk of extinction), trends are clearly differentiated across scenario categories (e.g., baseline versus reduce-loss). For other BDI classes (e.g., species diversity, species distributions, and habitat transformation), the categories overlapped: For instance, for the BDI class habitat transformation or species distributions, there is some overlap between baseline and worst-case scenarios. This is likely due to the scenario categorization implemented, coming from independent sets of scenarios (business as usual versus worst-case) or because we clustered different indicators. The high uncertainty range of all scenarios is associated with a higher number of BDIs compared while comparing fewer BDIs results in a lower uncertainty range. Although we provide a first attempt to compare outputs of different scenarios, there should be more guidance on how to adequately compare BDIs.

Not all drivers of loss are extensively covered

Currently, land use is regarded as the main direct driver of biodiversity loss (*41*–*44*). However, several studies suggest that the impacts of climate change are expected to intensify, surpassing the effects of land use (*45*–*47*).

Despite biodiversity being affected by multiple and interacting pressures, such as climate and land-use changes, pollution, invasive species, and overexploitation (*5*, *15*), most of the studies in this meta-analysis (68%) are based on environmental change projections that represent a single driver only, a limitation already identified in earlier reviews and studies (*16*, *48*). The majority of existing global biodiversity scenarios assess the consequence of land-use change on biodiversity (79% of papers), and fewer papers assess the effect of climate change (37% of papers). Only a minority of papers (25%) accounted for other pressures that climate and land use, such as fragmentation or pollution; biological invasions were never included (Figs. 2 and 4). The disproportionate accounting of different pressures is likely a result of modeling limitations for these pressures and for their impact on biodiversity, due to the inherent complexity of the task at a global scale (*5*). The lack of projections that account for the combined effect of climate, land-use change, and other pressures represents another major research gap in global biodiversity scenarios, despite previous calls for integration (*3*, *16*).

Nearly all bending-the-curve scenarios account for one pressure only, land-use change, and only two bending-the-curve scenarios account for the additive effect of land-use and climate change (*13*, *22*). All other scenarios that account for climate change (alone or with the additive effect of land-use change) produce at best a reduction in loss of biodiversity but do not bend the curve (Fig. 4). Bending the curve is quite challenging if the impact of climate change is accounted for (*4*) as climate is expected to become warmer than today even in optimistic scenarios (*49*, *50*). Therefore, we urgently need scenarios that take multiple pressures into account and avoid risking misrepresenting the real threats to biodiversity and suggesting that it is possible to bend the trend too easily, as identified by previous findings (*13*, *51*–*53*).

However, there are also some modeling limitations. A recent study shows that most BDMs may overestimate climate change impacts because projections are based on statistical models relating climate to coarse species distributions and overlook species-local adaptations, making it very difficult to bend the curve (*4*). In addition, temporal nonlinearities will also need to be accounted when modeling the impact of climate and land-use changes together, factoring connectivity of the landscape under future climate change, to allow species migration (*54*, *55*).

Bending the curve needs an integrated effort

By comparing assumptions of bending-the-curve and reduce-loss scenarios, we found that bending-the-curve scenarios include more policies and from a more integrated set of domains (Fig. 5).

Half of the reduce-loss scenarios also include several policy measures (>5 actions). The fact that this does not result in net biodiversity gains is that the policies are often less ambitious as they are based on a combination of baselines [e.g., SSP1 and Representative Concentration Pathway (RCP) 2.6] (*23*, *56*). Other studies include multiple policies, spanning, however, across fewer action bundles (*3*, *12*). Some others are based on the same assumptions and policy measures as bending-the-curve scenarios but project different BDIs, which are less sensitive (*13*). In addition, bending the curve of different biodiversity aspects requires different restoration actions, spatial allocation, and amount of area to be protected, as already identified by previous studies (*3*). Therefore, the same combinations of policy options can lead to net gains for some BDIs, but not for others. For example, one scenario results in net gains in the BDI MSA but only a reduction in losses in the BDI LPI (*13*). Last, we found that nearly all bending-the-curve scenarios only account for one pressure, land-use change, while half of the reduce-loss scenarios account for multiple drivers of biodiversity loss (Fig. 4) (*27*, *57*), suggesting that representing the real threats to biodiversity will make bending the curve more challenging.

Previous studies show that typical efficient mitigation efforts (e.g., bioenergy) cause damage to biodiversity through their land requirement (*58*–*60*). Therefore, accounting for alternative mitigation measures (e.g., renewables and improved energy efficiency) will be needed to meet biodiversity goals (*61*). Including both impacts of climate change and climate mitigation on biodiversity, as well as additional drivers, will require the creation of more ambitious scenarios based on an integrated portfolio of policy measures.

Recommendations for improving biodiversity scenarios

Our key findings show three major research gaps in biodiversity scenario literature. First, although gaining momentum, there are still few global scenarios in literature that bend the curve of biodiversity loss to guide recent global commitments of the GBF. Second, given the high diversity of BDIs used, future projections of biodiversity are hardly comparable. Standardization of reporting of BDIs is urgently needed to facilitate comparison of studies' outputs. In addition, increased effort in producing scenarios based on inter-model comparisons is needed, which will allow to assess progress toward global KMGBF goals and targets. Third, not all drivers of biodiversity loss are extensively covered in scenarios. Direct drivers of loss are disproportionally accounted for, with land-use change being the main driver studied. Nearly all bending-the-curve studies do not account for climate (with exception of two studies) but only account for land-use change, which risks suggesting that it is possible to bend the trend too easily. Updating models for including multiple pressures will be challenging due to modeling limitations. Last, we discuss how bending-the-curve scenarios differ from reduce-loss scenarios with respect to the policy measures included. Bending-the-curve scenarios are more ambitious and require integrated effort by including policy measures across multiple action bundles. This paper highlights the relevance of model-based scenario analysis, which not only is an important science field but also forms an input into biodiversity policymaking.

