A protocol for an intercomparison of biodiversity and ecosystem services models using harmonized land-use and climate scenarios

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Abstract. To support the assessments of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the IPBES Expert Group on Scenarios and Models is carrying out an intercomparison of biodiversity and ecosystem services models using harmonized scenarios (BES-SIM). The goals of BES-SIM are (1) to project the global impacts of land use and climate change on biodiversity and ecosystem services (i.e. nature contributions to people) over the coming decades, compared to the 20th century, using a set of common metrics at multiple scales, and (2) to identify model uncertainties and research gaps through the comparisons of projected biodiversity and ecosystem services across models. BES-SIM uses three scenarios combining specific Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs) to explore a wide range of land-use change and climate change futures. This paper describes the rationale for scenarios selection, the process of harmonizing input data for land use, based on the second phase of the Land Use Harmonization Project (LUH2), and climate, the biodiversity and ecosystem service models used, the core simulations carried out, the harmonization of the model output metrics, and the treatment of uncertainty. The results of this collaborative modelling project will support the ongoing global assessment of IPBES, strengthen ties between IPBES and the Intergovernmental Panel on Climate Change (IPCC) scenarios and modelling processes, advise the Convention on Biological Diversity on its development of a post-2020 strategic plans and conservation goals, and inform the development of a new generation of nature-centred scenarios.

1 Introduction

Understanding how anthropogenic activities impact biodiversity, ecosystems, and their interactions with human societies is essential for nature conservation and sustainable development. Land use and climate change are widely recognized as two of the main drivers of future biodiversity change (Hirsch and Secretariat of the Convention on Biological Diversity, 2010; Maxwell et al., 2016; Sala, 2000; Secretariat of the Convention on Biological Diversity and United Nations Environment Programme, 2014) with potentially severe impacts on ecosystem services and ultimately human well-being (Cardinale et al., 2012; Millennium Ecosystem Assessment (Program), 2005). Habitat and land-use changes, resulting from past, present and future human activities, have immediate impacts on biodiversity and ecosystem services whereas the impacts of climate change have considerable lag times (Lehsten et al., 2015). Therefore, current and future land-use projections are essential elements for assessing biodiversity and ecosystem change (Titeux et al., 2016, 2017). Climate change has already observed direct and indirect impacts on biodiversity and ecosystems and it is projected to intensify as we approach the end of the century with potentially severe consequences on species and habitats, thereby also on ecosystem functions and ecosystem services at high levels of climate change (Pecl et al., 2017; Settele et al., 2015).

Global environmental assessments, such as the Millennium Ecosystem Assessment (MA 2005), the Global Biodiversity Outlooks (GBO), the multiple iterations of the Global Environmental Outlook (GEO), the Intergovernmental Panel on Climate Change (IPCC), and other studies have used scenarios to assess the impact of socio-economic development pathways on land use and climate and their consequences for biodiversity and ecosystem services (Jantz et al., 2015; Pereira et al., 2010). Models are used in quantifying the narratives of scenarios using selected and modellable drivers, which describe key components of a system or relationships between them (Ferrier et al. 2016). So far, these scenarios analysis exercises have been based on a single model or a small number of models, and cross-model harmonization and uncertainty analysis have been limited. The Expert Group on Scenarios and Models of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is addressing this issue by carrying out a biodiversity and ecosystem services model intercomparison with harmonized scenarios.

Over the last two decades, IPCC has fostered the development of global scenarios to inform climate mitigation and adaptation policies. The Representative Concentration Pathways (RCPs) describe different climate futures based on greenhouse gas emissions over the 21st century (van Vuuren et al., 2011). These emissions pathways have been converted into climate projections in the most recent Climate Model Inter-comparison Project (CMIP5). In parallel, the climate research community also developed the Shared Socio-economic Pathways (SSPs) which consist of trajectories of future human development with different socio-economic conditions and associated land-use projections (Popp et al., 2017; Riahi et al., 2017). The SSPs can be combined with RCP-based climate projections to explore a range of futures for climate change and land-use change and are being used in a wide range of impact modelling intercomparisons (Rosenzweig et al., 2017; van Vuuren et al., 2014). Therefore, the use of the SSP-RCP framework for modelling the impacts on biodiversity and ecosystem services provides an outstanding opportunity to build bridges between the climate, biodiversity and ecosystem services communities, and has been explicitly recommended as a research priority in the IPBES assessment on scenarios and models (Ferrier et al. 2016).

