# Title: Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900-2050

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**Abstract:** 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%-11% estimated by a range of indicators. Provisioning ecosystem services increased several-fold while regulating services decreased moderately. Going forward, policies towards 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 modelling uncertainties but also robustly shows that renewed policy efforts are needed to meet the goals of the Convention on Biological Diversity.

**One-Sentence Summary:** There are developmental pathways in which future biodiversity loss from land-use change slows and regulating services improve, but they entail significant societal changes, while climate change poses an increasing challenge.

**Main Text:**

During the last 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 socio-economic developments for biodiversity and ecosystem services

Scenario studies examine alternative future socio-economic 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*). While enlightening on the potential trajectories of biodiversity under global changes, these studies are hardly comparable. Existing scenario studies often use a single model for a single facet of biodiversity (*10*, *11*), or when comparing multiple models, use different projections for future land-use and climate (*6*), or lack comparison 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 inter-comparison 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 quantified a set of ecological metrics at multiple spatial scales to answer two main questions: (1) 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 to their impacts during the 20th century? (2) 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, socio-economic development, and the level of greenhouse gas emissions (climate policy). These combinations represent contrasting projections of future land-use and climate change (Table 1, Table S1, Figures S1-6): "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, Table S2) (*15*). The main inputs to these models were global maps for 12 land-use types (Table S3) and climate for 1900-2050, 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 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 ($\alpha$-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 ($\gamma$-metrics).

**Biodiversity projections**

When land-use change alone is considered, the rate of biodiversity loss that models estimated to have occurred during the 20$^{th}$ century (0.22-1.1% per decade, range of inter-model 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 (Figure 1a). However, a steeper biodiversity decline (0.92-5.1% per decade) is expected when the combined effects of land-use change and climate change impacts are considered (Figure 1b). When greenhouse gas concentrations stabilize and climate change is limited to 2°C (global sustainability scenario; Figure S6), biodiversity declines diminish by 40-74% by 2050 (depending on the metric) compared to the scenario without climate mitigation policy (fossil-fueled development). Larger differences can be expected for the second half of this century (Figure S2) when contrast between these scenarios continue to increase (*17*). These patterns are consistent across biodiversity metrics, with some notable differences. The model intercomparison suggests that reductions in mean local species richness are of similar magnitude to global species richness changes, while biodiversity metrics based on global habitat extent across species or mean intactness are up to an order of magnitude more sensitive to land-use change (Figure 1). While 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 (Figure 1a). The uncertainties due to inter-model variation are large, particularly for the climate change impacts, which are based on a smaller subset of models

(Figure 1b). In addition, spatial patterns of biodiversity change exhibit differences across models (Figure S7).

Global averages mask larger species reductions estimated by the models at the level of individual grid-cells (Figure 2). During the 20th century, reductions in local species richness occurred across much of the world, with pronounced losses in Central America, the Andes, the Southeast of Brazil, West Africa, East Africa, South-East Asia, Eastern Australia and South-West Australia, and Madagascar (Figure 2a). In the future, some of these regions are projected to see further biodiversity losses from land-use change (Figure 2b-d).Other regions start seeing losses for the first time, particularly in the Northern boreal regions as forestry activities increase, and regions in the Amazon and central Africa because of conversion to pasture (Figure S5). In contrast, some areas in Western Europe, Northern Asia, North America, Australia, and Southern South America (Figure 2b-c) register increases in local species richness as a result of farmland abandonment and decrease of forestry (Figure 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, as many of these regions have already incurred significant historical biodiversity losses (Figure 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 (Figure 2b). In the regional rivalry scenario, more regionalized socio-economic development leads to multiple fronts of biodiversity loss across the world, with large swaths of Africa experiencing biodiversity declines, while biodiversity recovers in parts of North America, Europe and North Asia (Figure 2c). In the fossil-fueled development scenario, with more globalization, biodiversity loss concentrates in Southeast South America, Central Africa, East Africa and South Asia (Figure 2d). When climate change is also considered, the losses are further exacerbated: biodiversity losses occur in much of the world, and are especially concentrated in the highly biodiverse areas in the Neotropics and Afrotropics (Figure 2e-g).