MATERIALS AND METHODS

The methodological framework used for this meta-analysis followed a combined approach using the stages outlined for the systematic mapping of existing literature in environmental sciences (*62*) and completing this with information on quantitative data to perform a meta-analysis. We set inclusion criteria, searched and screened the literature, extracted metadata and data, harmonized and compared data, and described and visualized the findings. Below, we briefly describe the search strategy and records screening as well as the (meta)data screening.

Search strategy and record screening

The databases Scopus and Web of Science were used to systematically review the literature. We developed a search strategy with various terms associated with biodiversity crisis, global analysis, scenarios, integrated assessment modeling, future years, and policy to identify relevant articles published for the period January 2007 to July 2023 (for the full search strategy, see table S1). To make sure that the search strategy would be appropriate to identify the relevant literature, we identified eight benchmark studies with the help of expert knowledge of coauthors (see the Supplementary Materials). We refined the search strategy terms until all of the eight benchmark studies would appear as a result of our search. Given the high difference in number of records retrieved using a minimal variation of the search strategy, two database searches were performed using two versions of the same search strategy. The difference between the two search strategies is query #3 and #4, used as separate or merged queries (table S1).

Inclusion criteria were original, English-language, and quantitative modeling papers on a global scale using scenarios to project, reduce, halt, or bend the curve of biodiversity loss. Exclusions were continental- or local-scale analysis, papers set in the past or present with no future projections, review, and comment papers. Articles focusing on single species were also not included because these are not representative of the global biodiversity status.

Record screening was performed with the support of the artificial intelligence (AI) tool ASReview (*63*, *64*). This AI tool ranks records from most relevant to least relevant based on previous knowledge (five relevant articles and five irrelevant articles) provided by the user. We ranked papers using ASReview for both sets of records. For the first set, title and abstract of all records were manually screened on the basis of the eligibility criteria. For the second set, we manually screened the first 10% of the ranked articles (title and abstract) on the basis of the same eligibility criteria. Overall, 1640 records were identified from the first database search, and 3626 records from the second. Of the first set of 1640 records, 424 duplicates were removed with automation tools. The resulting 1216 articles were ranked from best to worse with the support of ASReview. Subsequently, title and abstract of all records were manually screened on the basis of the eligibility criteria. As a result, 56 papers were included. Of these 56 papers, 52 were found in the first 10% of the ranked records.

Of the second set of 3662 records identified from the second database search, 439 duplicates were removed with automation tools. The resulting 3223 documents were ranked from best to worst with the support of ASReview. The first 10% (documents $n = 323$) of the ranked articles were manually screened (title and abstract) on the basis of the same eligibility criteria used for the first database search. As a result, 49 documents were included. These were compared with the selected documents from the first database search. Overall, eight additional articles were found and added to the already included 56 papers. Five papers were manually added on the basis of expert knowledge of coauthors, resulting in a total of 69 papers. Last, 12 papers were excluded after performing a full-text screening, resulting in a total of 57 included papers (flowchart of record retrieval and selection is available in fig. S1).

Metadata extraction, data harmonization, and meta-analysis

Metadata from selected references were extracted via a predesigned extraction form containing the following information: title, authors, journal, publication date, realm (land or water), BDIs and their projections, BDMs and other models describing pressures on biodiversity, drivers of loss, projected period, and scenario type. We identified a total of 42 BDIs of the 57 papers. Of the 42 BDIs, 2 could not be classified on the basis of our classification scheme, and 5 described the aquatic realm, which we did not consider for further analysis because of insufficient quantitative data (quantitative projections of BDIs only available for three papers) (information on the aquatic BDIs can be found in the Supplementary Materials). Therefore, we analyzed a total of 35 terrestrial BDIs.

Quantitative data on BDIs were extracted in 35 of the 57 selected papers. Quantitative data for the remaining 19 papers could not be retrieved because studies did not always provide complete data for all the BDIs modeled (such as the beginning or end of the projected year or absolute BDI values in the base year). A meta-analysis was conducted to categorize scenarios and compare trends of biodiversity change over time across scenarios. Given the large differences in which indicators are calculated, a direct comparison of absolute values of BDIs was meaningless. Hence, BDI values were harmonized as follows. First, the projected values of BDIs were interpolated to 2030, 2050, and 2100. Then, the values were converted to a proportional change for the years 2030, 2050, and 2100 relative to a common base year of the analysis (which we chose to be 2015). Further explanation of the harmonization process is available in the Supplementary Materials. Projections of BDIs were plotted by scenario category.

