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Title: Declines in terrestrial biodiversity and regulating services driven by land-use change can be slowed but climate change impacts are accelerating

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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% measured by a range of indicators. Provisioning ecosystem services increased several-fold while regulating services decreased moderately. Policies towards sustainability have the potential to slow down biodiversity loss from land-use change and the demand for provisioning services, while reducing or even reversing declines in regulating services. But negative impacts on biodiversity due to climate change look set 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 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 higher than ever before, with extinction rates for vertebrates of 0.5% to 1% per century, 50 to 100 times higher than the mean extinction rates in the Cenozoic fossil record (*1–4*). Although the proximate causes of this loss are multiple, ultimately a growing human population and economy have led to an increasing demand for land and natural resources causing habitat conversion and loss (*5*). Increases in the production of crops and livestock happened alongside widespread degradation of ecosystems' capacity to provide regulating services such as pollination and water quality, raising concerns about the long-term sustainability of recent development trends, especially given that both human population and per-capita consumption are increasing in many regions (*6*). 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 part of the solution to many of the UN Sustainable Development Goals, including achieving zero hunger by 2030 (*7*, *8*). Therefore, it is key to assess implications of future socio-economic developments for biodiversity and ecosystem services, also given their spatial congruence (*9*).

Scenario studies examine alternative future socio-economic development pathways and their impacts on direct drivers such as land-use and climate, often using integrated assessment models (*9*). Consequences of these scenarios for biodiversity and ecosystem services can be assessed using biodiversity and ecosystem function and services models (*10*, *11*). Several studies have explored the future trends of biodiversity and ecosystem services, finding an acceleration of extinction rates 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 strong regional variations (*10*, *12–15*). 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 (*14*, *16*), or when comparing multiple models, use different projections for future land-use and climate (*10*) or lack comparison of biodiversity and ecosystem services impacts (*17*). Therefore, the source of uncertainties in these studies is difficult to ascertain (*18*) 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 the first 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 common ecological metrics from the grid cell scale (α-metrics), to the regional (i.e., subregions as defined by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES) and global scale (γ-metrics) to answer two main questions: (1) What are the 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 and to differences between models (i.e. structural uncertainty)?

We explored a range of plausible futures using the scenario framework of the Shared Socio-Economic Pathways (SSP) and Representative Concentration Pathways (RCP) (*19*). 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 and S2): "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) and of land-use change and climate change combined.

We brought together eight models of biodiversity and five models of ecosystem function and services (Table 1, Table S2) (*20*). Depending on the model, up to three biodiversity metrics were calculated (SM Materials and Methods): species richness (S), mean species habitat extent ($\dot{H}$), and species-abundance based biodiversity intactness (I). For ecosystem functions and services, we classified model outputs into nine classes covering a range of provisioning and regulating services (*21*) (Table S1). We calculated the metrics at the grid cell level (α), at the regional level, and at the global level (γ).

Biodiversity projections

The reduction in biodiversity that models estimated to have occurred during the 20th century (0.22-1.13% per decade, range of inter-model means across metrics, Figure 1a) is expected to continue in the coming decades at a slower pace (global sustainability scenario), or to decline at a similar pace (regional rivalry and fossil-fueled development scenarios) when land-use change alone is considered. However, a steeper decline is expected when the combined effects of land-use change and climate change impacts are considered (Figure 1b). The scenario where we are able to stabilize greenhouse gas concentrations and limit climate change to 2°C (global sustainability scenario; Figure S2) projects 40-74% lower biodiversity declines by 2050 than the scenario with no climate mitigation policy (fossil-fueled development) depending on the metric, with bigger differences expected for the second half of this century as the contrast between these scenarios continues to increase (*22*). These patterns are consistent across biodiversity metrics with some notable differences. Reductions in local species richness are of similar magnitude to global species richness changes, while biodiversity metrics based on global habitat extent across species or abundance-based intactness are up to an order of magnitude more sensitive to land-use change (Figure 1b). 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).

Global averages mask some even 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, Central North America, and Madagascar (Figure 2a). In the future, some of these regions, particularly in the tropics, are projected to see further biodiversity losses from land-use change (Figure 2b-d), while some regions start seeing losses for the first time, particularly in the Northern boreal regions as forestry activities increase, and regions in central Africa because of conversion to pasture (Figure S1e). 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 S1c). However, these limited increases in species richness are not enough to noticeably improve biodiversity intactness as many of these regions already incurred significant historical biodiversity losses (Figure S3).

The three future scenarios exhibit important regional contrasts of biodiversity change. 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, a 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 a more globalized world sees biodiversity loss concentrated in Southeast South America, Central Africa, East Africa and South and South-east Asia (Figure 2d). When climate is also considered, the losses are further exacerbated: losses occur in much of the world, and especially concentrated in the highly biodiverse areas in the Neotropics and Afrotropics (Figure 2e-g).

Spatial patterns are broadly consistent across models, although some disagreement exists (Figure S5). When relative changes in species richness are compared with absolute changes (Figure S6), it is apparent that the latter are larger in tropical regions and continents (except Australia), as temperate areas and islands often have lower species richness. However, the majority of the differences in the model-estimated trends are not due to the variation in biodiversity across regions, but to contrasting land-use and climate impacts in those regions, as our biodiversity metrics, the relative local and regional species richness trends, are independent of the initial species richness on those regions (SM Data Files and Figure 4).

Ecosystem service projections

During the 20th century, models estimate material ecosystem services, such as food and timber provisioning, to have increased at the global scale, 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 S1a) 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. Limited change in total ecosystem carbon is anticipated, although in the global sustainability change it increases at a rate of 1% per decade, and by 0.2% per decade in the regional rivalry scenario. The existence of larger increases in the global sustainability scenario are likely due to the slightly faster increase in secondary forest and lower deforestation rates (Figure S1, S7) (*23*).

As with biodiversity, there is high spatial heterogeneity in future ecosystem service dynamics (Figures 4, S10). 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 see increases of 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, such as Western Europe, Eastern Europe, and Central Africa (Figure 4a). However, regional biodiversity declines in most regions, as a consequence of the still significant climate change, and to a lesser extent, land-use change.

There is some inter-model variation in the projections of individual ecosystem services, although the limited number of models that we had for each ecosystem service limits model intercomparisons (Table S2). Models for ecosystem carbon (Figure S8) and timber provisioning (Figure S9) exhibit strong spatial agreement. Still, the global or regional variation between the most contrasting scenarios is often greater than variation between models (eg. for timber production, pollination and nitrogen retention in Fig 3 and for the Caribbean and Southern Africa in Fig. 4).

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, in agreement with recent findings based on single metrics (*14*) and in contrast to an earlier review (*10*). One reason for this finding is that future rates of land-use change are not projected to increase in any of the scenarios examined here relative to the last century rates (Figure S1a). This contrasts with two of the climate change scenarios, where rates of temperature change will still increase in the future (Figure S2). 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 of these impacts (*24*). Biodiversity models typically use empirical relationships at the local scale between habitat conversion and biodiversity responses and project those relationships at larger scales (*25*). In contrast, the impacts of climate are based on statistical models relating current climate with coarse species distribution patterns and assume that those relationships will hold in the future (*26*). 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 in most cases ignore the possibility of local-scale adaptation. In addition, our projections assumed no species migration from climate change in any of the models, while responses to land-use change in some models allowed for species migration or species richness increases (Table S2). Although, observations of dispersal rates suggest they may be closer to no dispersal assumptions than to the full dispersal assumptions (*27*), the differences in projections of biodiversity impacts from climate change between assuming no dispersal or allowing for full dispersal are known to be very large (*28*). For instance, in the AIM model the local average species richness is reduced by 2.6% per decade in the fossil fuel development scenario without dispersal but only by 0.2% under full dispersal (Figures S3, S5). Further research, particularly on model calibration and validation is required to make the projection of land-use and climate-change impacts more comparable, and to ascertain the amount of dispersal that is happening for different taxa.

The differences in the results of the different biodiversity models for similar output metrics with identical land-use and climate-change inputs raises the need for further refinement and calibration of the models. This is a large challenge that will need a combination of new model intercomparisons and additional biodiversity observations at spatial and temporal scales that can be used to calibrate the models (*29*, *30*). In addition, further efforts in refining the land-use categories besides the relatively coarse categories used here are needed. Improving the handling of intra-model uncertainty, and harmonizing the exact biodiversity metrics outputted by the models is important (*20*, *30*). Large inter-model variation also remains for ecosystem services, with the additional challenge of the limited number of global models for regulating services available.

While the inter-model variability, both for biodiversity and ecosystem services models (Fig 1, Fig. 3) is arguably at least as large as the variation between scenarios, it is important to also consider the intra-model projections across scenarios. The projections across scenarios rank in the same direction and relative order for most of the models, suggesting that these are relatively robust to the inter-model uncertainties. In addition, the spatial distribution of biodiversity and ecosystem services trends aggregated into three categories (Fig. 4) also exhibits contrasts between scenarios in several regions greater than the variation between models.

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% (inter-model mean ± SE) 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 (*31*). This estimate is consistent with the 1.0% vertebrate likely extinctions documented by the IUCN during this period (*2*). Some of the documented extinctions have been caused by other 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 (*32*), which suggest that some extinctions from historical land-use change are still forthcoming. In addition, when the projections of two of the multi-taxa models are compared across taxa (Figure S3), the relative ranking of the vulnerability of the taxa is consistent with the ranking of proportion of species threatened in each taxonomic group (*33*), with amphibians the most vulnerable and birds the least vulnerable. However, mammals have the second highest vulnerability among these taxa, but in our models have similar declines to birds, suggesting other causes than land-use may be driving their demise.

The inter-model mean estimate of local species richness change during the last century is -2.2%± 1.7% with one of the models (cSAR-iDiv) even reporting a slight increase. Recent studies have found no statistically significant trends in local species richness in global meta-analyses of community time series (*34*–*36*). The inter-model range of values (Figure 1b) is consistent with such meta-analysis failing to detect a statistically significant trend, either because the signal is too small to be detectable amongst the noise in available time series 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 (*37*, *38*). 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 the implementation of the ambitious goals of the Kunming-Montreal Global Biodiversity Framework of the Convention on Biological Diversity (*39*). Accordingly, extinctions of known threatened species should be halted by 2050 and extinction rates of all species should be reduced tenfold. In addition, ecosystem services declining need to be restored by 2050. The global sustainability scenario comes close to achieving this extinction rate reduction when one only considers the effect of land use, but even the modest climate change in this scenario leads to an acceleration of extinctions. In this scenario we are also able to continue to increase material services while slightly improving the majority of regulating ecosystem services, which have been declining in the last century. These results provide some hope, particularly because the examined scenarios do not deploy all the policies that could be put in place to protect biodiversity and ecosystem services in the coming decades (*17*). For instance, in the global sustainability scenario there is still a loss of pasture and grazing land, which are important habitats for many species, further declines in primary vegetation which is a major global driver of species extinctions (*40*), and bioenergy deployment which despite contributing to mitigate climate change can also reduce species habitats (*41*). Introducing further measures such as further regulation of deforestation, increasing effectiveness of protected areas (*42*), stronger changes in consumption patterns (*43*), and sensible natural climate solutions (*44*), could result in even 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 (*45*, *46*), to identify better development policies and biodiversity management practices.

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Supplementary Materials

Materials and Methods

Figures S1-S10

Tables S1-S4

References (*36-80*)

Data S1-S2

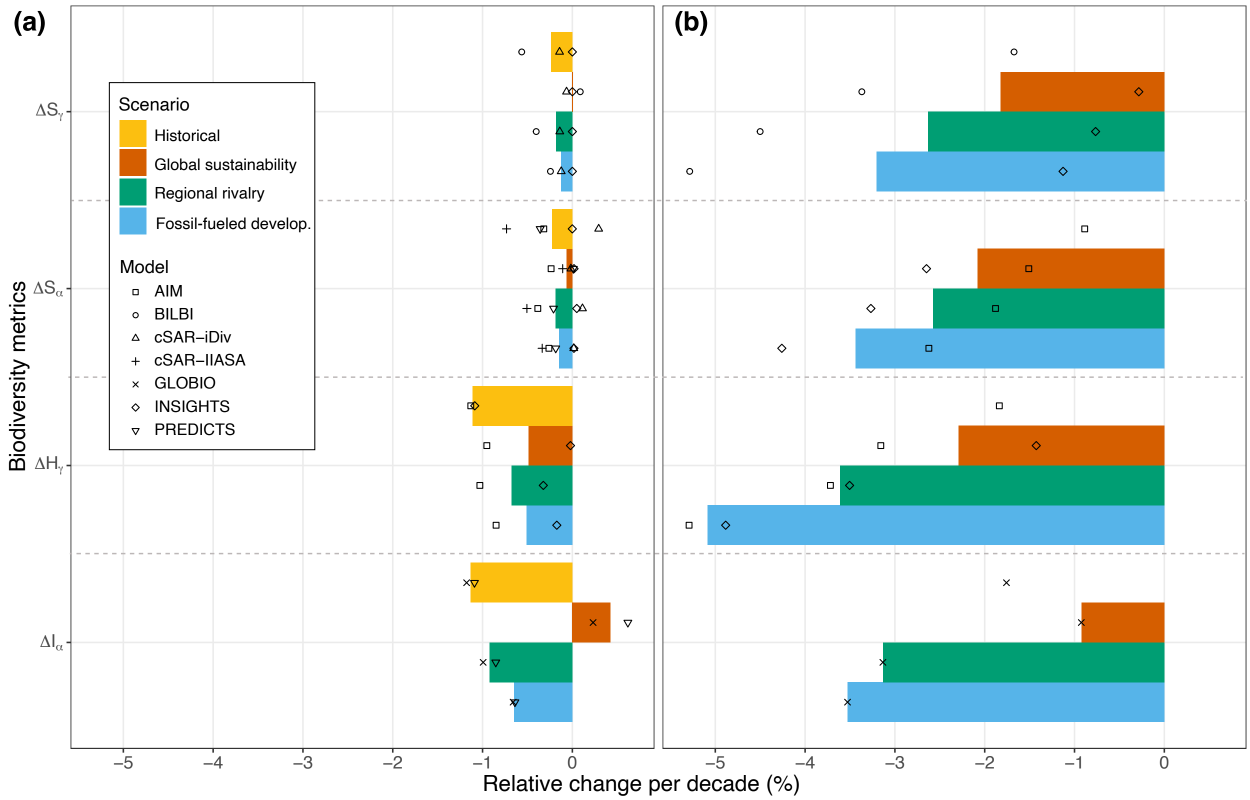


Fig. 1. Historical trends (1900-2015) and projections for each scenario to 2050 of different biodiversity metrics. (a) from land-use change impacts alone; **(b)** from land-use change and climate change impacts combined. Metrics correspond to relative changes per decade in: global species richness (ΔS_γ),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

