Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050

Science (New York, N.Y.)

Pereira, Henrique M.; Martins, Inês S.; Rosa, Isabel M.D.; Kim, Hye Jin; Leadley, Paul et al

https://doi.org/10.1126/science.adn3441

BIODIVERSITY LOSS

Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050

Henrique M. Pereira[1,2,3]*, Inês S. Martins[1,2,4], Isabel M. D. Rosa[1,2,5], HyeJin Kim[1,2,6], Paul Leadley[7], Alexander Popp[8,9], Detlef P. van Vuuren[10,11], George Hurtt[12], Luise Quoss[1,2], Almut Arneth[13], Daniele Baisero[14,15], Michel Bakkenes[10], Rebecca Chaplin-Kramer[16,17], Louise Chini[12], Moreno Di Marco[14], Simon Ferrier[18], Shinichiro Fujimori[19,20], Carlos A. Guerra[1,21], Michael Harfoot[22], Thomas D. Harwood[18,23], Tomoko Hasegawa[20,24], Vanessa Haverd[18]†, Petr Havlík[25], Stefanie Hellweg[26], Jelle P. Hilbers[10,27], Samantha L. L. Hill[22,28], Akiko Hirata[29,30], Andrew J. Hoskins[18,31], Florian Humpenöder[8], Jan H. Janse[10,32], Walter Jetz[33,34], Justin A. Johnson[35], Andreas Krause[13,36], David Leclère[25], Tetsuya Matsui[29,30], Johan R. Meijer[10], Cory Merow[37], Michael Obersteiner[25,23], Haruka Ohashi[29], Adriana De Palma[28], Benjamin Poulter[38], Andy Purvis[28,39], Benjamin Quesada[13,40], Carlo Rondinini[14], Aafke M. Schipper[10,27], Josef Settele[1,41,42], Richard Sharp[16], Elke Stehfest[10], Bernardo B. N. Strassburg[43,44], Kiyoshi Takahashi[20], Matthew V. Talluto[46], Wilfried Thuiller[47], Nicolas Titeux[1,41,48], Piero Visconti[25,48,50], Christopher Ware[18], Florian Wolf[1,2], Rob Alkemade[10,51]

Based on an extensive model intercomparison, we assessed trends in biodiversity and ecosystem services from historical reconstructions and future scenarios of land-use and climate change. During the 20th century, biodiversity declined globally by 2 to 11%, as estimated by a range of indicators. Provisioning ecosystem services increased several fold, and regulating services decreased moderately. Going forward, policies toward sustainability have the potential to slow biodiversity loss resulting from land-use change and the demand for provisioning services while reducing or reversing declines in regulating services. However, negative impacts on biodiversity due to climate change appear poised to increase, particularly in the higher-emissions scenarios. Our assessment identifies remaining modeling uncertainties but also robustly shows that renewed policy efforts are needed to meet the goals of the Convention on Biological Diversity.

During the past century, humans have caused biodiversity loss at rates that are 30 to 120 times higher than the mean extinction rates in the Cenozoic fossil record (*1*). Although multiple proximate causes drive this loss, ultimately, a growing human population and economy have demanded increasing land and natural resources, causing habitat conversion and loss (*2*). Increased production of crops and livestock happened alongside widespread degradation of ecosystems' capacity to provide regulating services such as pollination and water quality (*3*). The biodiversity crisis is increasingly at the center of international policy-making under multilateral agreements such as the Convention on Biological Diversity. Restoring biodiversity and ecosystem services can actually provide important solutions to many of the UN Sustainable Development Goals (*4*). Therefore, it is key to assess implications of future socioeconomic developments for biodiversity and ecosystem services

Scenario studies examine alternative future socioeconomic development pathways and their impacts on direct drivers of biodiversity loss such as land-use and climate, often using integrated assessment models (*5*). Consequences of these scenarios for biodiversity and ecosystem services can be assessed using biodiversity and ecosystem function and services models (*6*, *7*). Several studies have explored the future trends of biodiversity and ecosystem services, finding that extinction rates range from 100 to 10 000 times higher than the fossil record, and the continuation of trends of increasing provisioning services with the degradation of some regulation services, although with differences across studies and scenarios (*6*, *8*, *9*). Although these studies are enlightening about the potential trajectories of biodiversity under global changes, they are hardly comparable across models. Existing scenario studies often use a single model for a single facet of biodiversity (*10*, *11*) or, when comparing multiple models, different projections for future land-use and climate (*6*), or they lack comparisons of biodiversity and ecosystem services impacts (*12*). Therefore, the source of uncertainties in these studies is difficult to ascertain (*13*), and an integrated analysis of biodiversity and ecosystem services scenarios has remained elusive.

Assessing biodiversity and ecosystem service models with land-use and climate scenarios

Here, we present a model intercomparison of projections of biodiversity and ecosystem services using a set of land-use and climate change reconstructions from 1900 to 2015, and three future scenarios from 2015 to 2050. We