The scenarios were categorized on the basis of their storyline in nonpolicy (baseline and worst-case) and policy scenarios. We defined baseline as a business-as-usual, middle-of-the-road scenario that assumes the continuation of historical trends into the future and projects the effect of current policies on biodiversity (*8*). Worst-case was defined as a scenario that deliberately describes a more pessimistic future than the baseline, with high values of drivers of biodiversity loss. Policy scenarios were identified on the basis of the explicit indication of including biodiversity conservation policy and classified on the basis of the projected BDI trends as compared to both the baseline scenarios and the starting date. Reduce-loss scenarios lead to a reduction in rate of biodiversity loss compared to the relative baseline however not reaching higher level than that of the start of the projected period. Net-zero-loss scenarios led to BDI levels comparable to the start of the projected period. Bending-the-curve scenarios involve policy actions that are projected to reverse biodiversity declines compared to the start of the projected period. Because several publications projected different BDIs, for each publication, one BDI was chosen to base the scenario classification. Generally, in such case, BDIs were chosen on the basis of best performance to avoid an underestimation of scenarios. However, when possible, BDIs that were used across multiple publications were chosen to increase comparability across studies (for additional information, see the Supplementary Materials).

Last, to gain insight into the different assumptions underpinning bending-the-curve and reduce-loss scenarios, we compiled data on the policy measures incorporated into these scenarios. The extracted data used for harmonization and meta-analysis is available at https://zenodo.org/records/14910768.

Supplementary Materials

This PDF file includes:
Supplementary Text
Fig. S1
Tables S1 to S5
References

REFERENCES

1. CBD, "Kunming-Montreal Global Biodiversity Framework" (2022); www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf.
2. CBD, "Global Biodiversity Outlook 5" (2020); www.unep.org/resources/report/global-biodiversity-outlook-5-gbo-5.
3. D. Leclere, M. Obersteiner, M. Barrett, S. Butchart, A. Chaudhary, A. De Palma, F. DeClerck, M. Di Marco, J. Doelman, M. Durauer, R. Freeman, M. Harfoot, T. Hasegawa, S. Hellweg, J. Hilbers, S. Hill, F. Humpenoder, N. Jennings, T. Krisztin, G. Mace, H. Ohashi, A. Popp, A. Purvis, A. Schipper, A. Tabeau, H. Valin, H. van Meijl, W. Van Zeist, P. Visconti, R. Alkemade, R. Almond, G. Bunting, N. Burgess, S. Cornell, F. Di Fulvio, S. Ferrier, S. Fritz, S. Fujimori, M. Grooten, T. Harwood, P. Havlik, M. Herrero, A. Hoskins, M. Jung, T. Kram, H. Lotze-Campen, T. Matsui, C. Meyer, D. Nel, T. Newbold, G. Schmidt-Traub, E. Stehfest, B. Strassburg, D. van Vuuren, C. Ware, J. Watson, W. Wu, L. Young, Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* **585**, 551–556 (2020).
4. H. M. Pereira, I. S. Martins, I. M. D. Rosa, H. Kim, P. Leadley, A. Popp, D. P. Van Vuuren, G. Hurtt, L. Quoss, A. Arneth, D. Baisero, M. Bakkenes, R. Chaplin-Kramer, L. Chini, M. Di Marco, S. Ferrier, S. Fujimori, C. A. Guerra, M. Harfoot, T. D. Harwood, T. Hasegawa, V. Haverd, P. Havlík, S. Hellweg, J. P. Hilbers, S. L. L. Hill, A. Hirata, A. J. Hoskins, F. Humpenöder, J. H. Janse, W. Jetz, J. A. Johnson, A. Krause, D. Leclère, T. Matsui, J. R. Meijer, C. Merow, M. Obersteiner, H. Ohashi, A. De Palma, B. Poulter, A. Purvis, B. Quesada, C. Rondinini, A. M. Schipper, J. Settele, R. Sharp, E. Stehfest, B. B. N. Strassburg, K. Takahashi, M. V. Talluto, W. Thuiller, N. Titeux, P. Visconti, C. Ware, F. Wolf, R. Alkemade, Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050. *Science* **384**, 458–465 (2024).
5. IPBES, The methodological assessment report on scenarios and models of biodiversity and ecosystem services, version v1, Zenodo (2016); https://doi.org/10.5281/zenodo.3235429.
6. I. M. D. Rosa, H. M. Pereira, S. Ferrier, R. Alkemade, L. A. Acosta, H. R. Akcakaya, E. den Belder, A. M. Fazel, S. Fujimori, M. Harfoot, K. A. Harhash, P. A. Harrison, J. Hauck, R. J. J. Hendriks, G. Hernández, W. Jetz, S. I. Karlsson-Vinkhuyzen, H. Kim, N. King, M. T. J. Kok, G. O. Kolomytsev, T. Lazarova, P. Leadley, C. J. Lundquist, J. García Márquez, C. Meyer, L. M. Navarro, C. Nesshöver, H. T. Ngo, K. N. Ninan, M. G. Palomo, L. M. Pereira, G. D. Peterson, R. Pichs, A. Popp, A. Purvis, F. Ravera, C. Rondinini, J. Sathyapalan, A. M. Schipper, R. Seppelt, J. Settele, N. Sitas, D. van Vuuren, Multiscale scenarios for nature futures. *Nat. Ecol. Evol.* **1**, 1416–1419 (2017).
7. I. M. D. Rosa, A. Purvis, R. Alkemade, R. Chaplin-Kramer, S. Ferrier, C. A. Guerra, G. Hurtt, H. Kim, P. Leadley, I. S. Martins, A. Popp, A. M. Schipper, D. Van Vuuren, H. M. Pereira, Challenges in producing policy-relevant global scenarios of biodiversity and ecosystem services. *Glob. Ecol. Conserv.* **22**, e00886 (2020).
8. D. P. Van Vuuren, M. T. J. Kok, B. Girod, P. L. Lucas, B. De Vries, Scenarios in global environmental assessments: Key characteristics and lessons for future use. *Glob. Environ. Chang.* **22**, 884–895 (2012).
9. E. Nicholson, E. A. Fulton, T. M. Brooks, R. Blanchard, P. Leadley, J. P. Metzger, K. Mokany, S. Stevenson, B. A. Wintle, S. N. C. Woolley, M. Barnes, J. E. M. Watson, S. Ferrier, Scenarios and models to support global conservation targets. *Trends Ecol. Evol.* **34**, 57–68 (2019).