Model intercomparisons bring together different communities of practice for comparable and complementary modelling, in order to improve the robustness and comprehensiveness of the subject modelled, and to estimate associated uncertainties (Warszawski et al., 2014). In the last decades, various model intercomparison projects (MIPs) have been initiated to assess the magnitude and uncertainty of climate change impacts. For instance, the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) was initiated in 2012 to quantify and synthesize climate change impacts across sectors and scales (Frieler et al., 2015; Rosenzweig et al., 2017). The ISI-MIP aims to bridge sectors such as agriculture, forestry, fisheries, water, energy, and health with Global Circulation Models (GCMs), Earth System Models (ESMs), and Integrated Assessment Models (IAMs) for more integrated and impact-driven modelling and assessment (Frieler et al., 2017).

Here, we present the methodology used to carry out a Biodiversity and Ecosystem Services Scenario-based Intercomparison of Models (BES-SIM) in terrestrial and freshwater ecosystems. The BES-SIM project addresses the following questions: (1) What are the projected magnitudes and spatial distribution of biodiversity and ecosystem services under a range of climate and land-use future scenarios? (2) What is the magnitude of the uncertainties associated with the projections obtained from different models and scenarios? We brought together ten biodiversity models and six ecosystem functions and ecosystem services models to assess impacts of land-use change and climate scenarios in coming decades (up to 2070) and to hindcast changes to the last century (to 1900). The modelling approaches differ in several ways in how they treat biodiversity and ecosystem services responses to land use and climate changes, including the use of correlative, deductive, and process-based approaches, and in how they treat spatial scale and temporal dynamics. We assess different dimensions of biodiversity including species richness, species abundance, community composition, and habitat shifts, as well as a range of measures on ecosystem services such as food production, pollination, water quantity and quality, climate regulation, soil protection, and pest control. This paper provides an overview of the scenarios, models and metrics used in this intercomparison, thus a roadmap for further analyses that is envisaged to be integrated into the first global assessment of the IPBES (Figure 1).

2 Scenarios selection

All the models involved in BES-SIM used the same set of scenarios using particular combinations of SSPs and RCPs. In the selection of the scenarios, we used the following criteria: 1) data on projections should be readily available, and 2) the total set should cover a broad range of land-use change and climate change projections. The first criterion implied that we selected SSP-RCP combinations included in the ScenarioMIP protocol as part of CMIP6 (O’Neill et al., 2016), as harmonised data was available for these runs and these from the basis of the CMIP climate simulations. The second criteria implied a selection within the ScenarioMIP set of scenarios with a low and high degree of climate change and different land-use scenarios. The final selection was SSP1 with RCP2.6 (moderate land-use pressure and low level of climate change) (van Vuuren et al., 2017), SSP3 with RCP6.0 (high land-use pressure and moderately high level of climate change) (Fujimori et al., 2017), and SSP5 with RCP8.5 (medium land-use pressure and very high level of climate change) (Kriegler et al., 2017), thus allowing us to assess a broad range of plausible futures (Table 1). Further, by combining projections of low and high anthropogenic pressure of land-use with low and high level of climate change projections, we can test these drivers’ individual and synergistic impacts on biodiversity and ecosystem services.