[1]German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig 04103, Germany. [2]Institute of Biology, Martin Luther University Halle-Wittenberg, Halle (Saale) 06108, Germany. [3]BIOPOLIS, CIBIO/InBIO, Universidade do Porto, Vairão 4485-661, Portugal. [4]Leverhulme Centre for Anthropocene Biodiversity, Department of Biology, University of York, York, YO10 5DD, UK. [5]Kenvue Portugal, JNTL Consumer Health Ltd, Porto Salvo 2740-262, Portugal. [6]UK Centre for Ecology and Hydrology, Lancaster LA1 4AP, UK. [7]Ecologie Systématique Evolution, Université Paris-Saclay, CNRS, AgroParisTech, Gif-sur-Yvette 91190, France. [8]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam 14473, Germany. [9]Faculty of Organic Agricultural Sciences, University of Kassel, Witzenhausen D-37213, Germany. [10]PBL Netherlands Environmental Assessment Agency, Hague 2500 GH, Netherlands. [11]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht 3584 CB, Netherlands. [12]Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA. [13]Karlsruhe Institute of Technology, Department of Meteorology and Climate/Atmospheric Environmental Research, Garmisch-Partenkirchen 82467, Germany. [14]Department of Biology and Biotechnologies, Sapienza Università di Roma, Rome I-00185, Italy. [15]KBA Secretariat, BirdLife International, Cambridge CB2 3QZ, UK. [16]Global Science, World Wildlife Fund, San Francisco, CA 94105, USA. [17]Institute on the Environment, University of Minnesota, Saint Paul, MN 55108, USA. [18]CSIRO Environment, Canberra, ACT 2601, Australia. [19]Department of Environmental Engineering, Katsura Campus, Kyoto University, Kyoto-city 615-8540, Japan. [20]National Institute for Environmental Studies, Ibaraki 305-8506, Japan. [21]Universidade de Coimbra, Coimbra 3004-530, Portugal. [22]United Nations Environment Programme, World Conservation Monitoring Centre, Cambridge CB3 0DL, UK. [23]Environmental Change Institute, Oxford OX1 3QY, UK. [24]Ritsumeikan University, Shiga 525-8577, Japan. [25]International Institute for Applied Systems Analysis, Laxenburg 2361, Austria. [26]Institute of Environmental Engineering, ETH Zurich, Zurich 8093, Switzerland. [27]Radboud University, Radboud Institute for Biological and Environmental Sciences, Nijmegen 6500 GL, Netherlands. [28]Department of Life Sciences, Natural History Museum, London SW7 5BD, UK. [29]Forestry and Forest Products Research Institute, Forest Research and Management Organization, Ibaraki 305-8687, Japan. [30]Faculty of Life and Environmental Sciences, University of Tsukuba, Ibaraki 305-8572, Japan. [31]James Cook University, Townsville, 4811 Queensland, Australia. [32]Netherlands Institute of Ecology NIOO-KNAW, Wageningen 6700AB, Netherlands. [33]Department of Ecology & Evolutionary Biology, Yale University, New Haven, CT 06511, USA. [34]Center for Biodiversity and Global Change, Yale University, New Haven, CT 06511, USA. [35]Department of Applied Economics, University of Minnesota, Saint Paul, MN 55108, USA. [36]Technical University of Munich, TUM School of Life Sciences, Freising 85354, Germany. [37]Ecology and Evolutionary Biology, University of Connecticut, Storrs, CT 06269, USA. [38]Biospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. [39]Department of Life Sciences, Imperial College London, Ascot SL5 7PY, UK. [40]"Interactions Climate-Ecosystems (ICE)" Research Group, Earth System Science Program, Faculty of Natural Sciences and Mathematics, Universidad del Rosario, Bogotá DC 63B-48, Colombia. [41]Helmholtz Centre for Environmental Research – UFZ, Department of Conservation Biology and Social-Ecological Systems, Halle 06210, Germany. [42]Institute of Biological Sciences, University of the Philippines, Laguna 4031, Philippines. [43]re.green, Rio de Janeiro 22470-060, Brazil. [44]Rio Conservation and Sustainability Science Centre, Department of Geography and the Environment, Pontifícia Universidade Católica, Rio de Janeiro 22451-900, Brazil. [45]International Institute for Sustainability, Rio de Janeiro 22460-320, Brazil. [46]Department of Ecology, University of Innsbruck, Innsbruck 6020, Austria. [47]Université Grenoble Alpes, CNRS, Université Savoie Mont Blanc, LECA, Laboratoire d'Écologie Alpine, Grenoble F-38000, France. [48]Luxembourg Institute of Science and Technology, Environmental Research and Innovation Department, Observatory for Climate, Environment and Biodiversity, Belvaux 4422, Luxembourg. [49]Institute of Zoology, Zoological Society of London, London NW1 4RY, UK. [50]Centre for Biodiversity and Environment Research, University College London, London C1E6BT, UK. [51]Earth System and Global Change Group, Wageningen University, Wageningen 6708PB Netherlands.
***Corresponding author. Email: hpereira@idiv.de**
†Deceased.

quantified a set of ecological metrics at multiple spatial scales to answer two main questions: (i) What are the predicted global impacts of land-use and climate change on multiple facets of biodiversity and ecosystem services over the coming decades compared with their impacts during the 20th century? and (ii) How much of the variation in projected impacts can be attributed to differences of development pathways in scenarios versus differences between models?

We explored a range of plausible futures using the scenario framework of the Shared Socio-Economic Pathways (SSP) and Representative Concentration Pathways (RCP) (*14*). We chose three specific SSP-RCP combinations representing different storylines of population growth, socioeconomic development, and level of greenhouse gas emissions (climate policy). These combinations represent contrasting projections of future land-use and climate change (Table 1, table S1, and figs. S1 to S6): "global sustainability," with low climate change and low land-use change; "regional rivalry," with intermediate climate change and high land-use change; and "fossil-fueled development," with high climate change and intermediate land-use change. For the biodiversity analysis, we consider both the impacts of land-use change alone [maintaining climate constant at historical levels (*15*)] and of land-use change and climate change combined.

We brought together eight models of biodiversity, including species distribution models, species-area relationship models, dose-response models, and one generalized dissimilarity model, and five models of ecosystem function and services, including dynamic global vegetation models and geographic information system–based models (Table 1 and table S2) (*15*). The main inputs to these models were global maps for 12 land-use types (table S3) and climate for 1900 to 2050, but other inputs were also used (table S4). Depending on the model, up to three biodiversity metrics were calculated (*15*): species richness (S), mean species habitat extent ($\dot{H}$), and biodiversity intactness (I). Taxonomic groups covered by these models included multiple vertebrate groups, plants, and invertebrates. We classified ecosystem model outputs into nine classes covering a range of provisioning and regulating ecosystem services and functions (*15*, *16*) (Table 1). We calculated the metrics at the grid cell level (α-metrics), at the regional level by subregions as defined by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and at the global level (γ-metrics).

Biodiversity projections

When land-use change alone is considered, the rate of biodiversity loss that models estimated to have occurred during the 20th century (0.22 to 1.1% per decade, range of intermodel means across metrics) is expected to continue at a slower pace (global sustainability scenario) or at a similar pace (regional rivalry and fossil-fueled development scenarios) in the coming decades (Fig. 1A). However, a steeper biodiversity decline (0.92 to 5.1% per decade) is expected when the combined effects of land-use change and climate change impacts are considered (Fig. 1B). When greenhouse gas concentrations stabilize and climate change is limited to 2°C (global sustainability scenario; fig. S6), biodiversity declines diminish by 40 to 74% by 2050 (depending on the metric) compared with the scenario without climate mitigation policy (fossil-fueled development). Larger