10. IPBES, "Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services" (IPBES secretariat, 2019).
11. L. M. Pereira, K. K. Davies, E. den Belder, S. Ferrier, S. Karlsson-Vinkhuyzen, H. Kim, J. J. Kuiper, S. Okayasu, M. G. Palomo, H. M. Pereira, G. Peterson, J. Sathyapalan, M. Schoolenberg, R. Alkemade, S. Carvalho Ribeiro, A. Greenaway, J. Hauck, N. King, T. Lazarova, F. Ravera, N. Chettri, W. W. L. Cheung, R. J. J. Hendriks, G. Kolomytsev, P. Leadley, J.-P. Metzger, K. N. Ninan, R. Pichs, A. Popp, C. Rondinini, I. Rosa, D. van Vuuren, C. J. Lundquist, Developing multiscale and integrative nature–people scenarios using the Nature Futures Framework. *People Nat.* **2**, 1172–1195 (2020).
12. M. T. J. Kok, R. Alkemade, M. Bakkenes, M. van Eerdt, J. Janse, M. Mandryk, T. Kram, T. Lazarova, J. Meijer, M. van Oorschot, H. Westhoek, R. van der Zagt, M. van der Berg, S. van der Esch, A.-G. Prins, D. P. van Vuuren, Pathways for agriculture and forestry to contribute to terrestrial biodiversity conservation: A global scenario-study. *Biol. Conserv.* **221**, 137–150 (2018).
13. M. T. J. Kok, J. R. Meijer, W.-J. van Zeist, J. P. Hilbers, M. Immovilli, J. H. Janse, E. Stehfest, M. Bakkenes, A. Tabeau, A. M. Schipper, R. Alkemade, Assessing ambitious nature conservation strategies in a below 2-degree and food-secure world. *Biol. Conserv.* **284**, 110068 (2023).
14. H. M. Pereira, S. Ferrier, M. Walters, G. N. Geller, R. H. G. Jongman, R. J. Scholes, M. W. Bruford, N. Brummitt, S. H. M. Butchart, A. C. Cardoso, N. C. Coops, E. Dulloo, D. P. Faith, J. Freyhof, R. D. Gregory, C. Heip, R. Höft, G. Hurtt, W. Jetz, D. S. Karp, M. A. McGeoch, D. Obura, Y. Onoda, N. Pettorelli, B. Reyers, R. Sayre, J. P. W. Scharlemann, S. N. Stuart, E. Turak, M. Walpole, M. Wegmann, Essential biodiversity variables. *Science* **339**, 277–278 (2013).
15. P. Jaureguiberry, N. Titeux, M. Wiemers, D. E. Bowler, L. Coscieme, A. S. Golden, C. A. Guerra, U. Jacob, Y. Takahashi, J. Settele, S. Díaz, Z. Molnár, A. Purvis, The direct drivers of recent global anthropogenic biodiversity loss. *Sci. Adv.* **8**, eabm9982 (2022).
16. N. Titeux, K. Henle, J. Mihoub, A. Regos, I. Geijzendorffer, W. Cramer, P. Verburg, L. Brotons, Biodiversity scenarios neglect future land-use changes. *Glob. Chang. Biol.* **22**, 2505–2515 (2016).
17. P. Leadley, "Biodiversity scenarios: Projections of 21st century change in biodiversity, and associated ecosystem services: A technical report for the Global Biodiversity Outlook 3" (Secretariat of the Convention on Biological Diversity, 2010).
18. H. M. Pereira, P. W. Leadley, V. Proença, R. Alkemade, J. P. W. Scharlemann, J. F. Fernandez-Manjarrés, M. B. Araújo, P. Balvanera, R. Biggs, W. W. L. Cheung, L. Chini, H. D. Cooper, E. L. Gilman, S. Guénette, G. C. Hurtt, H. P. Huntington, G. M. Mace, T. Oberdorff, C. Revenga, P. Rodrigues, R. J. Scholes, U. R. Sumaila, M. Walpole, Scenarios for global biodiversity in the 21st century. *Science* **330**, 1496–1501 (2010).
19. W. Jetz, M. A. McGeoch, R. Guralnick, S. Ferrier, J. Beck, M. J. Costello, M. Fernandez, G. N. Geller, P. Keil, C. Merow, C. Meyer, F. E. Muller-Karger, H. M. Pereira, E. C. Regan, D. S. Schmeller, E. Turak, Essential biodiversity variables for mapping and monitoring species populations. *Nat. Ecol. Evol.* **3**, 539–551 (2019).
20. G. M. Mace, M. Barrett, N. D. Burgess, S. E. Cornell, R. Freeman, M. Grooten, A. Purvis, Aiming higher to bend the curve of biodiversity loss. *Nat. Sustain.* **1**, 448–451 (2018).
21. E. J. Milner-Gulland, P. Addison, W. N. S. Arlidge, J. Baker, H. Booth, T. Brooks, J. W. Bull, M. J. Burgass, J. Ekstrom, S. O. S. E. Zu Ermgassen, L. V. Fleming, H. M. J. Grub, A. Von Hase, M. Hoffmann, J. Hutton, D. Juffe-Bignoli, K. Ten Kate, J. Kiesecker, N. F. Kümpel, M. Maron, H. S. Newing, K. Ole-Moiyoi, C. Sinclair, S. Sinclair, M. Starkey, S. N. Stuart, C. Tayleur, J. E. M. Watson, Four steps for the Earth: Mainstreaming the post-2020 global biodiversity framework. *One Earth* **4**, 75–87 (2021).