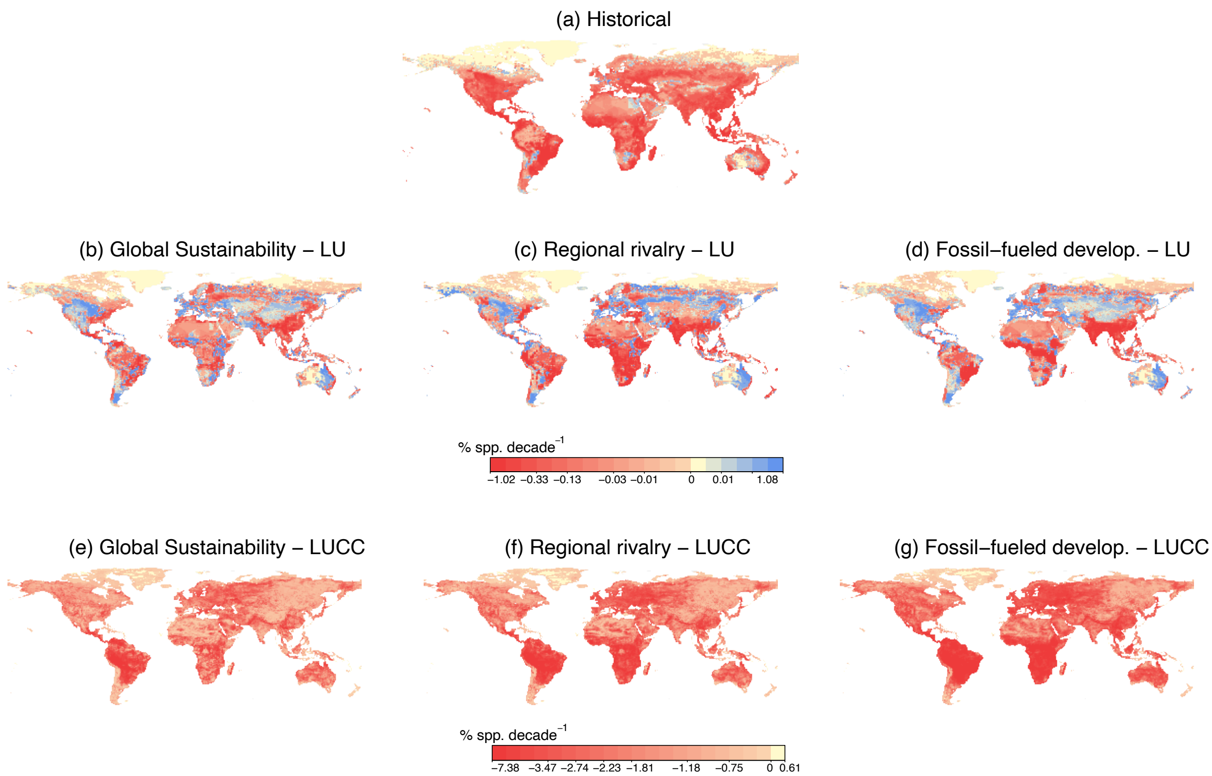


Fig. 2. Spatial distribution of diversity-weighted changes in local species richness (ΔSS_{α}). **(a)** Historical ΔSS_{α} changes from 1900 to 2015 (number of models, N=5). Future species richness changes from 2015 to 2050 driven by land-use change alone in each scenario (**b-d**; N=5) and by land-use 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.

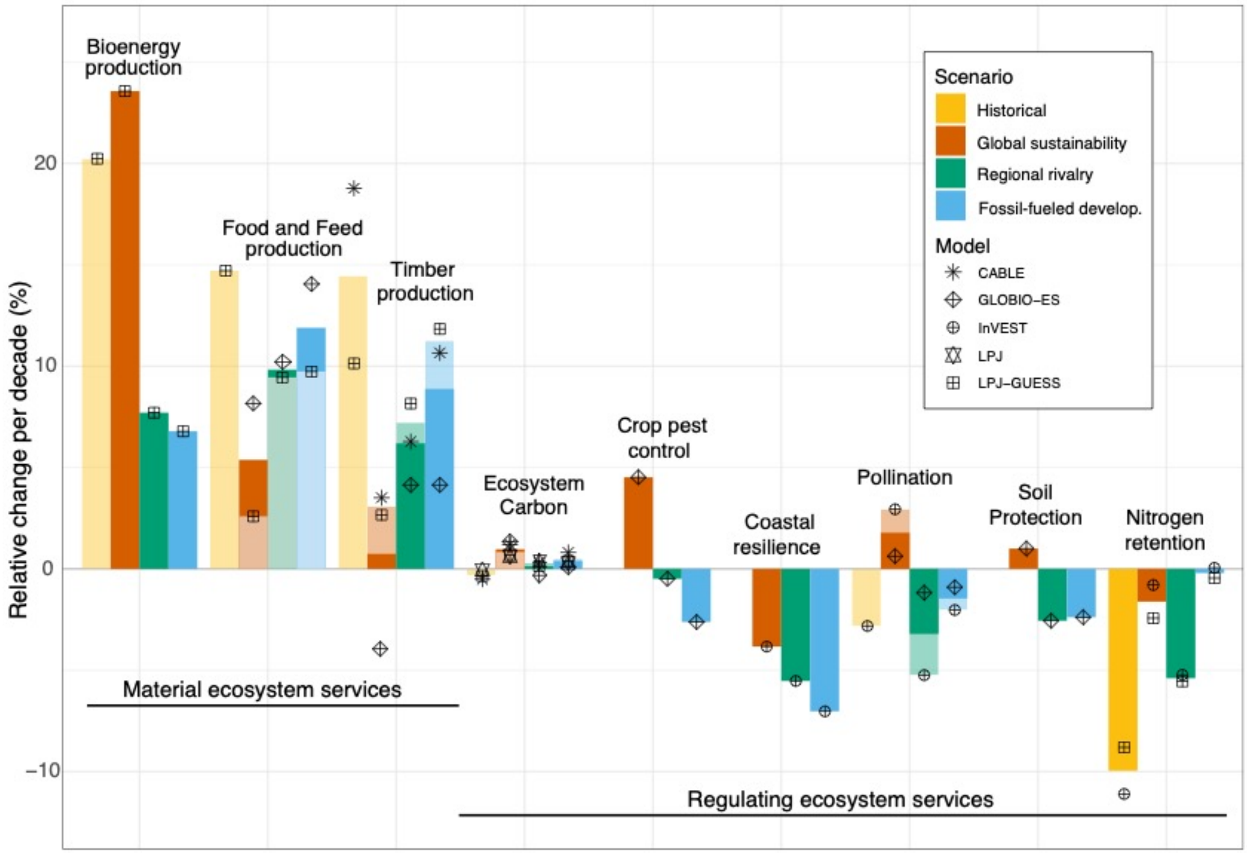


Fig. 3: Historical (1900-2015) rate of changes in material and regulating ecosystem services at the global level and future projections for each scenario (2015-2050). Bars represent means across models, with values for each individual model also shown. Light bars correspond to the subset of models that project historical changes.

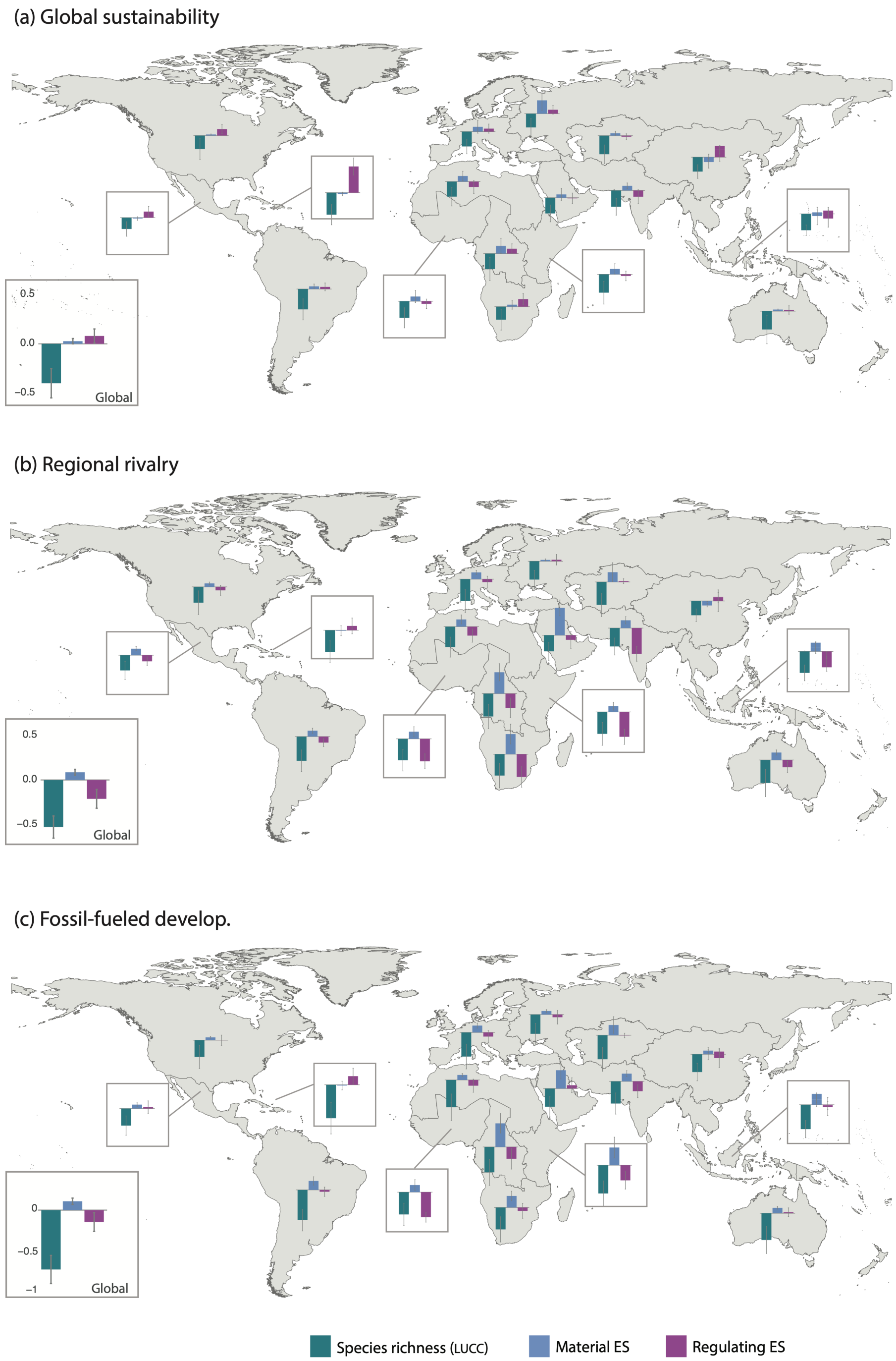
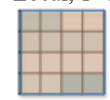
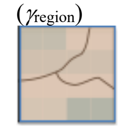
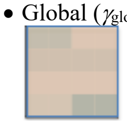


Figure 4. Projected regional and global (insets) changes in biodiversity and ecosystem services from 2015 to 2050. (a) Global Sustainability, (b) Regional rivalry, (c) Fossil-fueled development. Barplots show the average of the normalized values across biodiversity, material ecosystem service, and regulating 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. Bar 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. Error bars are standard errors. Maps in equirectangular projection.

Table 1. Brief description of the scenarios, models, and metrics. For more information see SM or (*21*).

Scenarios	Model	Metrics	Spatial scale of model output
SSP1xRCP2.6, Global sustainability 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. **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 non-forest birds cSAR-IIASA-ETH: countryside species-area relationship model for species richness of amphibians, birds, mammals, plants and reptiles BILBI: a generalized dissimilar modelling framework coupled with a species-area relationship to estimate species richness of plants PREDICTS: a mixed-effect model for species richness and community intactness of vertebrates GLOBIO: a dose-response model for community intactness	• Species richness (S), reported as relative change ($\Delta S = (S_{t1} - S_{t0})/S_{t0}$) or as absolute change ($\Delta SS = S_{t1} - S_{t0}$) • Mean species habitat extent ($\dot{H}$), reported as relative change in the habitat extent of each species $\Delta\dot{H} = \sum_{i=1}^{S}(H_{i,t1} - H_{i.t0})/H_{i.t0}/S$, • Species-abundance based intactness (I), reported both in absolute values and as relative change	• Local, 1º cell (α)  Global mean α values reported as spatial area weighted averages across grid cells (e.g. $\overline{\Delta S_{\alpha}}$) • Regional, 17 IPBES regions, (γ_{region})  • Global (γ_{global}) 
Land-use data 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 **Climate data** 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	**Ecosystem functions and services models** LPJ-GUESS: dynamic global vegetation model LPJ: dynamic global vegetation model CABLE-POP: dynamic global vegetation model GLOBIO-ES: a suite of geographic information system-based ecosystem functions and services models InVEST: a suite of geographic information system based ecosystem functions and services models	All ecosystem services metrics are reported as relative changes ($\Delta ES = (ES_{t1} - ES_{t0})/ES_{t0}$) **Material services** • Bioenergy production • Food and feed production • Timber production **Regulating services** • Ecosystem carbon • Crop pest control • Coastal resilience • Pollination • Soil protection • Nitrogen retention	

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Supplementary Materials for

Declines in terrestrial biodiversity and regulating services driven by land-use change can be slowed but climate change impacts are accelerating

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Figs. S1 to S10
Tables S1 to S4

Other Supplementary Materials for this manuscript include the following:

Data S1 to S3

Materials and Methods

This study was conducted under the auspices of the Expert Group on Scenarios and Models of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). The detailed protocol of this multi-model study was published in (*20*). Below we summarize the main methodological aspects.

Scenarios

All models used the same set of scenarios: SSP1xRCP2.6 ("global sustainability") with low land-use pressure and low level of climate change (*47*), SSP3xRCP6.0 ("regional rivalry") with high land-use pressure and intermediate level of climate change (*48*), and SSP5xRCP8.5 ("fossil-fueled development") with intermediate land-use pressure and high level of climate change (*49*) – to assess a broad range of plausible futures (Table S1). We used land-use projections for these scenarios ignoring the impacts of climate change, although the deployment of land-based climate mitigation strategies is considered in connection to each of the SSP-RCP combinations. Land-use projections for SSP3xRCP6.0 were not available, so we chose the closest land-use projections available, SSP3xRCP7.0.

Land use data

All models used the Land Use Harmonization (*50–54*) version 2 dataset (LUH2, see http://luh.umd.edu/data.shtml for data). LUH2 provides global gridded land-use datasets at 0.25° resolution with annual time-steps comprising estimates of historical land-use change (850-2015) and future projections (2015-2100) under the assumptions of each Shared Socio-economic Pathway (SSP) (*55*). The 12 land use categories (Table S3) include the separation of primary and secondary natural vegetation into forest and non-forest sub-types, pasture into managed pasture and rangeland, and cropland into multiple crop functional types (C3 annual, C3 perennial, C4 annual, C4 perennial, and C3 nitrogen-fixing crops). The LUH2 dataset also computes all transitions between these 12 land use types, resulting in over 100 possible transitions per grid cell per year (e.g., crop rotations, shifting cultivation, agricultural changes, wood harvest) as well as various agricultural management layers (e.g., irrigation, synthetic nitrogen fertilizer, biofuel crops). Due to specific model parameterizations, each biodiversity and ecosystem service model used its own aggregation of the land use categories (Table S4).