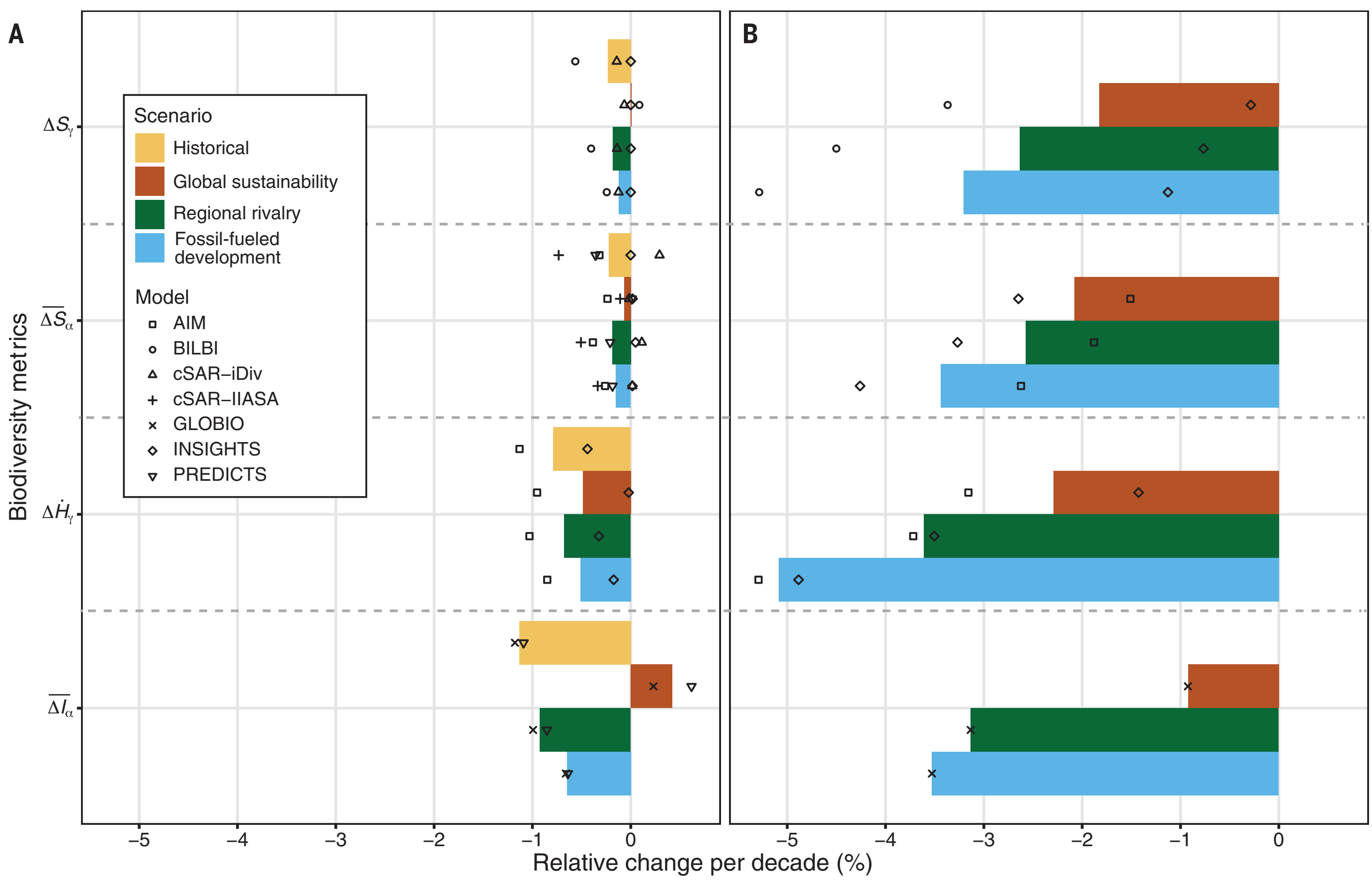

Fig. 1. Historical trends (1900 to 2015) and projections for each scenario to 2050 of different biodiversity metrics. (**A**) Land-use change impacts alone. (**B**) Land-use change and climate change impacts combined. Metrics correspond to relative changes per decade in global species richness (ΔS_γ), local species richness averaged across space ($\overline{\Delta S_\alpha}$), mean species global habitat extent ($\Delta \dot{H}_\gamma$), and local intactness averaged across space ($\overline{\Delta I_\alpha}$). Bars represent means across models, with values for each individual model also shown.

differences can be expected for the second half of this century, when contrasts between these scenarios continue to increase (*17*). These patterns are consistent across biodiversity metrics but with some notable differences. The model intercomparison suggests that reductions in mean local species richness are of similar magnitude to global species richness changes, whereas biodiversity metrics based on global habitat extent across species or mean intactness are up to fivefold more sensitive to land-use change (Fig. 1). Although in most models and metrics, the scenario with lowest land-use change (global sustainability) still leads to declines in biodiversity, models project a partial recovery in intactness in this scenario (Fig. 1A). The uncertainties due to intermodel variation are large, particularly for the climate change impacts, which are based on a smaller subset of models (Fig. 1B). In addition, spatial patterns of biodiversity change exhibit differences across models (fig. S7).

Global averages mask larger species reductions estimated by the models at the level of individual grid-cells (Fig. 2). During the 20th century, reductions in local species richness occurred across much of the world, with pronounced losses in Central America, the Andes, southeast Brazil, West Africa, East Africa, Southeast Asia, eastern Australia, southwest Australia, and Madagascar (Fig. 2A). In the future, some of these regions are projected to see further biodiversity losses from land-use change (Fig. 2, B to D). Other regions will start seeing losses for the first time, particularly in the northern boreal regions as forestry activities increase and in regions in the Amazon and central Africa due to conversion to pasture (fig. S5). By contrast, some areas in Western Europe, northern Asia, North America, Australia, and southern South America (Fig. 2, B anc C) will register increases in local species richness as a result of farmland abandonment and decrease of forestry (fig. S3). However, these limited increases in species richness (which are projected only when considering the impacts of land-use change alone) are not enough to noticeably improve biodiversity intactness, because many of these regions have already incurred large historical biodiversity losses (fig. S8). For instance, in Central and Western Europe, biodiversity intactness in 1900 was 0.76 on average (1 would be pristine), the lowest across all world regions. The global sustainability scenario (land-use change alone) increases intactness in this region only to 0.78 by 2050.

The three scenarios exhibit important regional contrasts of biodiversity change in response to land-use change alone. In the global sustainability scenario, further land-use–induced losses are moderate, and there are spatial clusters of biodiversity recovery in all continents (Fig. 2B). In the regional rivalry scenario, more regionalized socioeconomic development leads to multiple fronts of biodiversity loss across the world, with large swaths of Africa experiencing biodiversity declines, whereas biodiversity recovers in parts of North America, Europe and northern Asia (Fig. 2C). In the fossil-fueled development scenario, with more globalization, biodiversity loss concentrates in southeast South America, Central Africa, East Africa, and South Asia (Fig. 2D). When climate change is also considered, the losses are further exacerbated: Biodiversity losses occur in much of the world but are especially concentrated in the highly biodiverse areas in the neotropics and afrotropics (Fig. 2, E to G).