The first scenario (SSP1xRCP2.6) is characterized by relatively “environmentally-friendly world” with a low population growth, a relatively low demand for animal products, a high urbanization rate and a high agricultural productivity. These factors together lead to a decrease in land use of around 700 Mha globally over time (mostly pastures). This scenario is also characterised by low air pollution, while policies are introduced to limit the increase of greenhouse gases in the atmosphere, leading to an additional forcing of 2.6 W/m^2 before 2100. The second scenario (SSP3xRCP6.0) is characterised by “regional rivalry”, leading high population growth, slow economic development, material-intensive consumption and low food demand per capita. Agricultural land intensification is low, especially due to very limited transfer of new agricultural technologies to developing countries. This scenario has land-use change hardly regulated, with large conversion of land to human-dominated uses, and has a relatively high level of climate change with radiative forcing of 6.0 W/m^2 by 2100. The third scenario (SSP5xRCP8.5) is a world characterised by "strong economic growth" fuelled by fossil fuels, with low population growth, a high food demand per capita, a high urbanization rate but also a high agricultural productivity. As a result, the scenario leads to a modest increase in land use. Air pollution policies are stringent, motivated by local health concerns. This scenario leads to a very high level of climate change with a radiative forcing of 8.5 W/m^2 by 2100. Full descriptions of each SSP scenario are given in Popp et al. (2017) and Riahi et al. (2017).

3 Input data

A consistent set of land use and climate data was used across the models to the extent possible, using existing datasets. All models in BES-SIM used the newly released Land Use Harmonization dataset version 2 (LUH2, Hurtt et al., 2018). For the models that used climate data, we selected the climate projections of the past, present and future from CMIP5 / ISI-MIP2a (McSweeney and Jones, 2016) and its downscaled version from the WorldClim (Fick and Hijmans, 2017) , as well as MAGICC 6.0 (Meinshausen et al., 2011b, 2011a) from the Integrated Model to Assess the Global Environment (IMAGE) for GLOBIO models (Table 2). A complete list of input datasets and variables used by the models is documented in Table S1 of the Supplementary Materials.

3.1 Land cover and land-use change data

The land-use scenarios provide an assessment of land-use dynamics in response to a range of socio-economic drivers and their consequences for the land system. The IAMs used to model land-use scenarios – Integrated Model to Assess the Global Environment (IMAGE) for SSP1/RCP2.5, Asia-pacific Integrated Model (AIM) for SSP3/RCP7.0, and REMIND/The Model of Agricultural Production and its Impact on the Environment (REMIND/MAgPIE) for SSP5/RCP8.0 – include different economic and land-use modules for the translation of narratives into consistent quantitative projections across scenarios (Popp et al., 2017). It is important to note that the land-use scenarios used, although driven mostly by the SSP storylines, were projected to be consisted with the paired RCPs and include biofuel deployment to mitigate climate change. As there was no land-use projection for SSP3 with RCP6.0, we chose the available closest simulation SSP3/RCP7.0

The land-use projections from each of the IAMs was harmonized using the LUH2 methodology. LUH2 was developed for CMIP6 and provides a global gridded land-use dataset comprising estimates of historical land-use change (850-2015) and future projections (2015-2100), obtained by integrating and harmonizing land-use history with future projections of different IAMs (Jungclaus et al., 2017; Lawrence et al., 2016; O'Neill et al., 2016). Compared to the first version of the LUH (Hurtt et al., 2011), LUH2 (Hurtt et al., 2018) is driven by the latest SSPs, has a higher spatial resolution (0.25 vs 0.50 degree) and more detailed land-use transitions (12 versus 5 possible land-use states), and increased data-driven constraints (Heinimann et al., 2017; Monfreda et al., 2008). LUH2 provides over 100 possible transitions per grid cell per year (e.g., crop rotations, shifting cultivation, agricultural changes, wood harvest) and various agricultural management layers (e.g., irrigation, synthetic nitrogen fertilizer, biofuel crops), all with annual time steps. The 12 states of land 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 N fixing crops) (Table 3).

For biodiversity and ecosystem services models that rely on discrete, high-resolution land-use data (i.e., the GLOBIO model for terrestrial biodiversity and the InVEST model), the fractional LUH2 data were downscaled to discrete land-use grids (10 arc-seconds resolution; ~300 m) with the land-use allocation routine of the GLOBIO4 model. To that end, the areas of urban, cropland, pasture, rangeland and forestry from LUH2 were first aggregated across the LUH2 grid cells to the regional level of the IMAGE model, with forestry consisting of the wood harvest from forested cells and non-forested cells with primary vegetation. Next, the totals per region were allocated to 300m cells with the GLOBIO4 land allocation routine, with specific suitability layers for urban, cropland, pasture, rangeland, and forestry. After allocation, cropland was reclassified into three intensity classes (low, medium, high) based on the amount of fertilizer per grid cell. More details on the downscaling procedure are provided in Appendix 1 of the Supplement Material.