Climate data

Models used historical climate data and future projections associated with each SSPxRCP combination (*22*) from CMIP5 / ISIMIP2a (*56*) or its downscaled version from the WorldClim (*57*), or the projections from MAGICC 6.0 (*58*, *59*) (Table S4). Most models used the IPSL-CM5A-LR (*60*) projections which are mid-range across the 5 GCMs in ISIMIP2a (*61*) – that includes 12 climate variables at 0.5° resolution on daily time steps from the pre-industrial period 1951 to 2099 (*56*). The WorldClim downscaled dataset has 19 bioclimatic variables monthly from 1960 to 1990 and multi-year averages for specific points in time (e.g., 2050, 2070) up to 2070 at 1km resolution. MAGICC 6.0 climate data (*58*, *59*) in the IMAGE model framework (*62*) was used for the GLOBIO model.

Additional sources of data

Some models used additional information besides land-use data and climate data, including population density, road density, soil data, agricultural yields, topography, nitrogen deposition and others (Table S4). In addition, several of the models used data from LUH2 besides the 12 land-use categories, such as wood harvest, biofuel fraction, and crop irrigated fraction Table S4).

Biodiversity models

All models have been published in peer-reviewed journals (see Table S2 with key references provided for each model), although in some cases modifications have been made to the original model (see (*20*) for details about modifications). In total, 8 spatially-explicit models were used, these include three species distributions models - AIM-biodiversity, InSiGHTS, MOL; and five community models (cSAR-iDiv, cSAR-IIASA-ETH, BILBI, PREDICTS, GLOBIO. Three of these models, BILBI, PREDICTS and cSAR-iDiv share coefficients for the impacts of land-use on biodiversity from the PREDICTS database (*63*). The biodiversity models have different methodological approaches, taxonomic groups, spatial resolution and output metrics (Table S2), but they were harmonized as described below.

Ecosystem services models

For ecosystem functioning and services, five spatially-explicit models were used (see Table S2 with key references provided for each model). They include three process-based DGVM models – LPJ-GUESS, LPJ, and CABLE-POP – and two ecosystem services models – InVEST and GLOBIO-ES. These rely on different modelling approaches to estimate a wide range of biophysical outputs, which were harmonized as described in the next sections.

Scales of analysis (local, regional and global), harmonization of metrics, and time scales

Model outputs were produced at three spatial scales: one-degree grid cells (α metrics), at the regional level (regional γ metrics) for the 17 IPBES sub-regions (*64*), and at the global level (global γ metrics). The IPBES regions are: Caribbean, Central Africa, Central and Western Europe, Central Asia, East Africa, Eastern Europe, Mesoamerica, North Africa, North America, North East-Asia, Oceania, South America, South Asia, South-East Asia, Southern Africa, West Africa and Western Asia

The methodology adopted by each modelling team to aggregate from the original resolution of the model to one-degree cells was the arithmetic average of the values in the original resolution.

The model outputs addressed very different facets of biodiversity (e.g., species ranges, local species richness, global species extinctions, abundance-based intactness, and compositional similarity), as well as different facets of ecosystem services (e.g., pollination, carbon sequestration, soil erosion, wood production, nutrient export, coastal vulnerability), often with little overlap between different models. In addition, even for the same facet of biodiversity or ecosystem service, different models outputted different metrics. In order to ensure comparability, output metrics for each model were converted to proportional changes relative to the beginning time of the analysis (e.g., $\Delta y = \frac{y_{t1}-y_{t0}}{y_{t0}}$), where y_t is the value of the metric at time *t*, and t_0 and t_1 are respectively the beginning and the end of the time period. In addition, models that simulated a continuous time series of climate change impacts calculate y_t as 20-year averages around the midpoint *t* in order to account for inter-annual variability.

Most analysis were carried out either for historical changes from 1900 to 2015 or for future changes from 2015 to 2050. In order to compare the longer historical period (1900-2015) with the shorter scenarios period (2015-2050) we report % changes per decade. These are obtained as $[(\Delta y + 1)^{\wedge}(1/\Delta t)\text{-}1]*100$ where Δt is the time period measured in decades. In selected figures we provide additional time steps: in Fig S1(a) we provide land-use change values at decadal intervals; in Fig S2(a) we provide mean temperature values in yearly steps and 20-year averages centered in 1910, 1935, 1960, 1990, 2015 and 2050.

Biodiversity metrics

Outputs of each biodiversity model were assigned to one or more of the following harmonized biodiversity metrics (Table S2): species richness (S), mean species habitat extent ($\dot{H}$), and species-abundance based biodiversity intactness (I). The habitat extent metric for each species is typically calculated by species distribution models, as a intersection of the species climate-based range and habitat suitability (*65*, *66*). To provide an integrated metric across species, we calculate averages across species. Species-abundance biodiversity intactness is reported by community models and is a metric of impact of humans on biodiversity (*67*). It can be defined as the average abundance of species in site, relative to abundance in an undisturbed habitat (*63*, *68*).

While all metrics were reported as proportional changes relative to the beginning of a time period, intactness was also reported as an absolute score (relative to a pristine baseline). For mapping purposes, local changes in proportional species richness were converted in normalized changes in absolute species richness (ΔSS), by multiplying by the number of species in each cell and then dividing by the number of species in the richest cell. Global spatial averages of the local metrics were calculated across all terrestrial one-degree cells and are denoted with an overbar (e.g. $\overline{\Delta S_{\alpha}}$) to distinguish it from averages of a metric across species ($\dot{H}$).

All five community-based models (i.e. cSAR-iDiv, cSAR-IIASA, BILBI, PREDICTS, GLOBIO) are based on empirical responses of community composition (as measured by species richness or another indicator such as mean species abundance) to each land-use type, relative to native habitat, often measured at the site level at very small scales (e.g. 1 ha). To scale up these community composition responses to the grid-cell level (our α scale), cSAR-iDiv and cSAR-IIASA use the species area relationship, while PREDICTS uses a linear scaling, based on the relative fraction of the grid-cell covered by each habitat type (*69*). Everything else being equal, the species-area relationship approach tends to project smaller relative changes than the linear method for this kind of upscaling (*69*), but the habitat affinities and the number of species groups used also have an influence, and they all differ between the three models. BILBI, cSAR-iDiv and cSAR IIASA also scale up site-level responses to whole sub-continental regions and the globe (γ regional and γ global). For species distribution models (INSIGHTS, AIM, and MOL) the intersections of the species range with the habitat suitability and climate envelopes, is integrated across species for each spatial level of analysis, and no scaling relationships are needed. However, this kind of stacking of species distribution models ignore species interactions and may underestimate species declines at the grid cell level, as the species only disappear when either no suitable habitat or suitable climate is available anywhere in a grid cell.

In the end, the harmonized metrics analyzed were:

- $\Delta S_{\alpha}(x,y) = \frac{S_{\alpha}(x,y,t1) - S_{\alpha}(x,y,t0)}{S_{\alpha}(x,y,t0)}$, where $S_{\alpha}(x,y,t)$ is the number of species at cell (x,y) at time *t*;

- $\Delta SS_\alpha(x,y) = \Delta S_\alpha(x,y) \times \frac{S(x,y)}{Mean_{\{x,y\}}[S(x,y)]}$, where $S(x,y)$ is the number of species at cell (x,y) calculated from current species distribution maps, and the mean value is calculated across all cells;
- $\Delta S_\gamma(region) = \frac{S_\gamma(region,t1) - S_\gamma(region,t0)}{S_\gamma(region,t0)}$, where $S_\gamma(region, t)$ is the number of species in an IPBES sub-region or in the globe at time t;
- $\Delta \dot{H}_\gamma = \frac{1}{S\gamma}\sum_{i=1}^{S\gamma} \frac{H_\gamma(i,t1,i) - H_\gamma(i,t0)}{H_\gamma(i,t0)}$, where $H_\gamma(i,t)$ is the global habitat extent of species *i* at time *t*;
- $I_\alpha(x,y,t)$, which is the species-abundance based intactness value for cell (x,y) at time *t* relative to a pristine baseline, with 100% corresponding to a pristine habitat and 0% to a completely degraded habitat.

In addition, global spatial averages for α metrics were calculated using area-weights as follows:

- $\overline{\Delta S_\alpha} = \sum_{x,y} \Delta S_\alpha(x,y)\ w_{x,y}$
- $\overline{I_\alpha} = \sum_{x,y} I_\alpha(x,y)\ w_{x,y}$

where $w_{x,y}$ is the area of each one-degree cell divided by the global land surface area. Finally, metrics were reported as % changes standardised by the number of years between the beginning (t_0) and end (t_1) of the considered time period.

The harmonized biodiversity metrics need to be interpreted with care as the original model outputs mapped to the same harmonized metric can differ in some technical details. For instance, the GLOBIO model (*16*) outputs a metric called "Mean Species Abundance" (MSA) that is obtained " by dividing the abundance of each species found in relation to a given pressure level by its abundance found in an undisturbed situation within the same study, truncating the values at 1, and then calculating the arithmetic mean over all species present in the reference situation"; likewise the PREDICTS model (*70*) outputs a metric called "Abundance-based Biodiversity Intactness Index (BIIAb)" that represents "the average abundance of originally present species across a broad range of species, relative to abundance in an undisturbed habitat". While both metrics have been harmonized as representing species-abundance based intactness (*I*), they are calculated differently in the models (i.e., the former is the average of abundance ratios while the latter is the ratio of the sums). Similarly, models based on the countryside species-area relationship (*71*) produced similar metrics (relative change in species richness) but were calibrated for different taxonomic groups, and with different numbers of habitat affinity groups (Table S2).

Ecosystem services metrics

A similar effort was made to assign the metrics outputted by the ecosystem function and services models to a set of harmonized metrics (Table S2). We used the typology of the IPBES Nature's Contributions to People (NCPs) (*21*) to classify material and regulating services. For each of the following ecosystem services we assigned one biophysical metric from one or more models, sometimes changing the sign of the reported metric for consistency: bioenergy production; food and feed production; timber production; ecosystem carbon; crop pest control (more is better control); coastal resilience (more is greater resilience); pollination; soil protection; nitrogen retention (more is higher water quality).

The dynamic global vegetation models (DGVMs) tend to output similar metrics and have similar assumptions (*72*), but the two ecosystem service models (GLOBIO and InVEST) tended to output different metrics for the same service. DGVMs have been used in the climate change modeling community for decades so they benefit from a long history of multi-model inter-comparison (*73*). Therefore, while for certain metrics, such as ecosystem carbon pool, the metrics are calculated in a similar way and use equivalent biophysical units (e.g. Kg C), for other metrics, e.g., pollination, direct comparison of absolute values was not feasible. For instance, GLOBIO-ES (*74*) defines their metric of pollination services as the fraction of cropland potentially pollinated, relative to all available cropland, but InVEST (*75*) defines it as the proportion of agricultural lands whose pollination needs are met by sufficient amounts of natural habitat within the flight range of pollinators. As for biodiversity metrics, this issue was addressed by using proportional changes of each metric in each model at each scale of analysis.

At the grid cell level (α), proportional changes for ecosystem services were calculated as:

- $\Delta ES_{\alpha}(x,y) = \frac{S_{\alpha}(x,y,t1) - S_{\alpha}(x,y,t0)}{S_{\alpha}(x,y,t0)}$, where $ES_{\alpha}(x,y,t)$ is the total service (e.g., Ecosystem Carbon) at cell (x,y) at time t;

At the regional (γregion) or global (γglobal) proportional changes for ecosystem services were calculated as

- $\Delta ES_{\gamma}(region) = \frac{ES_{\gamma}(region,t1) - ES_{\gamma}(region,t0)}{ES\gamma(region,t0)}$, where $ES_{\gamma}(region,t)$ is the level of the service estimated for the whole region or for the globe at time t.

It is important to note that, in contrast with biodiversity metrics, there is a simple way of scaling α estimates to regional or global γ estimates for most ecosystem services: the relative change at the γ level can be calculated by first summing for a region the area-weighted absolute values of the ecosystem service in each cell $ES_{\alpha}(x,y,t)$ at each time step, and then calculating the relative change of those summed values. In addition, these sums can even be interpreted in many cases at the value of the ecosystem level at the regional or global level $ES_{\gamma}(region,t)$.

Comparison of biodiversity, regulating and material ecosystems services

To understand how biodiversity and ecosystem services varied concurrently in each IPBES sub-region (Figure 4) we mapped regional changes in biodiversity and in aggregated regulating and material ecosystem services, from 2015 to 2050 for all three scenarios. First, we normalized changes in regional species richness (ΔS_{γ}) and ecosystem service metrics for all scenarios and regions, by dividing the proportional changes for each sub-region and scenario and model metric by the maximum value of that metric for all subregions in all scenarios. In this way, we obtained a normalized ΔY with values between -1 and +1 for biodiversity or ecosystem service metric in each region and scenario. Next, we clustered all normalized model values into biodiversity metrics, material ecosystem services and regulating ecosystem services.

Intermodel means

For each metric for which comparable projections from multiple models exist, we calculated the means and standard error of the means, reporting as mean ± SE. Therefore, all models were treated equally in the analysis. For some models reporting metrics for more than one taxonomic group or sub-group (AIM, cSAR-IIASA, cSAR-iDiv), we report the average value across taxa weighted by the species richness of the taxonomic group.

Maps

All maps are in equirectangular projections (i.e. geographic coordinates).