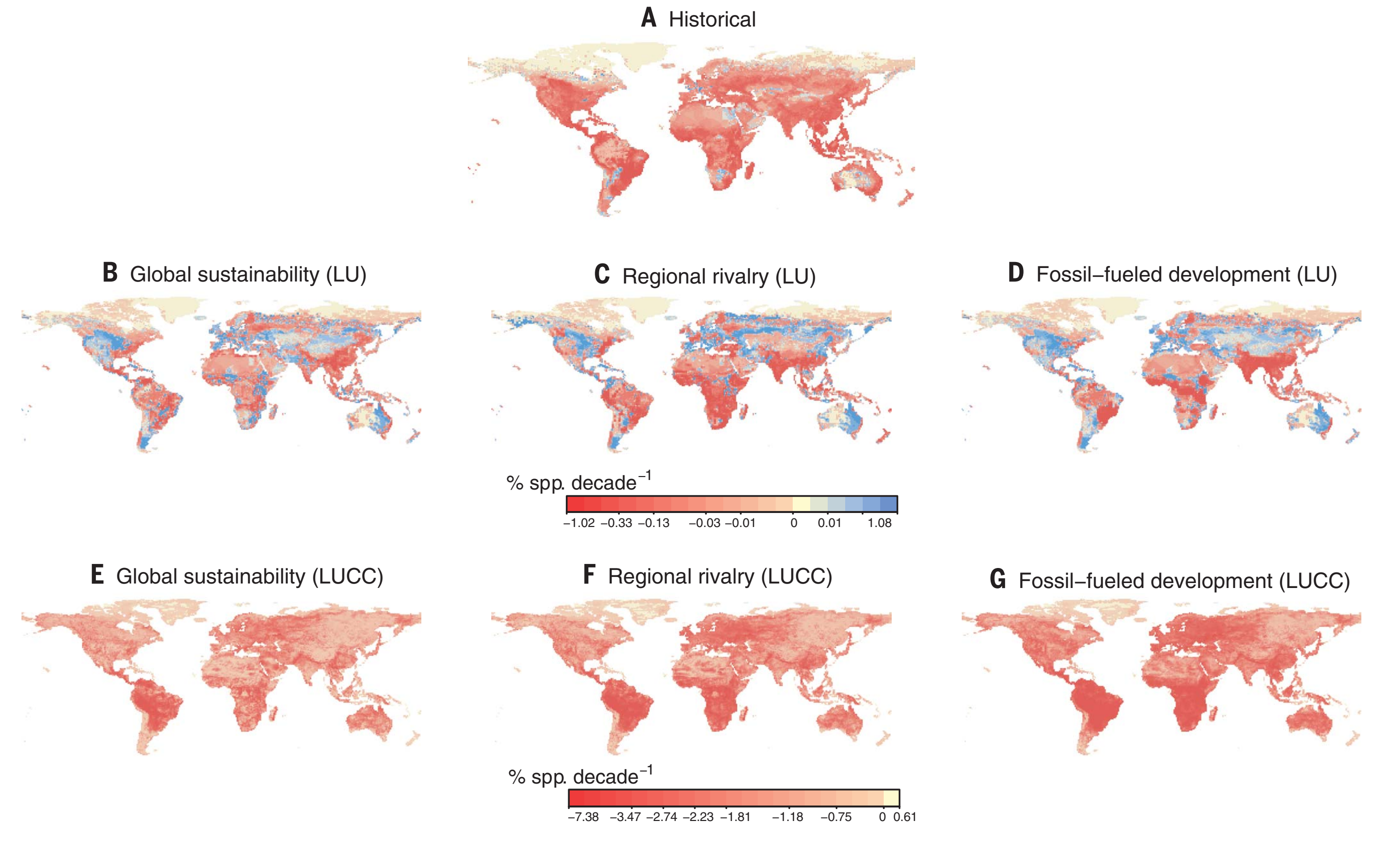

Fig. 2. Spatial distribution of diversity-weighted changes in local species richness (ΔSS_α). (**A**) Historical ΔSS_α changes from 1900 to 2015 (number of models, N = 5). (**B** to **G**) Future species richness changes from 2015 to 2050 driven by land-use (LU) change alone in each scenario [(B) to (D); N = 5] and by land-use change and climate change combined (LUCC) [(E) to (G); N = 2]. All values are based on intermodel means. Diversity-weighted changes in local species richness were calculated as the absolute change in species richness in each cell divided by the mean species richness across cells. Color scale is based on quantile intervals and differs for (A) to (D) and (E) to (G). Maps are in equirectangular projection.

Ecosystem service projections

During the 20th century, models estimate increases at the global scale in provisioning services such as food and timber, whereas regulating services such as pollination and nutrient retention declined (Fig. 3). The same overall trends are projected for the next few decades, although much less pronounced in the global sustainability scenario, where limited population growth combined with healthy diets and reduction of food waste leads to the smallest increases in food, feed, and timber demand. This, in combination with increases in agricultural productivity and other environmental policies, allows for improvements in some regulating ecosystem services and only moderate declines in others. The global sustainability scenario also has the largest increase in bioenergy production as a component of climate mitigation policies, which leads to land-use change (fig. S1) and impacts on biodiversity (Fig. 2B).

In the regional rivalry and fossil-fueled development scenarios, higher rates of increase in

Table 1. Brief description of the scenarios, models, and metrics. For more information see (*15*) or (*44*).

Scenarios	Model	Metrics	Spatial scale of model output
SSP1xRCP2.6, global sustainability Transformation of society toward sustainability through lifestyle and technological changes, strong land-use regulation, and climate mitigation, resulting in low to moderate land-use change and low climate change **SSP3xRCP6.0, regional rivalry** A world of increasing inequity and regional fragmentation, with resource-intensive development, low technology adoption, and no climate mitigation policy, resulting in intermediate climate change and high land-use change **SSP5xRCP8.5, fossil-fueled development** A world that emphasizes economic development based on high material use and a meat-rich diet, with some land-use regulation but no climate mitigation policies, resulting in high climate change and intermediate land-use change	**Biodiversity models** • AIM: species distribution model for the habitat extent of each amphibian, bird, mammal, plant, and reptile species; species richness can be derived • InSiGHTS: species distribution model for the habitat extent of each mammal species; species richness can be derived • MOL: species distribution model for the habitat extent of each amphibian, bird, and mammal species; species richness can be derived. • cSAR-iDiv: countryside species-area relationship model for the species richness of forest and nonforest birds • cSAR-IIASA-ETH: countryside species-area relationship model for species richness of amphibians, birds, mammals, plants, and reptiles • BILBI: generalized dissimilar modeling framework coupled with a species-area relationship to estimate species richness of plants • PREDICTS: mixed-effect dose-response model for species richness and community intactness of invertebrates, vertebrates, and plants • GLOBIO: dose-response model for community intactness of plants and vertebrates	• Species richness (S), reported as relative change between time steps t_0 and t_1 [$\Delta S = (S_{t1} - S_{t0})/S_{t0}$] or as diversity-weighted change [$\Delta SS = (S_{t1} - S_{t0})/\bar{S}$], where $\bar{S}$ is the mean species richness across cells; see fig. S9 for differences • Mean species habitat extent ($\dot{H}$) reported as relative change in the habitat extent of each species, averaged across species: $\Delta\dot{H} = \sum_{i=1}^{S}(H_{i,t1} - H_{i,t0})/H_{i,t0}/S$ • Species-abundance based intactness (I), reported both in absolute values and as relative change	• Local, 1° cell (α); In addition, global mean α values are reported as spatial area-weighted averages across grid cells (e.g., $\overline{\Delta S_\alpha}$) • Regional, 17 IPBES subregions, (γ_{region}) • Global (γ_{global})
Land-use data Land Use Harmonization version 2 (LUH2), 1900 to 2015 (historical) and 2015 to 2050 (SSPs), available in annual time steps gridded at 0.25° resolution and with 12 land-use categories **Climate data** ISIMIP2a - IPSL-CM5A-LR (most models) 1900 to 2015 (historical) and 2015 to 2050 (RCPs) available in daily time steps gridded at 0.5° resolution and with 12 climate variables	**Ecosystem functions and services models** • LPJ-GUESS: dynamic global vegetation model • LPJ: dynamic global vegetation model • CABLE-POP: dynamic global vegetation model • GLOBIO-ES: suite of geographic information system–based ecosystem functions and services models • InVEST: suite of geographic information system–based ecosystem functions and services models	All ecosystem services metrics are reported as relative changes [$\Delta ES = (ES_{t1} - ES_{t0})/ES_{t0}$] **Material services** • Bioenergy production • Food and feed production • Timber production **Regulating services** • Ecosystem carbon • Crop pest control • Coastal resilience • Pollination • Soil protection • Nitrogen retention	