3.2 Climate data

General Circulation Models (GCMs) are based on fundamental physical processes (e.g., conservation of energy, mass, and momentum and their interaction with the climate system) and simulate climate patterns of temperature, precipitation and extreme events at a large scale (Frischknecht et al., 2016). Some GCMs now incorporate elements of Earth’s climate system (e.g. atmospheric chemistry, soil and vegetation, land and sea ice, carbon cycle) in ESMs (GCM with interactive carbon cycle), and have dynamically downscaled models with higher resolution data in Regional Climate Models (RCMs).

A large number of climate datasets are available today from multiple GCMs, but not all GCMs provide projections for all RCPs. Moreover, some models in BES-SIM required continuous time data. In order to harmonize the climate date to be used across biodiversity and ecosystem service models, we chose the bias-corrected climate projections from CMIP5, which were also adopted by ISIMIP2a (Hempel et al., 2013) or their downscaled versions available from WorldClim (Fick and Hijmans, 2017). Most analysis were carried out using a single GCM, the IPSL-CM5A-LR (Dufresne et al., 2013) to avoid a random selection of GCMs by the different teams (Table 2).

The ISI-MIP fast-track output from the IPSL model provides 12 climate variables on daily time steps from pre-industrial period 1951 to 2099 at 0.5-degree resolution (McSweeney and Jones, 2016). The WorldClim downscaled dataset has 19 bioclimatic variables derived from monthly temperature and rainfall for 1960-1990 with multi-year averages for specific points in time (e.g., 2050, 2070) up to 2070. Six models in BES-SIM used ISI-MIP2a dataset and three models used WorldClim. An exception was made to the GLOBIO models, which used MAGICC 6.0 climate data (Meinshausen et al., 2011b, 2011a) in the IMAGE model framework (Stehfest et al., 2014), to which GLOBIO is tightly connected (Table 2). The variables used from climate dataset in each model are listed in Table S1.

3.3 Other input data

In addition to the land-use and climate data, most models use additional input data to run their future and past simulations to estimate changes in biodiversity and ecosystem services. For instance, species occurrence data are an integral part of modelling in several of the biodiversity models (i.e. AIM-biodiversity, MOL, cSAR-iDiv, cSAR-IIASA-ETH, BILBI, InSiGHTS) while some models (i.e. cSAR-iDiv, BILBI) rely on estimates of habitat affinity coefficients (e.g. reductions in species richness in a modified habitat relative to the pristine habitat) from the PREDICTS. In DGVM models (i.e. LPJ-GUESS, LPJ, CABLE), atmospheric CO2 concentrations, irrigated fraction and wood harvest estimates are commonly used, while GLOBIO and GLOSP ecosystem services models rely on topography and soil type data for soil erosion measures. A full list of model-specific input data is listed in Table S1.

4 Models in BES-SIM

Biodiversity and ecosystem services models at the global scale have increased in number and improved considerably over the last decade, especially with advancement in biodiversity data availability and statistical modelling tools and methods (IPBES, 2016). In order for a model to be included in BES-SIM, it had either to be published in a peer-reviewed journal, or adopt published methodologies, with modifications made to modelling sufficiently documented and accessible for review (Table S2). Sixteen models participated in BES-SIM (Table 4, details on modelling methods can be found in Table S2). These models were mainly grouped into four classes: species-based, community-based, and ecosystem-based models of biodiversity, and models of ecosystem functions and services. The methodological approaches, the taxonomic or functional groups, the spatial resolution and the output metrics differ across models (Table 4). 16 models are spatially explicit and use land-use data as an input, with 12 of them also using climate data. We also used one model (BIOMOD2) to assess uncertainty of climate range projections that does not use land-use data.