22. P. Visconti, M. Bakkenes, R. J. Smith, L. Joppa, R. E. Sykes, Socio-economic and ecological impacts of global protected area expansion plans. *Philos. Trans. R. Soc. B. Biol. Sci.* **370**, 20140284 (2015).
23. A. Chaudhary, V. Pourfaraj, A. Mooers, Projecting global land use-driven evolutionary history loss. *Divers. Distrib.* **24**, 158–167 (2018).
24. L. Rasche, J. C. Habel, N. Stork, E. Schmid, U. A. Schneider, Food versus wildlife: Will biodiversity hotspots benefit from healthier diets? *Glob. Ecol. Biogeogr.* **31**, 1090–1103 (2022).
25. P. Leadley, A. Gonzalez, D. Obura, C. B. Krug, M. C. Londoño-Murcia, K. L. Millette, A. Radulovici, A. Rankovic, L. J. Shannon, E. Archer, F. A. Armah, N. Bax, K. Chaudhari, M. J. Costello, L. M. Dávalos, F. de Oliveira Roque, F. De Clerck, L. E. Dee, F. Essl, S. Ferrier, P. Genovesi, M. R. Guariguata, S. Hashimoto, C. I. Speranza, F. Isbell, M. Kok, S. D. Lavery, D. Leclère, R. Loyola, S. Lwasa, M. M. Geoch, A. S. Mori, E. Nicholson, J. M. Ochoa, K. Öllerer, S. Polasky, C. Rondinini, S. Schroer, O. Selomane, X. Shen, B. Strassburg, U. R. Sumaila, D. P. Tittensor, E. Turak, L. Urbina, M. Vallejos, E. Vázquez-Domínguez, P. H. Verburg, P. Visconti, S. Woodley, J. Xu, Achieving global biodiversity goals by 2050 requires urgent and integrated actions. *One Earth* **5**, 597–603 (2022).
26. P. Visconti, M. Bakkenes, D. Baisero, T. Brooks, S. Butchart, L. Joppa, R. Alkemade, M. Di Marco, L. Santini, M. Hoffmann, L. Maiorano, R. Pressey, A. Arponen, L. Boitani, A. Reside, D. van Vuuren, C. Rondinini, Projecting global biodiversity indicators under future development scenarios. *Conserv. Lett.* **9**, 5–13 (2016).
27. M. Di Marco, T. D. Harwood, A. J. Hoskins, C. Ware, S. L. L. Hill, S. Ferrier, Projecting impacts of global climate and land-use scenarios on plant biodiversity using compositional-turnover modelling. *Glob. Chang. Biol.* **25**, 2763–2778 (2019).
28. S. G. Marquardt, J. C. Doelman, V. Daioglou, A. Tabeau, A. M. Schipper, S. Sim, M. Kulak, Z. J. N. Steinmann, E. Stehfest, H. C. Wilting, M. A. J. Huijbregts, Identifying regional drivers of future land-based biodiversity footprints. *Glob. Environ. Chang.* **69**, 102304 (2021).
29. D. R. Williams, M. Clark, G. M. Buchanan, G. F. Ficetola, C. Rondinini, D. Tilman, Proactive conservation to prevent habitat losses to agricultural expansion. *Nat. Sustain.* **4**, 314–322 (2021).
30. L. M. Navarro, N. Fernández, C. Guerra, R. Guralnick, W. D. Kissling, M. C. Londoño, F. Muller-Karger, E. Turak, P. Balvanera, M. J. Costello, A. Delavaud, G. El Serafy, S. Ferrier, I. Geijzendorffer, G. N. Geller, W. Jetz, E.-S. Kim, H. Kim, C. S. Martin, M. A. McGeoch, T. H. Mwampamba, J. L. Nel, E. Nicholson, N. Pettorelli, M. E. Schaepman, A. Skidmore, I. Sousa Pinto, S. Vergara, P. Vihervaara, H. Xu, T. Yahara, M. Gill, H. M. Pereira, Monitoring biodiversity change through effective global coordination. *Curr. Opin. Environ. Sustain.* **29**, 158–169 (2017).
31. S. H. M. Butchart, M. Walpole, B. Collen, A. Van Strien, J. P. W. Scharlemann, R. E. A. Almond, J. E. M. Baillie, B. Bomhard, C. Brown, J. Bruno, K. E. Carpenter, G. M. Carr, J. Chanson, A. M. Chenery, J. Csirke, N. C. Davidson, F. Dentener, M. Foster, A. Galli, J. N. Galloway, P. Genovesi, R. D. Gregory, M. Hockings, V. Kapos, J.-F. Lamarque, F. Leverington, J. Loh, M. A. McGeoch, L. McRae, A. Minasyan, M. H. Morcillo, T. E. E. Oldfield, D. Pauly, S. Quader, C. Revenga, J. R. Sauer, B. Skolnik, D. Spear, D. Stanwell-Smith, S. N. Stuart, A. Symes, M. Tierney, T. D. Tyrrell, J.-C. Vié, R. Watson, Global biodiversity: Indicators of recent declines. *Science* **328**, 1164–1168 (2010).