Data and code

All the outputs of the models used in this analysis are publicly available. The maps outputted by the models are available from the GEO BON EBV portal, as follows

- BES-SIM GLOBIO, https://doi.org/10.25829/r7bt92
- BES-SIM PREDICTS, https://doi.org/10.25829/vt7qk9
- BES-SIM cSAR-IIASA, https://doi.org/10.25829/haq7d4
- BES-SIM cSAR-iDiv, https://doi.org/10.25829/5zmy41
- BES-SIM AIM, https://doi.org/10.25829/5wn357
- BES-SIM INSIGHTS, https://doi.org/10.25829/h2evr2
- BES-SIM LPJ-GUESS, https://doi.org/10.25829/z5v9t2
- BES-SIM LPJ, https://doi.org/10.25829/xq7a86
- SIM CABLE POP, https://doi.org/10.25829/ktnb68
- BES-SIM InVEST, https://doi.org/10.25829/zr4d27
- BES-SIM GLOBIO-ES, https://doi.org/10.25829/vqd4s4

All non-spatial metrics from the biodiversity models and ecosystem services are available as .xlsx files, Biodiversity.xlsx (Data S1), EcosystemServices.xlsx (Data S2), while all the code in R to produce the figures from the model outputs is available as a zip file (Data S3.zip)

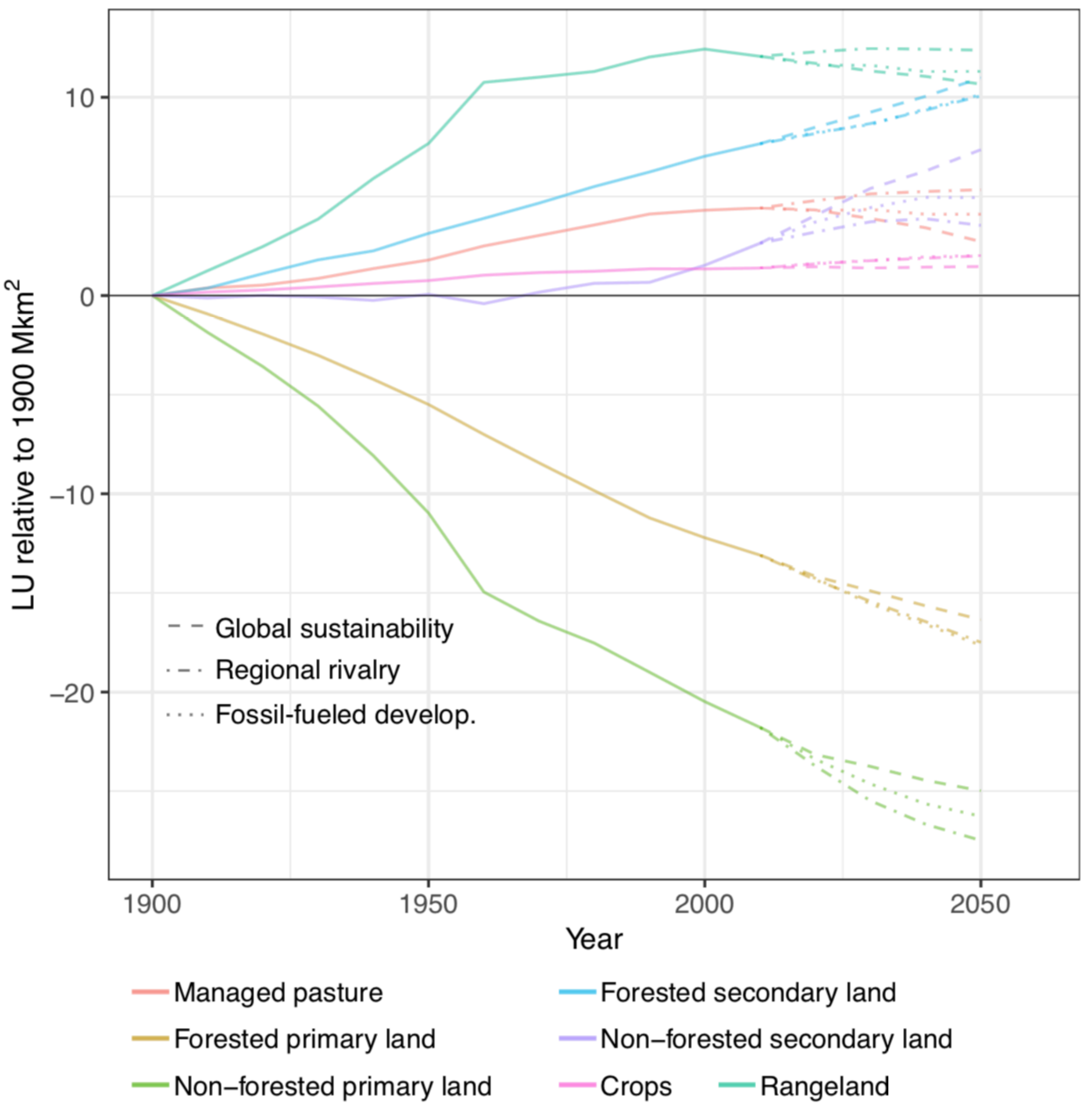

Fig. S1. (a) Global historical trends (1900-2015) in land-use and projected trends for each scenario (2015-2050). Lines correspond to absolute area changes relative to the year 1900. The original area covered by each land-use in 1900 was: forested primary land (36.0 Mkm^2), non-forested primary land (50.7 Mkm^2), forested secondary land (6.3 Mkm^2), non-forest secondary land (11.8 Mkm^2), managed pasture (3.5 Mkm^2), rangeland (12.9 Mkm^2), cropland (9.5 Mkm^2).

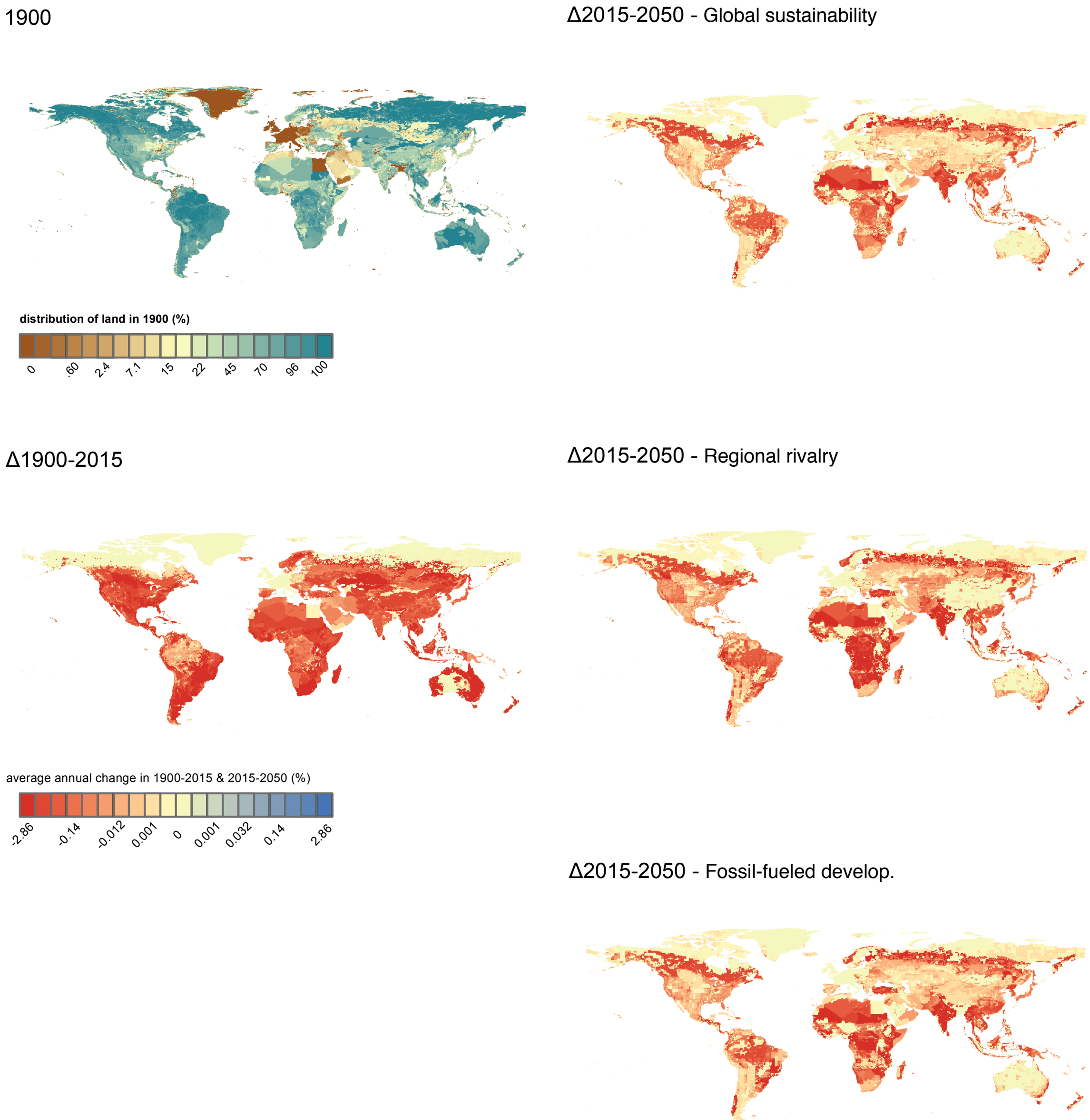

Figure S1 (b) Distribution of primary land (forest & non-forest) in 1900, historical changes (1900-2015) and future changes (2015-2050) in each scenario. Please note that changes are reported in absolute percentage points (i.e., y_{t1}-y_{t0} where y is the percentage of the area in a cell covered by that land use type). Color scales are based on quantile intervals considering all land cluster types for i) 1900 and ii) the past (Δ1900-2015) and future (Δ2015-2050) combined.

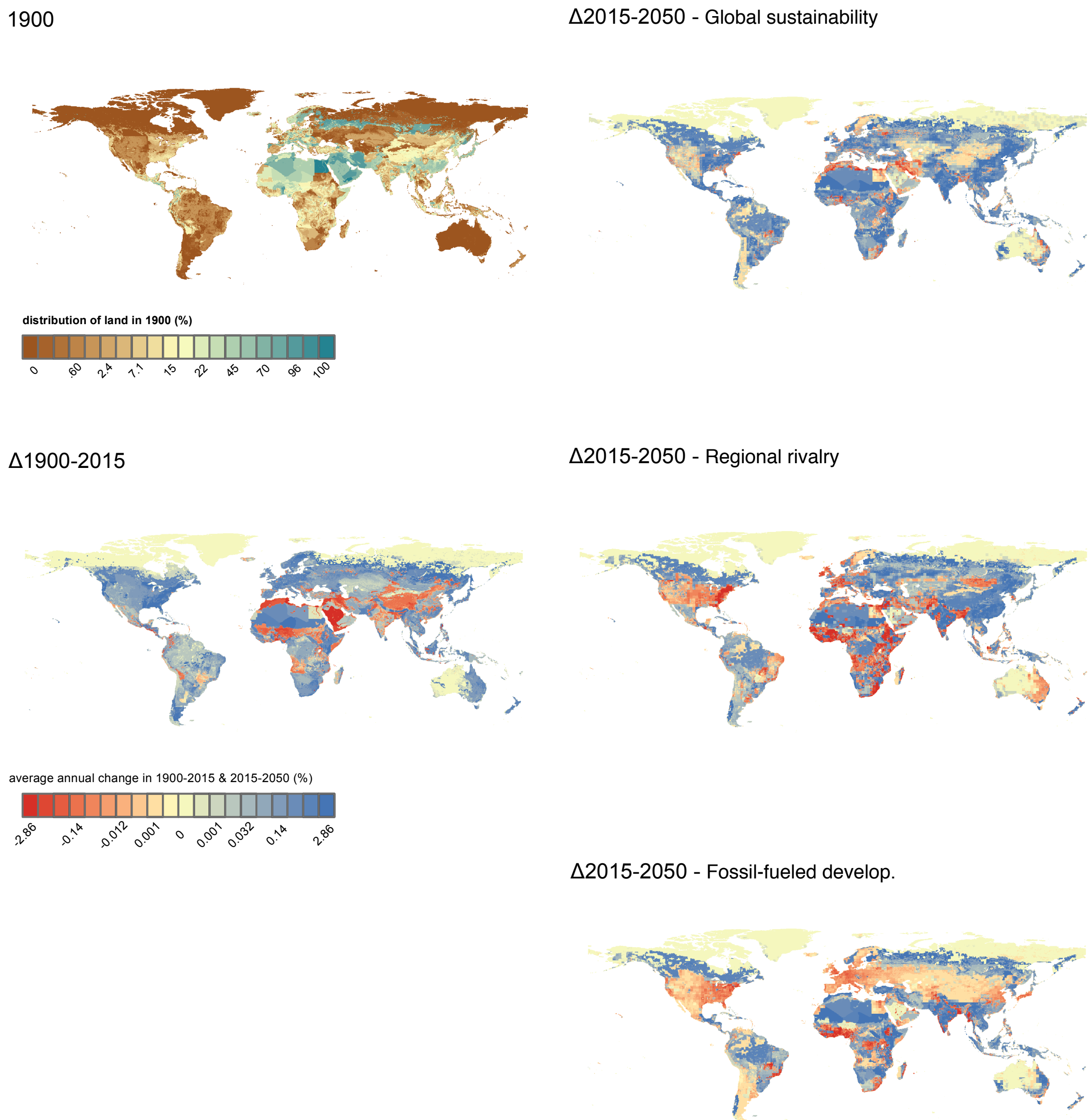

Figure S1 (c) Distribution of secondary land (forest & non-forest) in 1900, historical changes (1900-2015) and future changes (2015-2050) in each scenario. Please note that changes are reported in absolute percentage points (i.e. y_{t1}-y_{t0} where y is the percentage of the area in a cell covered by that land use type). Color scales are based on quantile intervals considering all land cluster types for i) 1900 and ii) the past (Δ1900-2015) and future (Δ2015-2050) combined.