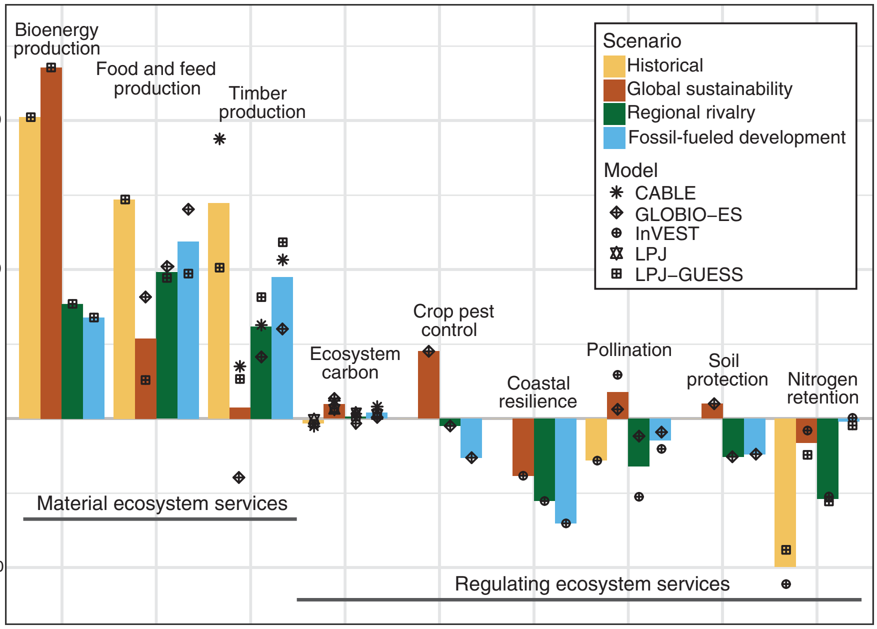

Fig. 3. Historical (1900 to 2015) rate of changes in material and regulating ecosystem services at the global level and future projections for each scenario (2015 to 2050) from land-use and climate change combined. Bars represent means across models, with values for each individual model also shown.

food and feed and timber supply are projected (~10% per decade), particularly in the latter scenario, although this is still predicted to be smaller than during the past century (~15% per decade). This is likely due to decelerating population growth and smaller demand for timber products. Regulating services will decline in these scenarios, with decreases projected for crop pest control, coastal resilience, pollination, soil protection, and nitrogen retention (Fig. 3). In contrast to biodiversity projections, the scenario with intermediate climate change, regional rivalry, generally has more negative consequences for regulating services than the scenario with highest climate change, fossil-fueled development. This suggests that the more pronounced land-use changes in "regional rivalry" will dominate. One exception is the increasing vulnerability of coastal populations, which is predominantly affected by increasing climate change (Fig. 3). Limited change in total ecosystem carbon is anticipated, increasing at a rate between 0.1% (regional rivalry scenario) and 1% (global sustainability scenario) per decade. The larger increases in the global sustainability scenario are likely due to the slightly faster increase in secondary forest and lower deforestation rates (figs. S2, S3, and S10) (*17*).

There is also high spatial heterogeneity in future ecosystem service dynamics (Fig. 4 and fig. S11). In the fossil-fueled development and regional rivalry scenarios, some regions, such as Central Africa, Southern Africa, West Africa, East Africa, and South Asia, are projected to increase provisioning ecosystem services, whereas substantial declines of regulating services and biodiversity occur (Fig. 4, B and C). Several regions exhibit lower declines in regulating services in the fossil-fueled development scenario than in the regional rivalry scenario. In the global sustainability scenario, the trade-offs between provisioning and regulating services are smaller, with some regions even registering increases in both provisioning and regulating services: Western Europe, Eastern Europe, and Central Africa (Fig. 4A). However, climate change, and to a lesser extent land-use change, still drives regional biodiversity declines in most regions.

There is some intermodel variation in the projections of individual ecosystem services, although the limited number of models that project each ecosystem service limits intercomparisons (table S2). Models for ecosystem carbon (fig. S12) and timber provisioning (fig. S13) exhibit low to moderate spatial agreement. The intramodel projections rank in the same direction and relative order across scenarios for most of the models for both biodiversity and ecosystem services (Figs. 1 and 3). This suggests that the differences across scenarios are relatively robust to intermodel uncertainties.