32. S. Bojinski, M. Verstraete, T. C. Peterson, C. Richter, A. Simmons, M. Zemp, The concept of essential climate variables in support of climate research, applications, and policy. *Bull. Am. Meteorol. Soc.* **95**, 1431–1443 (2014).
33. F. Affinito, J. M. Williams, J. E. Campbell, M. C. Londono, A. Gonzalez, Progress in developing and operationalizing the monitoring framework of the global biodiversity framework. *Nat. Ecol. Evol.* **8**, 2163–2171 (2024).
34. S. H. M. Butchart, M. Di Marco, J. E. M. Watson, Formulating smart commitments on biodiversity: Lessons from the aichi targets. *Conserv. Lett.* **9**, 457–468 (2016).
35. D. Obura, The Kunming-Montreal global biodiversity framework: Business as usual or a turning point? *One Earth* **6**, 77–80 (2023).
36. K. Frieler, S. Lange, F. Piontek, C. P. O. Reyer, J. Schewe, L. Warszawski, F. Zhao, L. Chini, S. Denvil, K. Emanuel, T. Geiger, K. Halladay, G. Hurtt, M. Mengel, D. Murakami, S. Ostberg, A. Popp, R. Riva, M. Stevanovic, T. Suzuki, J. Volkholz, E. Burke, P. Ciais, K. Ebi, T. D. Eddy, J. Elliott, E. Galbraith, S. N. Gosling, F. Hattermann, T. Hickler, J. Hinkel, C. Hof, V. Huber, J. Jägermeyr, V. Krysanova, R. Marcé, H. Müller Schmied, I. Mouratiadou, D. Pierson, D. P. Tittensor, R. Vautard, M. Van Vliet, M. F. Biber, R. A. Betts, B. L. Bodirsky, D. Deryng, S. Frolking, C. D. Jones, H. K. Lotze, H. Lotze-Campen, R. Sahajpal, K. Thonicke, H. Tian, Y. Yamagata, Assessing the impacts of 1.5°C global warming – Simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). *Geosci. Model Dev.* **10**, 4321–4345 (2017).
37. H. Kim, I. M. D. Rosa, R. Alkemade, P. Leadley, G. Hurtt, A. Popp, D. P. Van Vuuren, P. Anthoni, A. Arneth, D. Baisero, E. Caton, R. Chaplin-Kramer, L. Chini, A. De Palma, F. Di Fulvio, M. Di Marco, F. Espinoza, S. Ferrier, S. Fujimori, R. E. Gonzalez, M. Gueguen, C. Guerra, M. Harfoot, T. D. Harwood, T. Hasegawa, V. Haverd, P. Havlík, S. Hellweg, S. L. L. Hill, A. Hirata, A. J. Hoskins, J. H. Janse, W. Jetz, J. A. Johnson, A. Krause, D. Leclère, I. S. Martins, T. Matsui, C. Merow, M. Obersteiner, H. Ohashi, B. Poulter, A. Purvis, B. Quesada, C. Rondinini, A. M. Schipper, R. Sharp, K. Takahashi, W. Thuiller, N. Titeux, P. Visconti, C. Ware, F. Wolf, H. M. Pereira, A protocol for an intercomparison of biodiversity and ecosystem services models using harmonized land-use and climate scenarios. *Geosci. Model Dev.* **11**, 4537–4562 (2018).
38. T. M. R. Gérard, S. J. Norder, J. A. Verstegen, J. C. Doelman, S. C. Dekker, F. Van Der Hilst, Trade-offs and synergies between climate change mitigation, biodiversity preservation, and agro-economic development across future land-use scenarios in Brazil. *Glob. Chang. Biol.* **31**, e70418 (2025).
39. A. Purvis, Bending the curve of biodiversity loss requires a 'satnav' for nature. *Philos. Trans. R. Soc. B* **380**, 20230210 (2025).
40. C. P. Nadeau, M. C. Urban, J. R. Bridle, Climates past, present, and yet-to-come shape climate change vulnerabilities. *Trends Ecol. Evol.* **32**, 786–800 (2017).
41. C. W. Davison, C. Rahbek, N. Morueta-Holme, Land-use change and biodiversity: Challenges for assembling evidence on the greatest threat to nature. *Glob. Chang. Biol.* **27**, 5414–5429 (2021).
42. S. L. Maxwell, R. A. Fuller, T. M. Brooks, J. E. M. Watson, Biodiversity: The ravages of guns, nets and bulldozers. *Nature* **536**, 143–145 (2016).
43. T. Newbold, L. N. Hudson, S. L. L. Hill, S. Contu, I. Lysenko, R. A. Senior, L. Börger, D. J. Bennett, A. Choimes, B. Collen, J. Day, A. De Palma, S. Díaz, S. Echeverria-Londoño, M. J. Edgar, A. Feldman, M. Garon, M. L. K. Harrison, T. Alhusseini, D. J. Ingram, Y. Itescu, J. Kattge, V. Kemp, L. Kirkpatrick, M. Kleyer, D. L. P. Correia, C. D. Martin, S. Meiri,