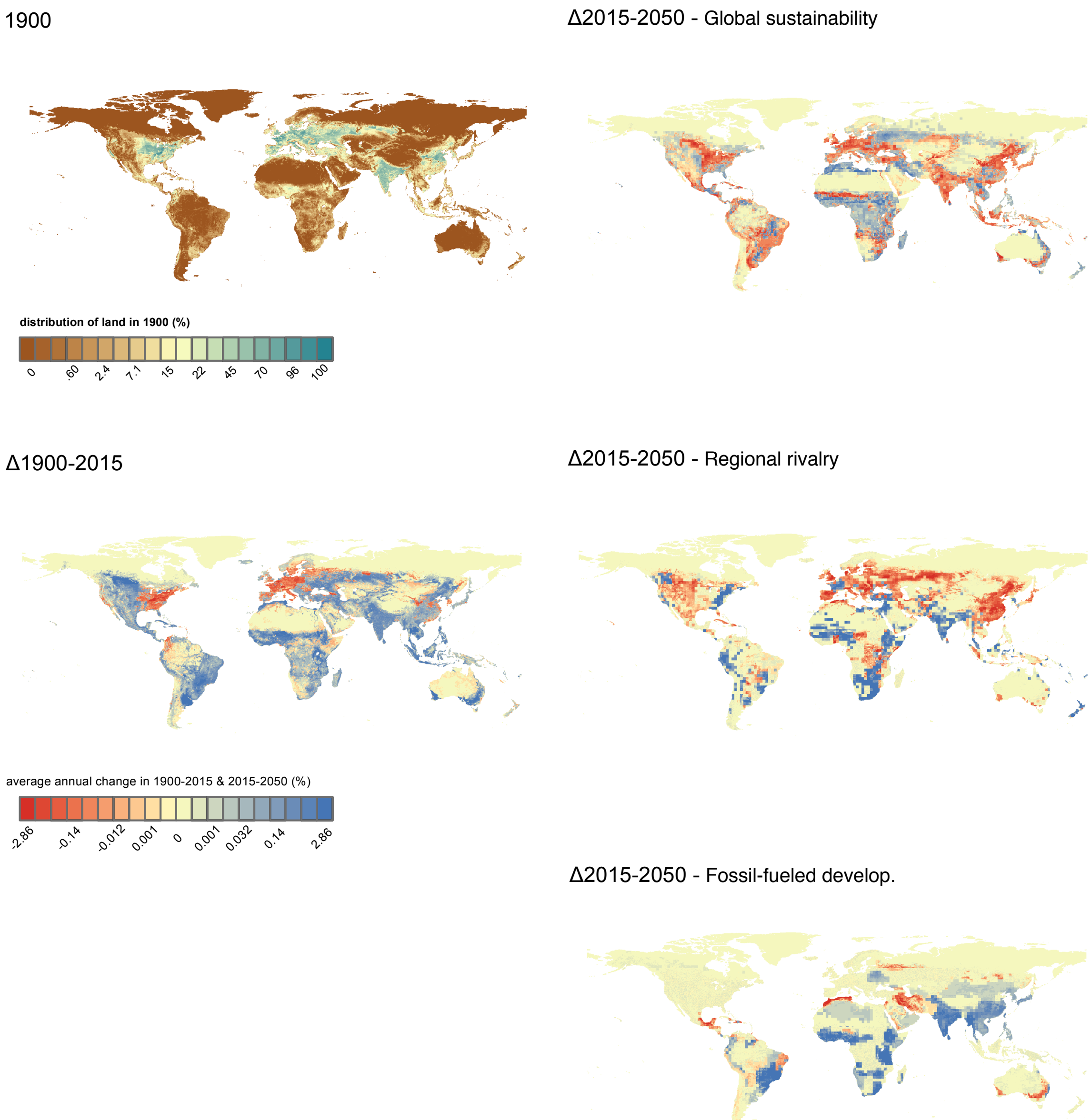

Figure S1 (d) Distribution of cropland (C3 & C4) in 1900, historical changes (1900-2015) and future changes (2015-2050) in each scenario, in percentage. Please note that changes are reported in absolute percentage points (i.e. y_{t1}-y_{t0} where y is the percentage of the area in a cell covered by that land use type). Color scales are based on quantile intervals considering all land cluster types for i) 1900 and ii) the past (Δ1900-2015) and future (Δ2015-2050) combined.

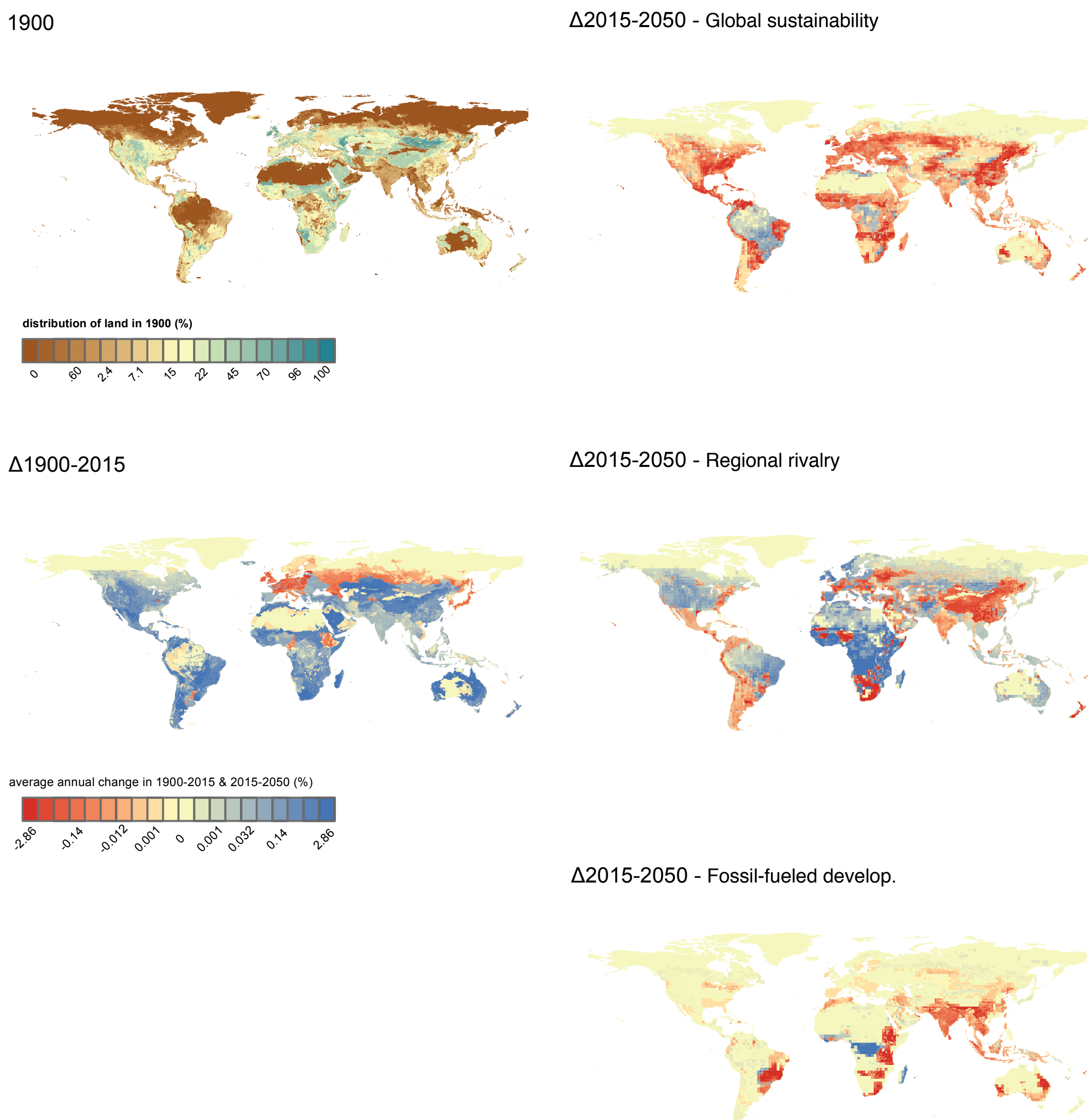

Figure S1 (e) Distribution of pasture and rangeland in 1900, historical changes (1900-2015) and future changes (2015-2050) in each scenario, in percentage. Please note that changes are reported in absolute percentage points (i.e. y_{t1}-y_{t0} where y is the percentage of the area in a cell covered by that land use type). Color scales are based on quantile intervals considering all land cluster types for i) 1900 and ii) the past (Δ1900-2015) and future (Δ2015-2050) combined.

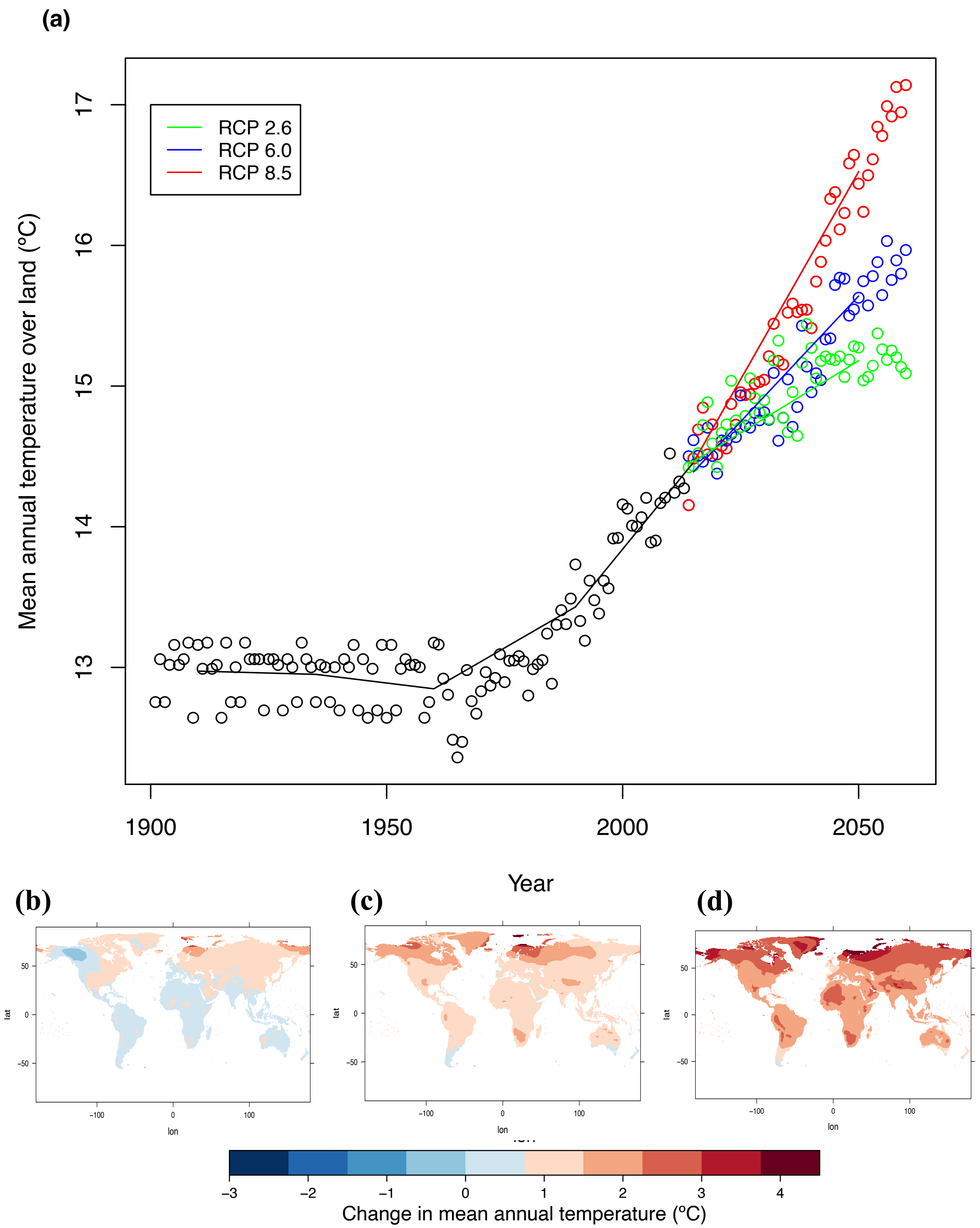

Fig. S2. (a) Global historical trends (1990-2015) in mean annual temperature and for each scenario (2015-2050). Spatial distribution of absolute changes in mean annual temperature in each scenario (2015-2050): **(b)** global sustainability - RCP2.6, **(c)** regional rivalry - RCP6.0, **(d)** fossil-fueled development - RCP8.5.

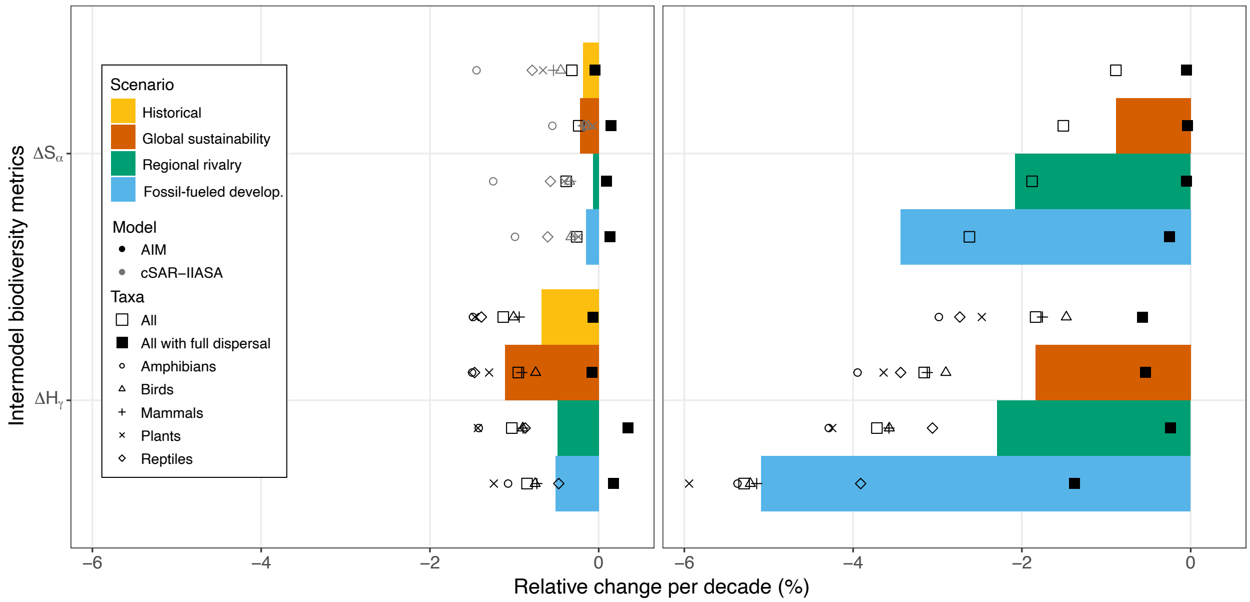

Fig. S3 Historical trends in biodiversity since 1900 and future projections for each scenario to 2050. Change in different dimensions of biodiversity for the historical period (1900-2015) and for each future scenario (2015-2050) with values for each taxon displayed for two models: **(b)** from land-use alone; **(c)** from land-use change and climate change combined. Metrics correspond to proportional changes 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 ($\overline{\Delta I_\alpha}$). Colored bars are means across models.