4.1 Species-based models of biodiversity

Species-based models aim to predict historical, current, and future potential distribution and abundance of individual species. These can be developed using correlative methods based on species observation and environmental data (Aguirre-Gutiérrez et al., 2013; Guisan and Thuiller, 2005; Guisan and Zimmermann, 2000), as well as expert based solutions where data limitations exist (Rondinini et al., 2011). Depending on the methodologies employed and the ecological aspects modelled, they can be known as species distribution models, ecological niche models, bioclimatic envelop models and habitat suitability models (Elith and Leathwick, 2009), and they have been used to forecast environmental impacts on species distribution and status.

In BES-SIM, four species-based models were included: AIM-biodiversity, InSiGHTS, MOL and BIOMOD2 (Table 4, Table S2). The first three models project individual species distributions across a large number of species by combining projections of climate impacts on species ranges with projections of land-use impacts on species ranges. AIM (Ohashi et al., in prep.) uses Global Biodiversity Information Facility (GBIF) occurrence data to train statistical models for current land use and climate and uses these models to project future species distributions. InSiGHTS (Rondinini et al., 2011; Visconti et al., 2016) and MOL (Jetz et al., 2007; Merow et al., 2013) both rely on expert-based range maps as a baseline. INSIGHTS and MOL used an hierarchical approach with two steps: first, a statistical model trained on current species ranges is used to assess future climate suitability within species ranges; second, an expert-based model detailing associations between species and habitat types is used to assess the impacts of land-use in the climate suitable portion of the species range. BIOMOD2 (Thuiller, 2004; Thuiller et al., 2009) was used to assess uncertainties in climate-envelope-based projections and was not include in the comparisons with other models of the impacts of land-use change (see section 7. Uncertainties).

4.2 Community-based models of biodiversity

Community-based models predict the assemblage of species using environmental data and assess changes in community composition through species presence and abundance (D'Amen et al., 2017). Output variables of community-based models include assemblage-level metrics such as the proportion of species persisting in a landscape, mean species abundances, and compositional similarity relative to a baseline (typically corresponding to a pristine landscape). Three models in BES-SIM (cSAR-iDiv, cSAR-IIASA-ETH, BILBI) rely on versions of the species-area relationship (SAR) to estimate the proportion of species persisting in human-modified habitats relative to native habitat, while three models (PREDICTS, GLOBIO Aquatic, GLOBIO Terrestrial) estimate a range of assemblage-level metrics based on correlative relationships between biodiversity responses and pressure variables (Table 4).

Both the cSAR-iDiv (Martins and Pereira, 2017) and the cSAR-IIASA-ETH (Chaudhary et al., 2015) models are based on the countryside species-area relationship, which uses habitat affinities to weight the areas of the different habitats in a landscape. The habitat affinities are calibrated from field studies by calculating the change in species richness in a modified habitat relative to the native habitat. The habitat affinities of the cSAR-iDiv model are estimated from the PREDICTS dataset (Hudson et al., 2014) while the habitat affinities of the cSAR-IIASA-ETH come from a previously published database of studies (Chaudhary et al., 2015). The cSAR-iDiv model considers two functional species groups (forest species and non-forest species) for one taxonomic group (birds) while the cSAR-IIASA-ETH uses a single functional group for multiple taxonomic groups (amphibians, birds, mammals, plants and reptiles).

BILBI (Hoskins et al., in prep.; Ferrier et al., 2004, 2007) couples application of the species-area relationship with correlative statistical modelling of continuous patterns of spatial turnover in the species composition of communities as a function of environmental variation. Through space-for-time projection of compositional turnover, this coupled model enables the effects of both climate change and habitat modification to be considered in estimating the proportion of species persisting (in this study for vascular plant species globally).

PREDICTS (Newbold et al., 2016; Purvis et al., 2018) uses a hierarchical mixed-effects framework to model how a range of site-level biodiversity metrics respond to land use and related pressures, using a global database of 767 studies, including over 32,000 sites and 51,000 species. GLOBIO (Alkemade et al., 2009; Janse et al., 2015; Schipper et al., 2016) is an integrative modelling framework for aquatic and terrestrial biodiversity that builds upon correlative relationships between biodiversity intactness and pressure variables, established with meta-analyses of biodiversity monitoring data retrieved from the literature.