M. Novosolov, Y. Pan, H. R. P. Phillips, D. W. Purves, A. Robinson, J. Simpson, S. L. Tuck, E. Weiher, H. J. White, R. M. Ewers, G. M. MacE, J. P. W. Scharlemann, A. Purvis, Global effects of land use on local terrestrial biodiversity. *Nature* **520**, 45–50 (2015).
44. T. Newbold, L. N. Hudson, S. L. L. Hill, S. Contu, C. L. Gray, J. P. W. Scharlemann, L. Börger, H. R. P. Phillips, D. Sheil, I. Lysenko, A. Purvis, Global patterns of terrestrial assemblage turnover within and among land uses. *Ecography* **39**, 1151–1163 (2016).
45. T. Newbold, "Future effects of climate and land-use change on terrestrial vertebrate community diversity under different scenarios" (Royal Society Publishing, 2018), vol. 285; www.scopus.com/inward/record.uri?eid=2-s2.0-85048766844&doi=10.1098%2frspb.2018.0792&partnerID=40&md5=f087be4a1b35f44b1d4cb4ce41612500.
46. M. Pacifici, P. Visconti, S. H. M. Butchart, J. E. M. Watson, F. M. Cassola, C. Rondinini, Species' traits influenced their response to recent climate change. *Nat. Clim. Change* **7**, 205–208 (2017).
47. J. J. Wiens, J. Zelinka, How many species will Earth lose to climate change? *Glob. Chang. Biol.* **30**, e17125 (2024).
48. C. Bellard, C. Leclerc, F. Courchamp, Combined impacts of global changes on biodiversity across the USA. *Sci. Rep.* **5**, 11828 (2015).
49. IPCC, *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, ed. 1, 2021); www.cambridge.org/core/product/identifier/9781009157896/type/book.
50. UNEP, "Emissions Gap Report 2024: No more hot air … please! With a massive gap between rhetoric and reality, countries draft new climate commitments" (2024); www.undp.org/sites/g/files/zskgke326/files/2025-01/egr2024.pdf.
51. A. Arneth, Y. Shin, P. Leadley, C. Rondinini, E. Bukvareva, M. Kolb, G. Midgley, T. Oberdorff, I. Palomo, O. Saito, Post-2020 biodiversity targets need to embrace climate change. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 30882–30891 (2020).
52. H. Ohashi, T. Hasegawa, A. Hirata, S. Fujimori, K. Takahashi, I. Tsuyama, K. Nakao, Y. Kominami, N. Tanaka, Y. Hijioka, T. Matsui, Biodiversity can benefit from climate stabilization despite adverse side effects of land-based mitigation. *Nat. Commun.* **10**, 5240 (2019).
53. B. Soergel, E. Kriegler, I. Weindl, S. Rauner, A. Dirnaichner, C. Ruhe, M. Hofmann, N. Bauer, C. Bertram, B. L. Bodirsky, M. Leimbach, J. Leininger, A. Levesque, G. Luderer, M. Pehl, C. Wingens, L. Baumstark, F. Beier, J. P. Dietrich, F. Humpenöder, P. Von Jeetze, D. Klein, J. Koch, R. Pietzcker, J. Strefler, H. Lotze-Campen, A. Popp, A sustainable development pathway for climate action within the UN 2030 Agenda. *Nat. Clim. Chang.* **11**, 656–664 (2021).
54. R. Cornford, F. Spooner, L. McRae, A. Purvis, R. Freeman, Ongoing over-exploitation and delayed responses to environmental change highlight the urgency for action to promote vertebrate recoveries by 2030. *Proc. R. Soc. B. Biol. Sci.* **290**, 20230464 (2023).
55. C. D. Thomas, A. Cameron, R. E. Green, M. Bakkenes, L. J. Beaumont, Y. C. Collingham, B. F. N. Erasmus, M. F. de Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A. S. van Jaarsveld, G. F. Midgley, L. Miles, M. A. Ortega-Huerta, A. T. Peterson, O. L. Phillips, S. E. Williams, Extinction risk from climate change. *Nature* **427**, 145–148 (2004).
56. D. Baisero, P. Visconti, M. Pacifici, M. Cimatti, C. Rondinini, Projected global loss of mammal habitat due to land-use and climate change. *One Earth* **2**, 578–585 (2020).
57. A. M. Schipper, J. P. Hilbers, J. R. Meijer, L. H. Antão, A. Benítez-López, M. M. J. de Jonge, L. H. Leemans, E. Scheper, R. Alkemade, J. C. Doelman, S. Mylius, E. Stehfest, D. P. van Vuuren, W.-J. van Zeist, M. A. J. Huijbregts, Projecting terrestrial biodiversity intactness with GLOBIO 4. *Glob. Chang. Biol.* **26**, 760–771 (2019).
58. S. V. Hanssen, Z. J. N. Steinmann, V. Daioglou, M. Čengić, D. P. Van Vuuren, M. A. J. Huijbregts, Global implications of crop-based bioenergy with carbon capture and storage for terrestrial vertebrate biodiversity. *GCB Bioenergy* **14**, 307–321 (2021).
59. V. Heck, H. Hoff, S. Wirsenius, C. Meyer, H. Kreft, Land use options for staying within the Planetary Boundaries–Synergies and trade-offs between global and local sustainability goals. *Glob. Environ. Chang.* **49**, 73–84 (2018).
60. S. Roe, C. Streck, R. Beach, J. Busch, M. Chapman, V. Daioglou, A. Deppermann, J. Doelman, J. Emmet-Booth, J. Engelmann, O. Fricko, C. Frischmann, J. Funk, G. Grassi, B. Griscom, P. Havlik, S. Hanssen, F. Humpenöder, D. Landholm, G. Lomax, J. Lehmann, L. Mesnildrey, G.-J. Nabuurs, A. Popp, C. Rivard, J. Sanderman, B. Sohngen, P. Smith, E. Stehfest, D. Woolf, D. Lawrence, Land-based measures to mitigate climate change: Potential and feasibility by country. *Glob. Chang. Biol.* **27**, 6025–6058 (2021).
61. D. P. Van Vuuren, E. Stehfest, D. E. H. J. Gernaat, M. Van Den Berg, D. L. Bijl, H. S. De Boer, V. Daioglou, J. C. Doelman, O. Y. Edelenbosch, M. Harmsen, A. F. Hof, M. A. E. Van Sluisveld, Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nat. Clim. Change* **8**, 391–397 (2018).
62. K. L. James, N. P. Randall, N. R. Haddaway, A methodology for systematic mapping in environmental sciences. *Environ. Evid.* **5**, 7 (2016).
63. ASReview LAB, ASReview LAB software documentation, version v1.3, Zenodo (2023); https://doi.org/10.5281/zenodo.10066693.
64. R. van de Schoot, J. de Bruin, R. Schram, P. Zahedi, J. de Boer, F. Weijdema, B. Kramer, M. Huijts, M. Hoogerwerf, G. Ferdinands, A. Harkema, J. Willemsen, Y. Ma, Q. Fang, S. Hindriks, L. Tummers, D. L. Oberski, An open source machine learning framework for efficient and transparent systematic reviews. *Nat. Mach. Intell.* **3**, 125–133 (2021).
65. R. C. Henry, A. Arneth, M. Jung, S. S. Rabin, M. D. Rounsevell, F. Warren, P. Alexander, Global and regional health and food security under strict conservation scenarios. *Nat. Sustain.* **5**, 303–310 (2022).
66. C. Fastré, W.-J. Van Zeist, J. E. M. Watson, P. Visconti, Integrated spatial planning for biodiversity conservation and food production. *One Earth* **4**, 1635–1644 (2021).
67. J. R. Allan, H. P. Possingham, S. C. Atkinson, A. Waldron, M. Di Marco, S. H. M. Butchart, V. M. Adams, W. D. Kissling, T. Worsdell, C. Sandbrook, G. Gibbon, K. Kumar, P. Mehta, M. Maron, B. A. Williams, K. R. Jones, B. A. Wintle, A. E. Reside, J. E. M. Watson, The minimum land area requiring conservation attention to safeguard biodiversity. *Science* **376**, 1094–1101 (2022).