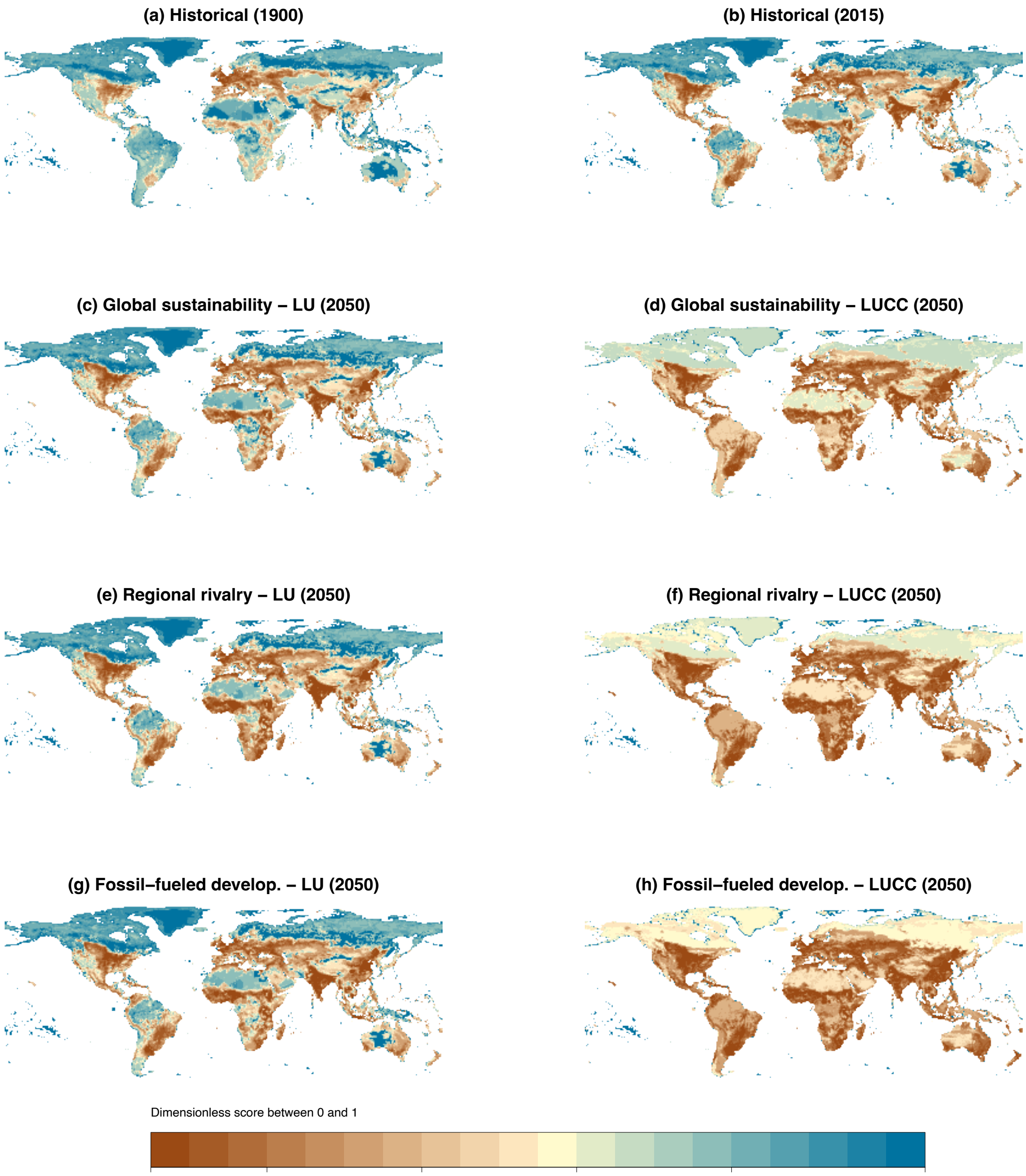

Fig. S4. Spatial distribution of intactness (*I*): **(a)** year 1900; **(b)** 2015; **(c-d)** 2050 in the fossil-fueled development scenario based on land-use change alone **(c)** and on the combined impacts of land-use change and climate **(d)**. Values correspond to the inter-model mean between PREDICTS and GLOBIO, except for **(d)** which is based only on GLOBIO. Values are scores relative to a pristine baseline (a score of 1 corresponds to pristine, while a score of 0 corresponds to fully degraded). Color scale is based on quantile intervals when considering all maps features. Projections for other scenarios for each model are available from http://portal.geobon.org.

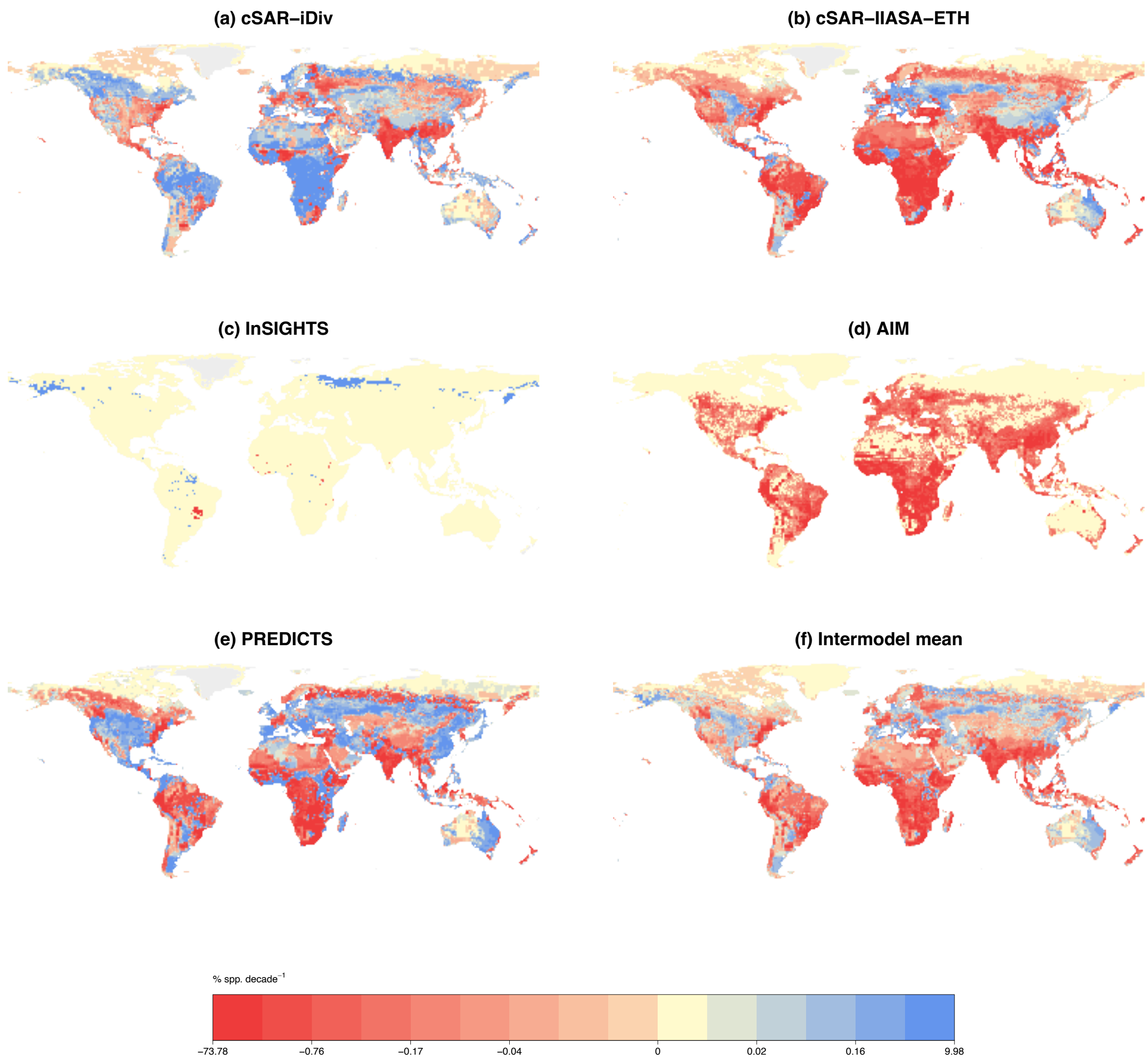

Fig. S5. Spatial agreement between biodiversity models. Projection of normalized changes in local species richness per year (ΔSS_{α}) during 2015-2050 caused by land-use change alone for the regional rivalry scenario: **(a)** cSAR-iDiv model; **(b)** cSAR-IIASA-ETH model; **(c)** InSIGHTS model; **(d)** AIM-B model; **(e)** PREDICTS model; **(f)** inter-model mean. A value of 1% yr^{-1} corresponds to a decline in the number of local species equal to 1% species of the most speciose grid cell. Color scale is based on quantile intervals when considering all maps features.

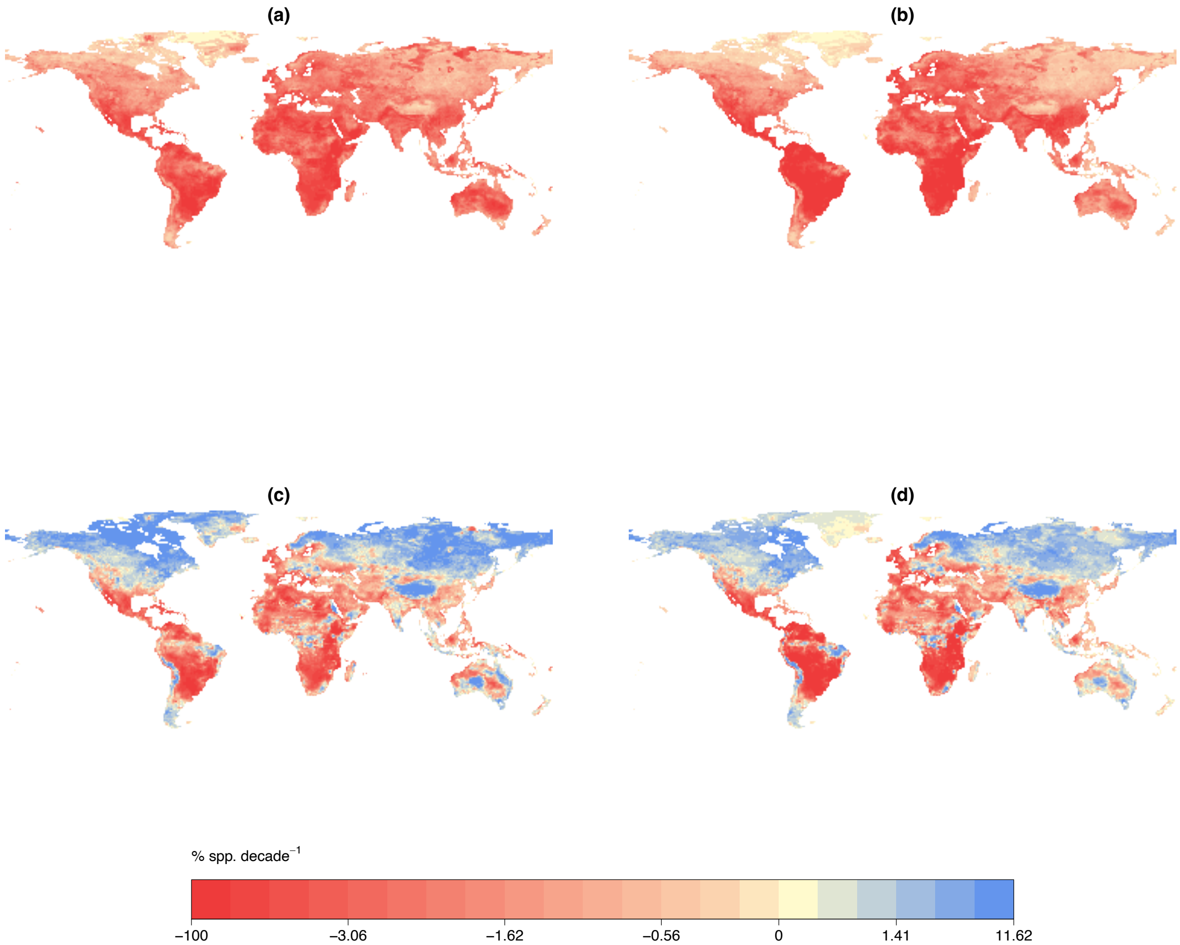

Fig. S6. Biodiversity metrics of the AIM model for the fossil fueled development scenario for 2015-2050: assuming species cannot disperse (a) and (b); assuming species can disperse without any limits (c) and (d). **(a) and (c)** proportional changes in local species richness (ΔS_{α}); **(b) and (d)** normalized changes in local species richness per year (ΔSS_{α}). Color scale is based on quantile intervals when considering all maps features.

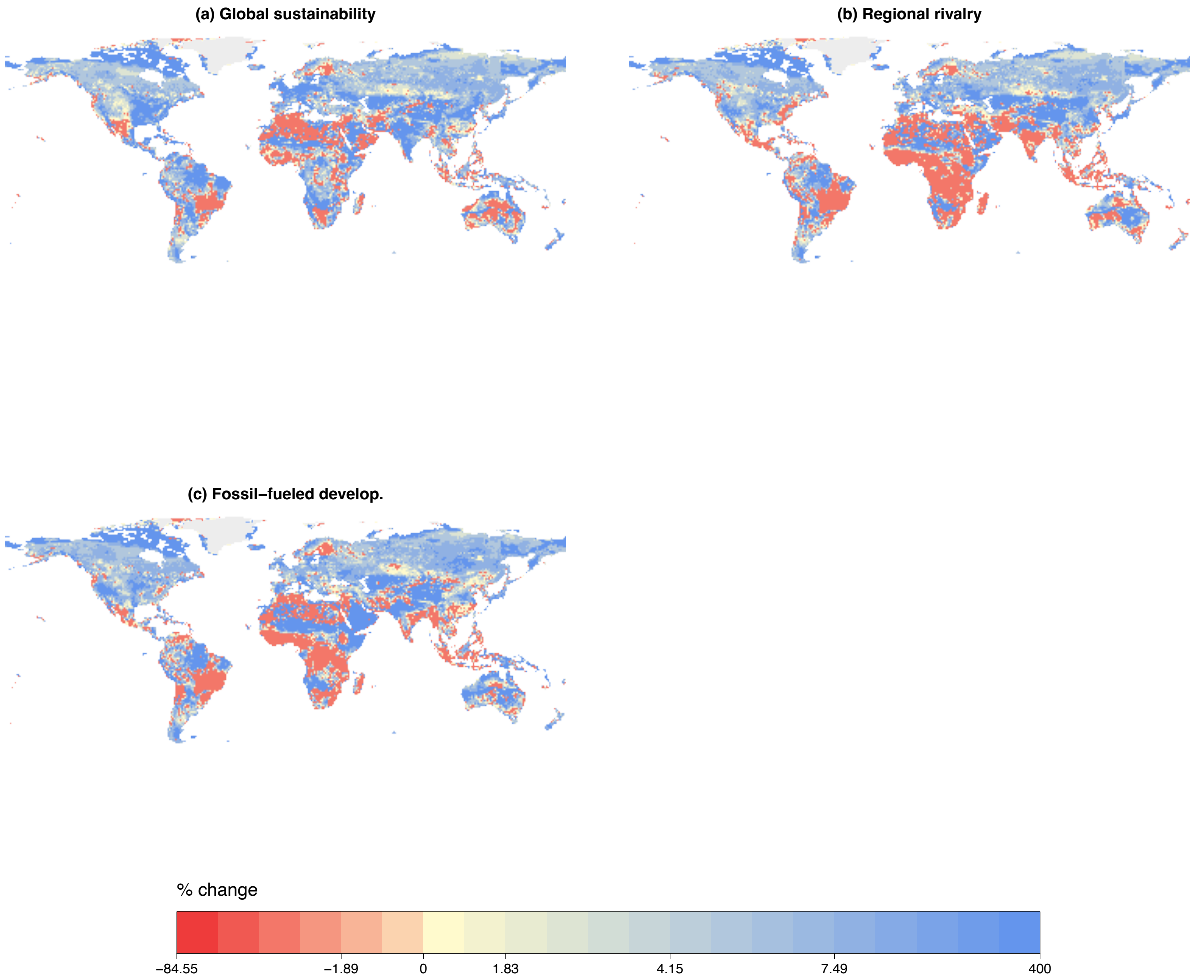

Fig. S7. Ecosystem carbon pools across scenarios. Inter-model mean of proportional changes for 2015-2050 (N=4, CABLE-POP, LPJ, LPJ-GUESS, GLOBIO-ES): (a) global sustainability, (b) regional rivalry, (c) fossil-fueled development. Color scale is based on quantile intervals when considering all maps features.