4.3 Ecosystem-based model of biodiversity

The Madingley model (Harfoot et al., 2014b) is a mechanistic individual-based model of ecosystem structure and function. It encodes a set of fundamental ecological principles to model how individual heterotrophic organisms with a body size greater than 10 μg that feed on other living organisms interact with each other and with their environment. The model is general in the sense that it applies the same set of principles for any ecosystem to which it is applied, and is applicable across scales from local to global. To capture the ecology of all organisms, the model adopts a functional trait based approach with organisms characterised by a set of categorical traits (feeding mode, metabolic pathway, reproductive strategy and movement ability), as well as continuous traits (juvenile, adult and current body mass). Properties of ecological communities emerge from the interactions between organisms, influenced by their environment. The functional diversity of these ecological communities can be calculated as well as the dissimilarity over space or time between communities (Table S2).

4.4 Models of ecosystem functions and services

In order to measure ecosystem functions and services, three Dynamic Global Vegetation Models (DGVMs) (i.e., LPJ-GUESS, LPJ, CABLE) and three ecosystem services models (i.e., InVEST, GLOBIO, GLOSP) were engaged in this model intercomparison. The DGVMs are process-based models that simulate responses of potential natural vegetation and associated biogeochemical and hydrological cycles to changes in climate and atmospheric CO_2 and disturbance regime (Prentice et al., 2007). Processes in anthropogenically managed land (crop, pasture and managed forests) are also increasingly being accounted for (Arneth et al., 2017). DGVMs can project changes in future ecosystem state and functioning, and habitat structure, however, they are limited in capturing species-level biodiversity change because vegetation is represented by a small number of plant functional types (PFTs) (Bellard et al., 2012; Thuiller et al., 2013).

The InVEST (Sharp et al., 2014) suite includes 18 models that maps and measures the flow and value of ecosystem goods and services across a land or a seascape, based on biophysical processes of the structure and function of ecosystems, accounting for both supply and demand. The GLOBIO model (Alkemade et al., 2009, 2014; Schulp et al., 2012) estimates ecosystem services based on outputs from the IMAGE model (Stehfest et al., 2014), the global hydrological model PCRaster Global Water Balance (PCR-GLOBWB, van Beek et al., 2011), and the Global Nutrient Model (Beusen et al., 2015). It is based on correlative relationships between ecosystem functions and services and particular environmental variables (mainly land use), quantified based on literature data. Finally, the GLOSP (Guerra et al., 2016) is a 2D model that estimates the level of global and local soil erosion and protection using the Universal Soil Loss Equation.

5 Output metrics

Given the diversity of modelling approaches, a wide range of biodiversity and ecosystem services metrics can be produced by the model set (Table S2). For the biodiversity model intercomparison analysis, three main categories of common output metrics were used, across two scales – local (α) and global (γ): number of species per unit area (N), proportion of species persisting (P); abundance-based intactness (I); and mean suitable habitat extent across species (H) (Table 6). The proportion of species persisting is the projected species richness relative to the initial species richness, calculated at the local scale (alpha: Pα) or aggregated to IPBES subregional and global scales (gamma: Pγ). Intactness, which can be estimated in several ways, refers to the difference between the current community composition and the inferred original state in the native vegetation. This metric is available only at the local scale (Iα) and for two community-based models (i.e., GLOBIO and PREDICTS). The habitat change (H) measures mean available habitat across species and can be reported locally (Hα) and at the global scale (Hγ) for species-level models (i.e. AIM-biodiversity, InSiGHTS, MOL) (Table 6).

For ecosystem functions and services, each model's output metrics were mapped onto the new classification of Nature's Contributions to People (NCP) published by the IPBES scientific community (Díaz et al., 2018). Among the 18 possible NCPs, the combination of models participating in BES-SIM were able to provide measures for 10 NCPs, including regulating metrics on pollination (e.g., proportion of agricultural lands whose pollination needs are met), climate (e.g., vegetation carbon, total carbon uptake and loss), water quantity (e.g., monthly runoff), water quality (e.g., nitrogen and phosphorus leaching, algal blooms), soil protection (e.g., erosion risk), hazards (e.g., costal resilience, flood risk) and detrimental organisms (e.g. fraction of cropland potentially protected by the natural pest, relative to all available cropland), and material metrics on bioenergy (e.g. bioenergy-crop production), food and feed (e.g. total crop production) and materials (e.g. wood harvest) (Table 6). Some of these metrics require careful interpretation in the context of NCPs (e.g., risk indices) and additional translation of increasing or declining measures of ecosystem functions and services (e.g., food and feed, water quantity) into contextually relevant information (i.e., positive or negative impacts) on human well-being and quality of life. Given disparity of metrics across models within each NCP category, names and units of the metrics are listed in Table 6 with definitions and methods provided in Table S3.