Differences between models and future research needs

Our results suggest that climate change might become a more important driver of terrestrial biodiversity loss than land-use change by mid-century (Figs. 1 and 2), in agreement with recent findings based on single metrics (*10*) and in contrast to an earlier review (*6*). One explanation is that in the scenarios examined here, future rates of land-use change are not projected to increase relative to the past century rates (fig. S1). This contrasts with two of the climate change scenarios, where rates of temperature change still increase in the future (fig. S6). However, these results need to be interpreted with caution. There are differences in how biodiversity models capture the impacts of climate and land-use change and in the spatial grain at which these impacts are estimated (*18*). Biodiversity models in this study use empirical relationships between habitat conversion and biodiversity at the local scale and project those relationships at larger scales (*19*). By contrast, the impacts of climate are based on statistical models relating the current climate with coarse species distribution patterns and assume that those relationships will hold in the future (*20*). Thus, projections for land-use change impacts are based on observed local impacts, whereas projections for climate change are inferred from macroecological distribution patterns and mostly ignore the possibility of local-scale adaptation. In addition, our projections assumed no species migration with climate change, whereas some models allowed for species migration or increased species richness in response to land-use change (table S2). Assumptions about dispersal can drive large differences in projections of climate change on biodiversity impacts (*21*). For instance, in the AIM model, the average local species richness is reduced by 2.6% per decade in the fossil fuel development scenario without dispersal, but only by 0.2% with dispersal (figs. S9 and S14). Further model calibration and validation could make the projection of land-use and climate change impacts more comparable and also evaluate dispersal scenarios for different taxa.

The differences among biodiversity models for similar output metrics with identical land-use and climate change inputs highlight the need for further refinement and calibration of the models. New model intercomparisons should include additional biodiversity observations at spatial and temporal scales that can be used to calibrate the models (*22*, *23*). In addition, further efforts in refining land-use categories beyond the relatively coarse categories used here are needed. Improving the handling of intramodel uncertainty and harmonizing biodiversity metric output is also important (*23*).

Intermodel variation also remains for ecosystem services, with the additional challenge of the limited number of available global models. Spatial agreement between models for some ecosystem services may be related to these models having been previously subject to intercomparisons (*24*), being process based, or reporting comparable biophysical units. Perhaps

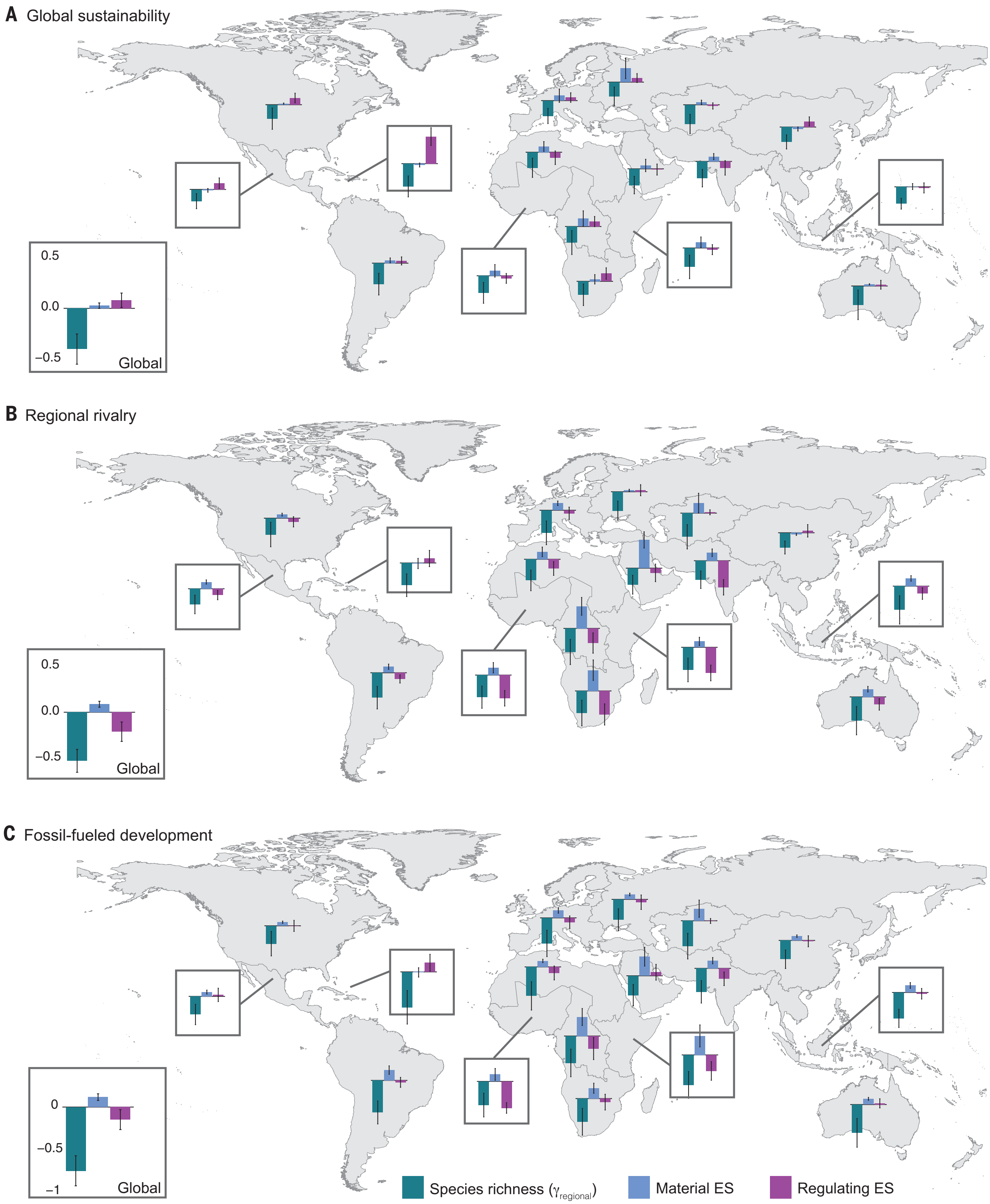

Fig. 4. Projected regional (IPBES subregions) and global (insets) changes in biodiversity and ecosystem services (2015 to 2050) from land-use and climate change combined. (**A**) Global sustainability. (**B**) Regional rivalry. (**C**) Fossil-fueled development. Barplots show mean ± SEM of the normalized values across biodiversity, material ecosystem service (ES), and regulating ecosystem service models. Values range from −1 to 1, where positive values correspond to an average increase in biodiversity or that category of ecosystem services across models and across services in that category. Bars are comparable for the same type of service across regions but should not be compared directly within each region because they are in different relative scales. Maps are in equirectangular projection.

more importantly, the ecosystem services models used in this study do not yet account for the empirical link between biodiversity and ecosystem services (*25*). Incorporating this relationship into the models could result in estimates of even greater erosion of ecosystem services (*26*).

Implications for detecting biodiversity trends and for biodiversity policy

Our analysis suggests that during the 20th century the planet lost almost 2.3 ± 1.7% (intermodel mean ± SEM) of species from land-use change impacts alone, ~200,000 species if one assumes the planet's diversity to be ~9 million species (*27*). This estimate is consistent with the 1.2% likely vertebrate extinctions documented by the International Union for Conservation of Nature (IUCN) during this period (*28*). Some of the documented extinctions have been caused by drivers that are not included in our models, particularly invasive alien species and direct exploitation. This may make the intermodel estimate seem high. However, it is important to consider the time lags between habitat loss and extinction (*29*), which suggest that some extinctions from historical land-use change are still forthcoming. In addition, when the projections of multi-taxa models are compared across taxa (fig. S14), the relative ranking of the vulnerability of the taxa is consistent with the ranking of the proportion of species threatened in each taxonomic group (*30*), with amphibians being the most vulnerable and birds the least. However, mammals have the second highest vulnerability but in our models have similar declines to birds, suggesting that causes other than land use may be driving their demise.