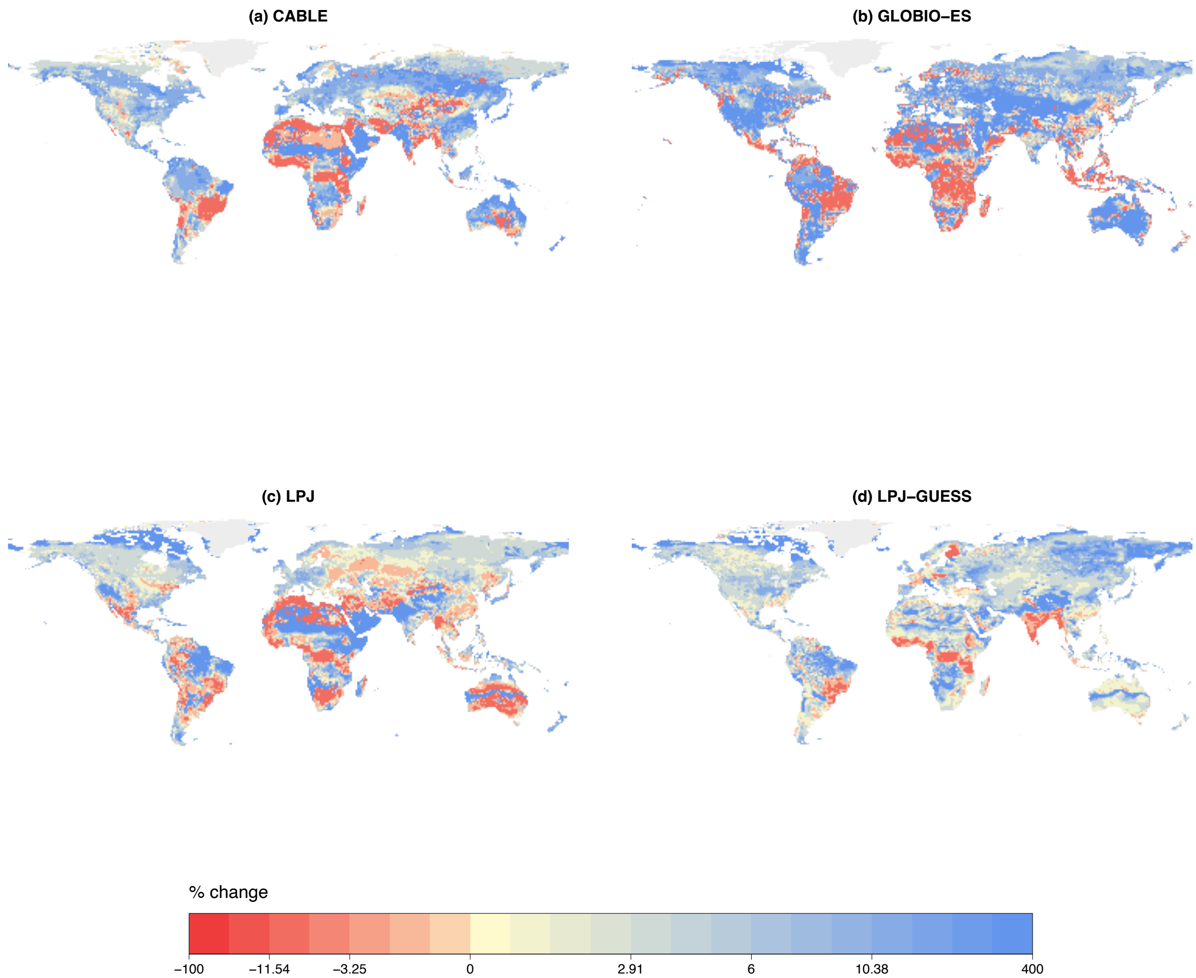

Fig. S8 Spatial agreement across models in ecosystem carbon for the fossil fuel development scenario for 2015-2050: **(a)** CABLE-POP, **(b)** GLOBIO-ES, **(c)** LPJ and **(d)** LPJ-GUESS. The inter-model mean can be found in Figure S7. Color scale is based on quantile intervals when considering all maps features.

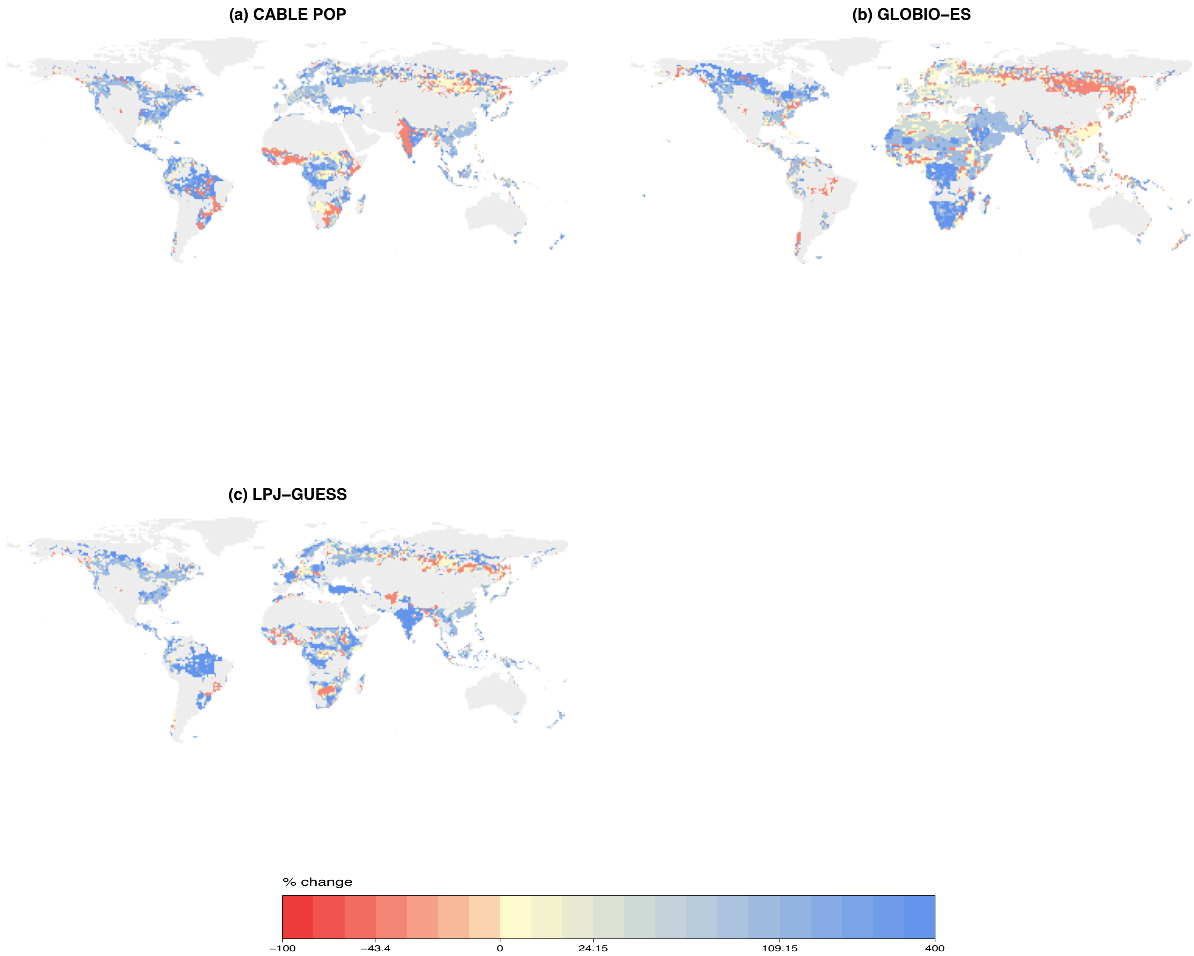

Fig. S9. Spatial agreement across models in projected timber production for the fossil fueled development scenario for 2015-2050: **(a)** CABLE, **(b)** GLOBIO-ES and **(c)** LPJ-GUESS. The inter-model mean can be found in Figure S7. Color scale is based on quantile intervals when considering all maps features.

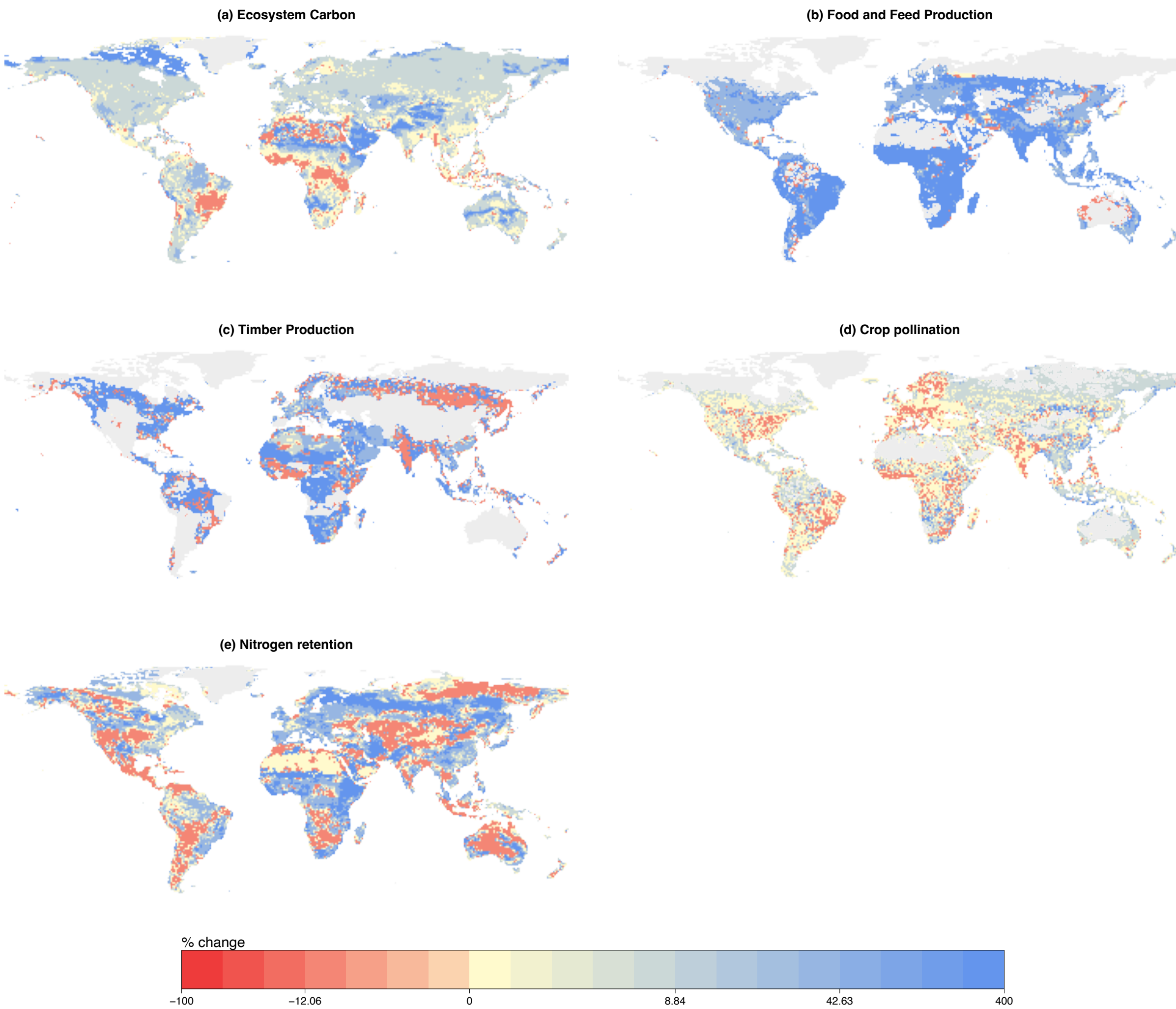

Fig. S10. Spatial distribution of ecosystem service changes. Inter-model mean projection of proportional changes (2015-2050) in the fossil fueled development scenario for: (a) Ecosystem carbon (N=4), (b) Food and feed production (N=2), (c) Timber production (N=2), (d) Crop pollination (N=2) and (e) Nitrogen retention (N=2). Colour scale is based on quantile intervals when considering all maps features.

Table S1. Characteristics of SSP and RCP scenarios (based on (*18*))

	SSP1xRCP2.6 Global sustainability	SSP3xRCP6.0 Regional Rivalry	SSP5xRCP8.5 Fossil-fueled Development
Land-use projections			
Population growth	Relatively low (8.5 billion in 2050)	Low to high (10 billion in 2050)	Relatively low (8.5 billion in 2050)
Economic growth	High to medium (284,565 GDP/PPP billion US$2005/yr in 2050)	Slow (177,284 GDP/PPP billion US$2005/yr in 2050)	High (360,926 GDP/PPP billion US$2005/yr in 2050)
Urbanization	High (92% in 2050)	Low (60% in 2050)	High (92% in 2050)
Equity and social cohesion	High	Low	High
International trade and globalization	Moderate	Strongly constrained	High
Policy focus	Sustainable development	Security	Development, free market, human capital
Institution effectiveness	Effective	Weak	Increasingly effective
Technology development	Rapid	Slow	Rapid
Land-use regulation	Strong	Limited	Medium
Agricultural productivity	High	Low	High
Consumption & diet	Low growth, low-meat	Resource-intensive	Material-intensive, meat-rich diet
Mitigation policies in land use	Full	Absent	Absent
Bioenergy	High	Low	Lowest
Climate projections			
Carbon intensity	Low	High	High
Energy intensity	Low	Intermediate	High
Radiative forcing	Peak at 3W/m^2 before 2100 and declines	Stabilizes to 6W/m^2 in 2100	Rising to 8.5 W/m^2 in 2100
Concentration (p.p.m)	Peak at 490 CO_2 equiv. before 2100 then declines	850 CO_2 equiv. (at stabilization after 2100)	>1,370 CO_2 equiv. in 2100
Methane emissions	Reduced	Stable	Rapid increase

Table S2. Model description, metrics, and scenarios. (S) species richness, ($\dot{H}$) mean species habitat extent, *(I)* and species-abundance based biodiversity intactness. Metrics were calculated at the one or more of the following spatial levels: grid cell (α), regional (regional γ) global level (global γ). The grid cell values were also reported as global averages.