6 Core simulations

The initial simulations for BES-SIM required three sets of outputs from the modelling teams: future (2015-2050 and 2015-2070) and past (1900-2015) changes (Table 7). For the past, present and future analyses, models were run from 1900 (or the closest year possible if there were data limitations) through 2070 to better assess the impact of climate change in models where feasible. Outputs comprised the absolute and relative changes in metric values between modelling years (e.g., species richness (SR) in 2015 and 2050 for 2015-2050), as well as the absolute and percentage changes in this period (e.g., the absolute change in SR from 2015 to 2050, as well as the relative change calculated as (SR_{2050} – SR_{2015})/SR_{2015}). Models that simulated a continuous time-series of climate change (and land-use change) impacts provided 20-year averages around these mid-points to account for inter-annual variability. Furthermore, the results were reported in three spatial units: globally and by IPBES subregions (gamma metrics), and at a one-degree spatial resolution (alpha metrics). The models ran simulations at their original spatial resolutions, and subsequently aggregated the outputs to the three reporting scales (global, IPBES subregions and one-degree grid cells) to facilitate intercomparison, using the arithmetic mean of the percentage change calculated at the original resolution (Table 4).

To measure the individual and synergistic impacts of land use and climate change on biodiversity and ecosystem services, models accounting for both types of drivers in their structure were run three times using land-use change only, climate change only, and the combination of both. For instance, to measure the impact of land use alone, the projections into 2050 (or 2070) were obtained while retaining climate data constant from present (2015) to the future (2050 or 2070). Similarly, to measure the impact of climate change alone, the climate projections into 2050 (or 2070) were obtained while retaining the land-use data constant from present (2015) to the future (2050 or 2070). Finally, to measure the impact of land use and climate change combined, models were run using projections of both land use and climate change into 2050 (or 2070).

Models were allowed to use their own re-categorization of the land-use classes in LUH2 dataset (Table S1) and select a climate dataset (e.g., Worldclim) that best suited their needs. For the past projections, models used past data in LUH2 and climate datasets with model specific assumptions in setting targets to year 1900 on variables for which historical data do not exist (Tables S1, S2). For the models that used ISI-MIP 2a IPSL climate dataset, random years from 1951 to 1960 were selected to fill the gap in climate input for years 1901 to 1950. The models (i.e., InSiGHTS, BILBI) that used WorldClim dataset did not simulate climate scenarios for the past projections given the gap in climate input before 1960. An overview of the model modifications and assumptions made to historical projections, which are specific to this intercomparison experiment, is provided in Table S2.

7 Uncertainties

Reporting uncertainty is a critical component of model intercomparison exercises (IPBES 2016). Within BES-SIM, uncertainties were explored in two ways: (1) each individual model had to report their original metrics' mean values, and where possible the 25th, 50th, and 75th percentiles based on different model parameterizations; and when combining the data provided by the different models, the average and the standard deviation of the common metrics (i.e., intermodel average and standard deviation of $P\gamma$, for example) were calculated; (2) the BIOMOD model was used in assessing the uncertainty in changes in species ranges arising from using different RCP scenarios, different GCMs, a suite of algorithms (e.g., random forest, logistic regression) and different species dispersal hypotheses to estimate change in species ranges and diversity distributions (change in alpha and beta diversity).

In the intercomparison analysis, we will conduct a comprehensive uncertainty analysis based on a variance partitioning approach on the outputs provided by the models of biodiversity. This will allow us to highlight uncertainties arising from the land use (SSPs), the climate (RCPs and GCMs), and, where relevant, the different taxa.