Recent studies have found no statistically significant trends in local species richness in global meta-analyses of community time series (*31*–*33*). Our intermodel mean estimate of local species richness change during the past century is –2.2 ± 1.7%, with the intermodel range straddling zero (Fig. 1B) because one of the models (cSAR-iDiv, which models only birds) reports a positive value. This is consistent with meta-analyses failing to detect a statistically significant trend either because the signal is too small to be detectable among the noise in available time series (*34*) or the trend is not negative. Nevertheless, there have been criticisms regarding these meta-analyses, such as those pointing out spatial sampling biases, limited duration of time series, and the response metric used (*35*). Our approach is based on continuous estimates over the land surface of the planet, addressing at least some of the sampling biases that occur in the available time series.

Countries are currently faced with implementing ambitious goals of the Kunming-Montreal Global Biodiversity Framework (*36*). According to this framework, extinctions of known threatened species should be halted by 2050, and extinction rates of all species should be reduced 10-fold. In addition, declining ecosystem services should be restored by 2050. The global sustainability scenario comes close to achieving extinction rate targets when only considering land-use change effects, but even the modest climate change in this scenario leads to accelerated extinctions. In addition, material services continue to increase, whereas most regulating ecosystem services, which have been declining in the past century, slightly improve in this scenario. These results provide some hope, particularly because the global sustainability scenario does not deploy all policies that could be enacted to protect biodiversity and ecosystem services in the future (*12*). For instance, although ambitious lifestyle and technological changes occur (Table 1 and table S1), there is still lost pasture and grazing land, further declines in primary vegetation (*37*), and bioenergy deployment, all of which can reduce species habitats (*38*). Introducing further measures for regulation of deforestation, effectiveness of protected areas (*39*), changes in consumption patterns (*40*), and sensible natural climate solutions (*41*) could result in better prospects for biodiversity and ecosystem services. This calls for a new generation of global scenarios and models that aim at achieving realistic positive futures for biodiversity (*42*, *43*) to identify better development policies.

REFERENCES AND NOTES

1. V. Proença, H. M. Pereira, "Comparing extinction rates: Past, present, and future" in *Reference Module in Life Sciences* (Elsevier, 2017); https://doi.org/10.1016/B978-0-12-809633-8.02128-2.
2. A. Marques *et al.*, *Nat. Ecol. Evol.* **3**, 628–637 (2019).
3. S. R. Carpenter *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 1305–1312 (2009).
4. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, *The IPBES Assessment Report on Land Degradation and Restoration* (IPBES Secretariat, 2018).
5. D. P. Van Vuuren *et al.*, *Environ. Res. Lett.* **7**, 024012 (2012).
6. H. M. Pereira *et al.*, *Science* **330**, 1496–1501 (2010).
7. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, *The Methodological Assessment Report on Scenarios and Models of Biodiversity and Ecosystem Services* (IPBES Secretariat, 2016).
8. S. R. Carpenter, L. P. Prabhu, E. M. Bennet, M. B. Zurek, Eds., *Ecosystems and Human Well-Being: Scenarios* (Island Press, Washington, 2005), vol. 2 of *Millennium Ecosystem Assessment*.
9. P. W. Leadley *et al.*, "Progress towards the Aichi biodiversity targets" (78, Secretariat of the Convention on Biological Diversity, Montreal, Canada, 2014).
10. T. Newbold, *Proc. Biol. Sci.* **285**, 20180792 (2018).
11. A. M. Schipper *et al.*, *Glob. Chang. Biol.* **26**, 760–771 (2020).
12. D. Leclère *et al.*, *Nature* **585**, 551–556 (2020).
13. W. Thuiller, M. Guéguen, J. Renaud, D. N. Karger, N. E. Zimmermann, *Nat. Commun.* **10**, 1446 (2019).
14. K. Riahi *et al.*, *Glob. Environ. Change* **42**, 153–168 (2017).
15. Materials and methods are available as supplementary materials.
16. S. Díaz *et al.*, *Science* **359**, 270–272 (2018).
17. D. P. van Vuuren, T. R. Carter, *Clim. Change* **122**, 415–429 (2014).
18. N. Titeux *et al.*, *Glob. Chang. Biol.* **22**, 2505–2515 (2016).
19. H. M. Pereira, L. Borda-de-Agua, "Modelling biodiversity dynamics in countryside and native habitats" in *Encyclopedia of Biodiversity* (Elsevier, ed. 2, 2013), **vol. 5**, pp. 321–328, https://doi.org/10.1016/B978-0-12-384719-5.00334-8.
20. C. Bellard, C. Bertelsmeier, P. Leadley, W. Thuiller, F. Courchamp, *Ecol. Lett.* **15**, 365–377 (2012).
21. C. D. Thomas *et al.*, *Nature* **427**, 145–148 (2004).
22. A. Gonzalez *et al.*, *Nat. Ecol. Evol.* **7**, 1947–1952 (2023).
23. I. M. D. Rosa *et al.*, *Glob. Ecol. Conserv.* **22**, e00886 (2020).
24. S. Sitch *et al.*, *Glob. Chang. Biol.* **14**, 2015–2039 (2008).
25. M. Loreau, A. Hector, F. Isbell, *The Ecological and Societal Consequences of Biodiversity Loss* (Wiley, 2022).
26. S. R. Weiskopf *et al.*, *Bioscience* **72**, 1062–1073 (2022).
27. C. Mora, D. P. Tittensor, S. Adl, A. G. B. Simpson, B. Worm, *PLOS Biol.* **9**, e1001127 (2011).
28. G. Ceballos *et al.*, *Sci. Adv.* **1**, e1400253–e1400253 (2015).
29. S. Dullinger *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **110**, 7342–7347 (2013).
30. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES Secretariat, 2019).
31. M. Dornelas *et al.*, *Science* **344**, 296–299 (2014).
32. M. Vellend *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **110**, 19456–19459 (2013).
33. S. A. Blowes *et al.*, *Science* **366**, 339–345 (2019).
34. J. W. Valdez *et al.*, *Ecography* **2023**, e06604 (2023).
35. A. Gonzalez *et al.*, *Ecology* **97**, 1949–1960 (2016).
36. Convention on Biological Diversity, *Decision 15/4. Kunming-Montreal Global Biodiversity Framework* (CBD, 2022); https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf.
37. Ł. Tracewski *et al.*, *Conserv. Biol.* **30**, 1070–1079 (2016).
38. C. Hof *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **115**, 13294–13299 (2018).
39. P. Visconti *et al.*, *Science* **364**, 239–241 (2019).
40. M. T. J. Kok *et al.*, *Biol. Conserv.* **221**, 137–150 (2018).
41. B. W. Griscom *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **114**, 11645–11650 (2017).
42. I. M. D. Rosa *et al.*, *Nat. Ecol. Evol.* **1**, 1416–1419 (2017).
43. H. Kim, *et al.*, *Glob. Environ. Change* **82**, 102681 (2023); https://doi.org/10.1016/j.gloenvcha.2023.102681.
44. H. Kim *et al.*, *Geosci. Model Dev.* **11**, 4537–4562 (2018).
45. R. Alkemade, M. Bakkenes, Global trends in ecosystem services (BES-SIM GLOBIO-ES), version 2, [German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, 2023]; https://doi.org/10.25829/VQD4S4.
46. D. Baisero, C. Rondinini, Global trends in biodiversity (BES-SIM INSIGHTS), version 1 [German Centre for Integrative Biodiversity Research (iDiv), 2023]; https://doi.org/10.25829/H2EVR2.
47. R. Chaplin-Kramer, R. Sharp, Global trends in ecosystem services (BES-SIM InVEST), version 2 [German Centre for Integrative Biodiversity Research (iDiv), 2023]; https://doi.org/10.25829/ZR4D27.
48. V. Haverd, Global trends in ecosystem services (BES-SIM CABLE POP), version 2 [German Centre for Integrative Biodiversity Research (iDiv), 2023]; https://doi.org/10.25829/KTNB68.
49. S. Hill, A. Purvis, Global trends in biodiversity (BES-SIM PREDICTS), version 1 [German Centre for Integrative Biodiversity Research (iDiv), 2022]; https://doi.org/10.25829/VT7QK9.
50. D. Leclere, M. Obersteiner, Global trends in biodiversity (BES-SIM cSAR-IIASA), version 1 [German Centre for Integrative Biodiversity Research (iDiv), 2022]; https://doi.org/10.25829/HAQ7D4.
51. I. Martins, H. Pereira, Global trends in biodiversity (BES-SIM cSAR-iDiv), version 1 [German Centre for Integrative Biodiversity Research (iDiv), 2022]; https://doi.org/10.25829/5ZMY41.
52. H. Ohashi, T. Hasegawa, Global trends in biodiversity (BES-SIM AIM), version 2 [German Centre for Integrative Biodiversity Research (iDiv), 2023]; https://doi.org/10.25829/5WN357.
53. B. Poulter, B. Quesada, Global trends in ecosystem services (BES-SIM LPJ), version 2 [German Centre for Integrative Biodiversity Research (iDiv), 2023]; https://doi.org/10.25829/XQ7A86.
54. B. Quesada, P. Anthoni, A. Arneth, Global trends in ecosystem services (BES-SIM LPJ-GUESS), version 2 [German Centre for Integrative Biodiversity Research (iDiv), 2023]; https://doi.org/10.25829/Z5V9T2.
55. A. Schipper, R. Alkemade, Global trends in biodiversity (BES-SIM GLOBIO), version 1 [German Centre for Integrative Biodiversity Research (iDiv), 2023]; https://doi.org/10.25829/R7BT92.
56. H. M. Pereira *et al.*, Data and code for: Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900-2050, version 1.2, Zenodo (2024); https://doi.org/10.5281/ZENODO.10702963.