## Ecosystem service projections

During the 20th century, models estimate increases at the global scale in provisioning services, such as food and timber, while regulating services, such as pollination and nutrient retention, declined (Figure 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 (Figure S1) and impacts on biodiversity (Figure 2b).

In the regional rivalry and the fossil fueled-development scenarios, higher rates of increase in food and feed and timber supply are projected (c. 10% per decade), particularly in the latter scenario, although still smaller than during the last century (c. 15% per decade). This is likely due to decelerating population growth and smaller demand for timber products. Regulating services decline in these scenarios, with decreases projected for crop pest control, coastal resilience, pollination, soil protection, and nitrogen retention (Figure 3). In contrast with the 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) - implying that the more pronounced land-use changes in 'regional rivalry' dominate. The exception is the increasing vulnerability of coastal populations, which is predominantly affected by increasing climate change (Figure 3). Limited change in total ecosystem carbon is anticipated; it increases at a rate between 0.1% per decade (regional rivalry scenario) and 1% per decade (global sustainability scenario). The larger increases in the global sustainability scenario are likely due to the slightly faster increase in secondary forest and lower deforestation rates (Figures S2-3, S10) (*17*).

There is also high spatial heterogeneity in future ecosystem service dynamics (Figures 4, S11). In the fossil-fueled development and regional rivalry scenarios, some regions - 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 (Figure 4b and 4c). 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 (Figure 4a). However, climate change, and to a lesser extent land-use change, still drive regional biodiversity declines in most regions.

There is some inter-model 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 (Figure S12) and timber provisioning (Figure S13) exhibit moderate spatial agreement.  Notably, the intra-model projections rank in the same direction and relative order across scenarios for most of the models, both for biodiversity and ecosystem services (Figures 1 and 3). This suggests that the differences across scenarios are relatively robust to inter-model 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 (Figures 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 last century rates (Figure S1). This contrasts with two of the climate change scenarios, where rates of temperature change still increase in the future (Figure 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*). In 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 while 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, while 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 (Figures S9, S14). Further model calibration and validation, could make the projection of land-use and climate-change impacts more comparable and 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 intra-model uncertainty, and harmonizing biodiversity metric output is also important (*23*).

Inter-model 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 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 in 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 20$^{th}$ century the planet lost almost 2.3% ± 1.7% (inter-model mean ± SEM) of species from land-use change impacts alone, roughly 200,000 species if one assumes the planet's diversity to be approximately 9 million species (*27*). This estimate is consistent with the 1.2% vertebrate likely extinctions documented by the IUCN during this period (*28*). Some of the documented extinctions have been caused by drivers which are not included in our models, particularly invasive alien species and direct exploitation. This may make the inter-model 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 (Figure 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 the most vulnerable and birds the least vulnerable. 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 inter-model mean estimate of local species richness change during the last century is -2.2%± 1.7%, with the inter-model range straddling zero (Figure 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 amongst the noise in available time series (*34*) or because the trend is not negative. Still, it is important to note there has been criticisms to these meta-analyses such as 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 tenfold. 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 while most regulating ecosystem services, which have been declining in the last 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 life-style and technological changes occur (Table 1, 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 novel generation of global scenarios and models that aim at achieving realistic positive futures for biodiversity (*42*, *43*) to identify better development policies.

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**Data and materials availability:** The maps outputted by the models are available from the GEO BON EBV portal (*44–54*) 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 the code in R to produce the figures and the spatial statistics are available from Zenodo (*55*). The land-use data used as inputs to the models are available at (*56*) while the climate data are available from Dryad (*57*).

**Supplementary Materials**

Materials and Methods

Figures S1-S14

Tables S1-S4

References (*59-121*)

**Fig. 1. Historical trends (1900-2015) and projections for each scenario to 2050 of different biodiversity metrics. (a)** from land-use change impacts alone; **(b)** from land-use change and climate change impacts combined. Metrics correspond to relative changes per decade in: global species richness ($\Delta S_{\gamma}$), 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.