Model	Description	Taxonomic scope	Metrics	Scenarios
AIM-biodiversity (Asia-Pacific Integrated Model – biodiversity) (*76*)	A species distribution model that estimates biodiversity loss based projected shift of species range under the conditions of land-use and climate change. Species range shifts were projected under two commonly used dispersal assumptions: 'no' migration, which did not allow for species colonization and 'full' migration, which allowed for species colonization. The "no-migration" estimates were used, unless stipulated otherwise.	Amphibians, birds, mammals, plants, reptiles	$S\alpha$ $S\gamma$ $H\gamma$	Historical Land use Land use and climate
InSiGHTS (*65*, *77*, *78*)	A high-resolution, cell-wise, species-specific hierarchical species distribution model that estimate the extent of suitable habitat (ESH) for mammals accounting for land and climate suitability. The model did not consider species colonization in this exercise from climate-change, but allowed colonization from land-use change within the climate space of the species.	Mammals	$S\alpha$ $S\gamma$ $H\gamma$	Historical Land use Land use and climate
MOL (Map of Life) (*66*, *79*)	An expert map-based species distribution model that projects potential losses in species occurrences and geographic range sizes given changes in suitable conditions of climate and land cover change. The model considered range loss within the currently known distribution, and not the species colonization in this exercise.	Amphibians, birds, mammals	$H\gamma$	Land use and climate

Model	Description	Taxonomic scope	Metrics	Scenarios
cSAR (Countryside Species Area Relationship) - iDiv (*80*)	A countryside species-area relationship model that estimates the number of species persisting in a human-modified landscape, accounting for the habitat preferences of different species groups.	Birds (forest and non-forest)	$S\alpha$ $S\gamma$	Historical Land use
cSAR-IIASA-ETH (*81*, *82*)	A countryside species area relationship model that estimates the impact of time series of spatially explicit land-use and land-cover changes on community-level measures of terrestrial biodiversity.	Amphibians, birds, mammals, plants, reptiles	$S\alpha$	Historical Land use
BILBI (Biogeographic modelling Infrastructure for Large-scale Biodiversity Indicators) (*83*, *84*)	A modelling framework that couples application of the species-area relationship with correlative generalized dissimilarity modeling (GDM)-based modelling of continuous patterns of spatial and temporal turnover in the species composition of communities (applied in this study to vascular plant species globally).	Vascular plants	$S\gamma$	Historical Land use Land use and climate
PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) (*63*, *85*, *86*)	The hierarchical mixed-effects model that estimates how four measures of site-level terrestrial biodiversity – overall abundance, within-sample species richness, abundance-based compositional similarity and richness-based compositional similarity – respond to land use and related pressures.	Vertebrates	$S\alpha$ $I\alpha$	Historical Land use
GLOBIO (GLObal BIOdiversity model for policy support) (*16*, *68*)	A modelling framework that quantifies the impacts of multiple anthropogenic pressures on biodiversity intactness, quantified as the mean species abundance (MSA) metric.	Vascular plants and warm-blooded vertebrates	$I\alpha$	Historical Land use Land use and climate

Model	Description	Taxonomic scope	Metrics	Scenarios
LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator) (*87–89*)	A big leaf model that simulates the coupled dynamics of biogeography, biogeochemistry and hydrology under varying climate, atmospheric CO_2 concentrations, and land-use land cover change practices to represent demography of grasses and trees in a scale from individuals to landscapes.	Not applicable	Bioenergy production Food and feed production Ecosystem carbon Nitrogen retention Timber production	Historical Land use Land use and climate
LPJ (Lund-Potsdam-Jena) (*90–92*)	A big leaf model that simulates the coupled dynamics of biogeography, biogeochemistry and hydrology under varying climate, atmospheric CO_2 concentrations, and land-use land cover change practices to represent demography of grasses and trees in a scale from individuals to landscapes.	Not applicable	Ecosystem carbon	Historical Land use Land use and climate
CABLE-POP (Community Atmosphere Biosphere Land Exchange) (*93*)	A "demography enabled" global terrestrial biosphere model that computes vegetation and soil state and function dynamically in space and time in response to climate change, land-use change, CO_2 concentrations and N-input.	Not applicable	Ecosystem carbon Timber production Food and feed production	Historical Land use Land use and climate
GLOBIO-ES (*74, 94*)	The model simulates the influence of various anthropogenic drivers on ecosystem functions and services.	Not applicable	Food and feed production Timber production Crop pest control Nitrogen retention Pollination Ecosystem carbon	Land use and climate

Model	Description	Taxonomic scope	Metrics	Scenarios
InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) (*75*, *95–98*)	A suite of geographic information system (GIS) based spatially-explicit models used to map and value the ecosystem goods and services in biophysical or economic terms.	Not applicable	Coastal resilience Pollination Nitrogen retention	Historical Land use and climate

Table S3. Description of land use categories in LUH2 (based on (*50*, *53*, *85*))

forested primary land (primf)	natural vegetation that has never been impacted by human activities (agriculture or wood harvesting) and that is potentially forest; there is no transition to primary land from any other land cover categories
non-forested primary land (primn)	natural vegetation that has never been impacted by human activities (agriculture or wood harvesting) and is non-forest based on the LUH2 potential forest land layer; there is no transition to primary land from any other land cover categories
potentially forested secondary land (secdf)	natural vegetation that is recovering from previous human disturbance (either wood harvesting or agricultural abandonment) and is potentially forest; secondary land can never return to primary land
potentially non-forested secondary land (secdn)	natural vegetation that is recovering from previous human disturbance (either wood harvesting or agricultural abandonment) and is potentially non-forest; secondary land can never return to primary land
managed pasture (pastr)	land where livestock is known to be grazed regularly or permanently with some level of management activities, with low aridity and high population density
rangeland (range)	land where livestock is known to be grazed regularly or permanently, with high aridity and low population density; not managed except by grazing (i.e., no external inputs of pesticides or fertilizers, or fire/mowing)
urban land (urban)	areas with human habitation and/or buildings where primary vegetation has been removed
C3 annual crops (c3ann)	land where native vegetation has been removed and replaced with C3 annual crops; includes biofuel crops
C3 perennial crops (c3per)	land where native vegetation has been removed and replaced with C3 perennial crops; includes biofuel crops
C4 annual crops (c4ann)	land where native vegetation has been removed and replaced with C4 annual crops; includes biofuel crops
C4 perennial crops (c4per)	land where native vegetation has been removed and replaced with C4 perennial crops; includes biofuel crops
C3 nitrogen-fixing crops (c3nfx)	land where native vegetation has been removed and replaced with C3 nitrogen fixing crops; includes biofuel crops

Table S4. Recategorization of land-use categories by each model, climate data used and additional sources of data in the model. Modified from (*20*).

Model	Land-use data – recategorization of LUH2 land-use classes in the model	Climate-data – data sources and variables used	Other data
AIM- biodiversity	Cropland (c3ann, c4ann, c3per, c4per, c3nfx) Pasture (pastr) Built-up area (urban) Forest (primf, secdf) Other natural land (primn, secdn, range)	ISIMIP2a IPSL - monthly mean maximum temperature, monthly mean minimum temperature, monthly precipitation	Species occurrence records (GBIF)
InSiGHTS	Cropland (c3ann, c3per, c3nfx, c4ann, c4per) Forest (primf, secdf) Non-forest (primn, secdn, range) Pasture (pastr) Urban (urban)	Worldclim v1 - annual mean temperature, diurnal range (mean of monthly), isothermality, temperature seasonality, max temperature of warmest month, minimum temperature of coldest month, temperature annual range, mean temperature of wettest, driest, warmest quarter, and coldest quarters, annual precipitation, precipitation of wettest and driest months, seasonality, wettest, driest, warmest, and coldest quarters	Global mammal habitat suitability models (*77*) Mammal range maps (IUCN)
MOL	Forest (primf, secdf) Grassland/shrubland/wetland (secdf, secdn) Rangeland (pastr, range) Urban (urban) Crops (c3ann, c3per, c3nfx, c4ann, c4per)	Worldclim v2 (present), v1.4 (future) - annual mean temperature, temperature seasonality, annual precipitation, precipitation seasonality, precipitation of driest quarter	Expert maps (IUCN) Species land cover preferences drawn from the literature
cSAR-iDiv	Primary vegetation (primf, primn Secondary vegetation (secdf, secdn) Pasture (pastr, range) Urban (urban) Cropland (c3ann, c4ann, c3nfx) Permanent (c3per, c4per)		Bird species occurrence data (Birdlife International) Coefficients for affinities (PREDICTS)
cSAR- IIASA-ETH	Urban (urban) Annual cropland (c3ann, c3nfx, c4ann) Perennial cropland (c3per, c4per) Pasture (pastr) Extensive forest (range, secdf, secdn) Pristine (primf, primn)		cSAR model parameters (*81*, *82*)
BILBI	Primary vegetation (primf, primn) Mature secondary vegetation	Worldclim v1.4 – BIO6 and BIO12 Climate variables derived by	Plant species occurrence records (GBIF) Soil attributes: pH, Clay %,

	(secdf, secdn) *if older than 50yrs* Intermediate secondary vegetation (secdf, secdn) *if 10-50 years old* Young secondary vegetation (secdf, secdn) *if younger than 10yrs* Rangelands (range) Managed pasture (pastr) Urban (urban) Perennial croplands (c3per, c4per) Nitrogen-fixing croplands (c3nfx) Annual croplands (c3ann, c4ann)	integrating Worldclim monthly temperature and precipitation estimates with radiative adjustment for terrain, and with soil water-holding capacity (Ferrier et al., 2013): max temperature of warmest month, max diurnal temperature range, actual evaporation, potential evaporation, min monthly water deficit, max monthly water deficit	Silt %, Bulk Density, Depth (*99*) Terrain attributes: Ruggedness Index (G. Arnatulli, Yale University), Topographic Wetness Index (WorldGrids) MODIS Vegetation Continuous Fields (NASA) Global Human Settlement Population Grid Coefficients: impact of land use on local native-species richness (PREDICTS)
PREDICTS	Primary vegetation (primf, primn) Secondary vegetation (secdf, secdn - split into three age bands: Mature, Intermediate and Young) Managed pasture (pastr) Rangeland (range) Urban (urban) Annual (c3ann, c4ann) Nitrogen-fixing (c3nfx) Perennial (c3per, c4per)	IMAGE model (MAGICC 6.0) - global mean temperature increase (ºC)	PREDICTS database (*100*) Human population density (GRUMP v1., HYDE (historical) and the corresponding SSPs as developed by (*101*) (future projection)). Agricultural suitability (*102*)
GLOBIO - Terrestrial	GLOBIO downscaled LUH2 data (see (*20*) for more details)		Nitrogen deposition (IMAGE model) Roads (GRIP dataset, (*103*)) Settlements in tropical regions (Humanitarian Data Exchange, Open Street Map)
LPJ-GUESS	Primary natural vegetation (primf, primn) Secondary natural vegetation (secdf, secdn) Pasture (pastr, range) C3 crops (c3ann, c3per, c3nfx) C4 crops (c4ann, c4per) Urban (modelled as natural vegetation)	ISIMIP2a IPSL - monthly min/max T, precipitation, shortwave radiation; atmospheric CO2, N-input, fractional land cover (crop irrigated yes/no, pasture, managed forest, natural)	Crop irrigated and biofuel fraction (LUH2 dataset) Wood harvest estimate (LUH2 dataset) Nitrogen deposition (*104*)
LPJ	Primary natural vegetation (primf, primn) Secondary natural vegetation (secdf, secdn) Pasture (pastr, range, c3ann, c3per, c3nfx, c4ann, c4per) urban (modelled as natural vegetation)	ISIMIP2a IPSL - monthly T, precipitation, shortwave radiation or cloudiness; atmospheric CO2, fractional land cover (pasture, managed forest, natural)	
CABLE	Primary natural vegetation (primf, primn) Secondary natural vegetation (secdf, secdn) Grass (pastr, range) Crops (c3ann, c3per, c3nfx, c4ann, c4per, c4nfx)	ISIMIP2a IPSL - daily min/max T, precipitation, shortwave radiation, longwave radiation, humidity, windspeed, atmospheric CO2, N-deposition, land-use transitions (crop, pasture, secondary forest, natural)	Wood harvest estimate (LUH2 dataset) Nitrogen deposition (*104*)

GLOBIO- ES	Primary forest (primf) Primary other vegetation (primn) Secondary forest (secdf) Pastures (pastr) Rangelands (range) Cropland (c3ann, c4ann, c3nfx) Perennials (c3per, c4per) secdn urban	IMAGE model (MAGICC 6.0) - aggregated monthly precipitation, monthly wet day frequency	Population size, GDP per capita, soil data, altitude range, slope (IMAGE model) Population density in river floodplains Water demand for electricity, industry and households (*105*)
InVEST	GLOBIO downscaled LUH2 data (see (*20*) for more details)	*Nutrient delivery* Worldclim v1.4 - precipitation *Coastal Vulnerability* CMIP5 AOGCMs - sea level rise	*Nutrient delivery* Digital elevation model (ASTER) Biophysical table (InVEST database) Rural population scenarios (*101*) Population raster (GPWv4, 2018) *Coastal Vulnerability* Natural Habitat polygons for mangrove, corals, and eel grass (WCMC) Continental Shelf polygon (COMARGE, Census of Marine Life) Digital elevation model (ASTER) Wind and wave exposure (WAVEWATCH III) Population raster (GPWv4 - 2018) *Pollination* Yield raster for 115 crops (*54*) Nutrient content of 115 crops (USDA 2011) Pollination dependence of 115 crops (*106*) Dietary requirements (*107*) Demographic population data (GPWv4 Age Dataset – 2018)

Data S1. Biodiversity projections from models **(separate file)**

Biodiversity.xlsx, containing the biodiversity metrics outputted by the models at the global and regional scales (in separate sheets). Each row corresponds to the output of a model for a particular scenario, year, taxa and metric. The columns are: scenario, LUCC (whether the projections were for land-use only or for land-use and climate change combined), model, region (the IPBES region or global for the global estimates), years, metric, taxa, units (% or absolute values), value, scale (alpha, gamma regional or gamma global), family (Sgamma, Salpha, Hgamma, or Intactness), original_model_metric.

Data S2. Ecosystem service projections from models **(separate file)**

EcosystemServices.xlsx containing the ecosystem metrics outputted by the models at the global and regional scales (in separate sheets). The columns are: scenario, LUCC (whether the projections were for land-use only or for land-use and climate change combined), model, region (the IPBES region or global for the global estimates), years, metric, units (% or biophysical units), value, scale, NCP name, source (calculated from spatial rasters or from CSV files provided by each model), signal_change (whether the signal should be changed for correct interpretation of the value) and original_model_metric.

Data S3. Code for the data analysis and figure generation **(separate file)**

Zip file with all the R scripts necessary to generate the different figures. Each R script is named after the figure name.