57. G. Hurtt *et al.*, "Land use harmonization (LUH2)" (Global Ecology Laboratory, University of Maryland, 2012); https://luh.umd.edu/data.shtml.
58. H. M. Pereira, P. Anthoni, L. Quoß, Monthly aggregated climate projections of IPSL-CM5A-LR ISIMIP2a fasttrack data for the BES SIM study, Dryad (2024); https://doi.org/10.5061/DRYAD.3N5TB2RR6.

ACKNOWLEDGMENTS

This study was carried out with the support of the IPBES Expert Group on Scenarios and Models and its technical support unit. We thank P. Anthoni for help with the climate data and J. Hines for comments on the manuscript. **Funding:** This work was supported by the German Research Foundation (grant DFG FZT 118 to H.M.P., I.S.M., I.M.D.R., H.K., J.S., L.Q., and N.T.); the NASA Carbon Monitoring System (grant 80NSSC21K1059 to G.H. and L.C.); the Environmental Restoration and Conservation Agency of Japan (grant JPMEERF20202002 to S.Fu., T.Ha., A.H., T.M., H.O., and K.T.); the E.O. Wilson Biodiversity Foundation (W.J.); and the Japan Society for the Promotion of Science (grant KAKENHI JP22H03817 to H.O. and grant KAKENHI 22K21331 to T.H. **Author contributions:** Conceptualization: R.A., P.L., H.M.P., D.P.v.V., A.Po., G.H.; Formal analysis: H.M.P., I.S.M., I.M.D.R., H.K. and L.Q.; Investigation: A.M.S., R.A., J.R.M., J.P.H., J.H.J., S.L. L.H., A.Pu., D.L., M.O., I.S.M., C.A.G., H.O., T.H., M.D.M., S.Fe., T.D.H., C.M., W.J., B.Q., A.K., A.A., B.P., V.H., R.C.-K., R.S., J.A.J., D.B., C.R., G.H., L.C., J.P.H., J.R.M.; Methodology: H.M.P., I.S.M., I.M.D.R., H.K., F.W. and L.Q.; Project administration: H.M.P., I.S.M., I.M.D.R., H.K.; Supervision: H.M.P.; Visualization: I.S.M., L.Q., H.K., H.M.P.; Writing – original draft: H.M.P.; Writing – review & editing: all authors. **Competing interests:** The authors declare no competing interests. W.J. is the scientific chair of the E.O. Wilson Biodiversity Foundation. B.B.N.S. is the founder, board member, and chief scientist at re.green, where he also has an equity share. **Data and materials availability:** The maps outputted by the models are available from the GEO BON EBV portal (*45*–*55*) and are listed in table S2. Additional outputs provided by the biodiversity and ecosystem services models as tabular data, the spatial statistics from the maps, the IPBES regions shapefile, and all code in R used to produce the figures and the spatial statistics are available from Zenodo (*56*). The land-use data used as inputs to the models are available at (*57*), and the climate data are available from Dryad (*58*).

SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.adn3441
Materials and Methods
Figs. S1 to S14
Tables S1 to S4
References (*59*–*121*)
MDAR Reproducibility Checklist

Submitted 18 December 2023; accepted 28 March 2024
10.1126/science.adn3441