**Fig. 2. Spatial distribution of diversity-weighted changes in local species richness (**$\Delta SS_{\alpha}$). **(a)** Historical $\Delta SS_{\alpha}$ changes from 1900 to 2015 (number of models, N=5). Future species richness changes from 2015 to 2050 driven by land-use change alone in each scenario (**b-d**; N=5) and by land-use change and climate change combined (**e-f**, N=2). All values are based on inter-model 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-d)** and **(e-g)**. Maps in equirectangular projection.

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

**Figure 4. Projected regional (IPBES subregions) and global (insets) changes in biodiversity and ecosystem services (2015-2050) 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, 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 as they are in different relative scales. Maps in equirectangular projection.

**Table 1. Brief description of the scenarios, models, and metrics. For more information see (*15*) or (*58*).**

| Scenarios | Model | Metrics | Spatial scale of model output |
|---|---|---|---|
| **SSP1xRCP2.6, Global sustainability**<br>Transformation of society towards sustainability, both through life-style changes and technological changes, strong land-use regulation, and climate mitigation, resulting in low to moderate land-use change and low climate change.<br><br>**SSP3xRCP6.0, Regional rivalry**<br>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.<br><br>**SSP5xRCP8.5, Fossil-fueled development**<br>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.<br><br>**Land-use data**<br>Land Use Harmonization v. 2 (LUH2), 1900-2015 (historical) and 2015-2050 (SSPs) available in annual time steps, gridded at 0.25º resolution, 12 land-use categories<br><br>**Climate data**<br>ISIMIP2a - IPSL-CM5A-LR (most models) 1900-2015 (historical) and 2015-2050 (RCPs), available in daily time steps, gridded at 0.5º resolution, 12 climate variables | **Biodiversity models**<br>AIM: species distribution model for the habitat extent of each amphibian, bird, mammal, plant and reptile species; species richness can be derived.<br>InSiGHTS: species distribution model for the habitat extent of each mammal species; species richness can be derived.<br>MOL: species distribution model for the habitat extent of each amphibian, bird and mammal species; species richness can be derived.<br>cSAR – iDiv: countryside species-area relationship model for the species richness of forest and non-forest birds<br>cSAR-IIASA-ETH: countryside species-area relationship model for species richness of amphibians, birds, mammals, plants and reptiles<br>BILBI: a generalized dissimilar modelling framework coupled with a species-area relationship to estimate species richness of plants<br>PREDICTS: a mixed-effect dose-response model for species richness and community intactness of invertebrates, vertebrates and plants<br>GLOBIO: a dose-response model for community intactness of plants and vertebrates | • Species richness ($S$), reported as relative change ($\Delta S = (S_{t1} - S_{t0})/S_{t0}$) or as absolute change ($\Delta SS = S_{t1} - S_{t0}$), see Fig. S14 for differences<br>• Mean species habitat extent ($\dot{H}$), reported as relative change in the habitat extent of each species $\Delta\dot{H} = \sum_{i=1}^{S}(H_{i,t1} - H_{i.t0})/H_{i.t0}/S$,<br>• Species-abundance based intactness ($I$), reported both in absolute values and as relative change | • Local, 1º cell ($\alpha$)<br>In addition, global mean $\alpha$ values are reported as spatial area weighted averages across grid cells (e.g. $\overline{\Delta S_{\alpha}}$)<br>• Regional, 17 IPBES subregions, ($\gamma_{region}$)<br><br>• Global ($\gamma_{global}$) |
| | **Ecosystem functions and services models**<br>LPJ-GUESS: dynamic global vegetation model<br>LPJ: dynamic global vegetation model<br>CABLE-POP: dynamic global vegetation model<br>GLOBIO-ES: a suite of geographic information system-based ecosystem functions and services models<br>InVEST: a suite of geographic information system based ecosystem functions and services models | All ecosystem services metrics are reported as relative changes ($\Delta ES = (ES_{t1} - ES_{t0})/ES_{t0}$)<br>**Material services**<br>• Bioenergy production<br>• Food and feed production<br>• Timber production<br>**Regulating services**<br>• Ecosystem carbon<br>• Crop pest control<br>• Coastal resilience<br>• Pollination<br>• Soil protection<br>• Nitrogen retention | |