Acknowledgments
Funding: F.A., D.P.v.V., and S.C.D. acknowledge funding from WWF-NL. D.P.v.V. and G.A. also acknowledge funding from the European Research Council under grant ERC-CoG PICASSO (no. 819566). D.L. acknowledges funding from the Horizon Europe research and innovation programme under grant agreement no. 101081744 (RAINFOREST project). **Author contributions:** F.A.: conceptualization; writing—original draft, data curation and formal analysis, and writing—review and editing. D.P.v.V. and S.C.D.: conceptualization, writing—original draft, and writing—review and editing. D.L, A.M., and C.N.: writing—original draft and writing—review and editing. G.A.: methodology for literature screening. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data and code needed to evaluate and reproduce the results in the paper are present in the paper and/or the Supplementary Materials. The extracted metadata and data used for harmonization and meta-analysis is available at https://zenodo.org/records/14910768.

Submitted 6 August 2025
Accepted 5 January 2026
Published 6 February 2026
10.1126/sciadv.aeb2277

Can we bend the curve: Trends in global biodiversity scenarios

Flavia Aschi, Stefan C. Dekker, David Leclère, Alexandra Marques, Christian Neumann, Geanderson Ambrosio, and Detlef P. van Vuuren

Sci. Adv. **12** (6), eaeb2277. DOI: 10.1126/sciadv.aeb2277

Science Advances (ISSN 2375-2548) is published by the American Association for the Advancement of Science. 1200 New York Avenue NW, Washington, DC 20005. The title *Science Advances* is a registered trademark of AAAS.