8 Discussion

This manuscript lays out the context, motives, processes, and approaches taken for the first round of the Biodiversity and Ecosystem Services Model Intercomparison Project (BES-SIM v1.0). This model intercomparison initiative aims to provide scientifically rigorous information to the IPBES and its ongoing and future assessments, the CBD and its strategic plans and conservation goals, and other relevant stakeholders on the expected status and trends of biodiversity and ecosystem services using a suite of metrics from a range of global models. The resulting outputs will include the analyses on the past, present and future impacts of land-use change, climate change and other drivers as embodied in a range of human development scenarios, coupled with associated climate projections. The model intercomparison analyses will put the future in the context of the past and the present.

The existing SSP and RCP scenarios provided a consistent set of past and future projections of two major drivers of terrestrial and freshwater biodiversity loss and ecosystem change – land use and climate. However, we acknowledge that these projections have certain limitations. These include limited inclusion of biodiversity-specific policies in the storylines (only the SSP1 baseline emphasises additional biodiversity policies) (O'Neill et al., 2016; Rosa et al., 2017), coarse spatial resolution, and land-use classes that are not sufficiently detailed to fully capture the response of biodiversity to land-use change (Harfoot et al., 2014a; Titeux et al., 2016, 2017). The heterogeneity of models and their methodological approaches, as well as additional harmonization required in data processing and lack of comparable metrics in ecosystem functions and services (Tables 7, S3), are areas for future work. In the future, it will be also important to capture the uncertainties associated with input data, with a focus on uncertainty in land-use and climate projections resulting from differences among IAMs and GCMs on each SSP and RCP scenarios, as they present a wide range of results with model specific assumptions and parameterizations (Popp et al., 2017). The gaps identified through BES-SIM and future directions for research and modelling will be published with analyses of the results on the model intercomparison and on individual models.

With growing demands for inter-sectoral collaboration in reaching the United Nations Aichi Biodiversity Targets and Sustainable Development Goals by 2020 and 2030 respectively, and ongoing discussion on the development of new biodiversity strategic plan 2020-2050 of the Convention on Biological Diversity, the initiation of BES-SIM was timely. Using consistent sets of scenarios with other model intercomparison projects, such as ScenarioMIP and CMIP6, will increase the potential for future collaboration and harmonization for more interactive modelling of ecological and socio-economic systems. Through such an effort, BES-SIM envisages to make scenarios and modelling more relevant and usable for biodiversity conservation and sustainable development. Furthermore, the climate science community has managed to put climate change on the agenda as a global challenge as a result of providing decision-makers with scientifically credible information on climate change and its impact on environment and society (Zhao, 2017). We envision BES-SIM to have a similarly important role in raising the general public's awareness to the issue of biodiversity loss and ecosystem degradation, and ultimately, its impacts on human well-being.

As a long-term perspective, BES-SIM is expected to provide critical foundation and insights for the ongoing development of nature-centred, multiscale Nature Futures scenarios (Rosa et al., 2017). Catalysed by the IPBES, this new scenarios and modelling framework will shift traditional ways of forecasting impacts of society on nature to more integrative, biodiversity-centred visions and pathways. With positive outlooks on sustainable future, Nature Futures scenarios are envisaged to be applicable and achievable in conservation policies and practice by integrating socio-ecological feedback loops across drivers, biodiversity, ecosystems, ecosystem services, and human well-being and by incorporating multiple systems of knowledge (Rosa et al., 2017). In a next round of BES-SIM, we intend to use biodiversity-centred storylines, with associated land-use and climate projections, to project dynamics of biodiversity and ecosystem services. Further, we would expand the modelling communities involved to improve the socio-ecological link to human well-being. This will help researchers, policymakers and practitioners to collectively identify areas of concern to explore alternatives pathways for sustainable future and to integrate stronger conservation policies in scenarios development.

9. Code and data availability

The protocol and supplementary materials for this model intercomparison will become downloadable from the BES-SIM website in the future. The LUH2 land-use data used for model runs are available on http://luh.umd.edu/data.shtml. The climate datasets used in BES-SIM can be downloaded from the respective websites (https://www.isimip.org/outputdata/, http://worldclim.org/version1)

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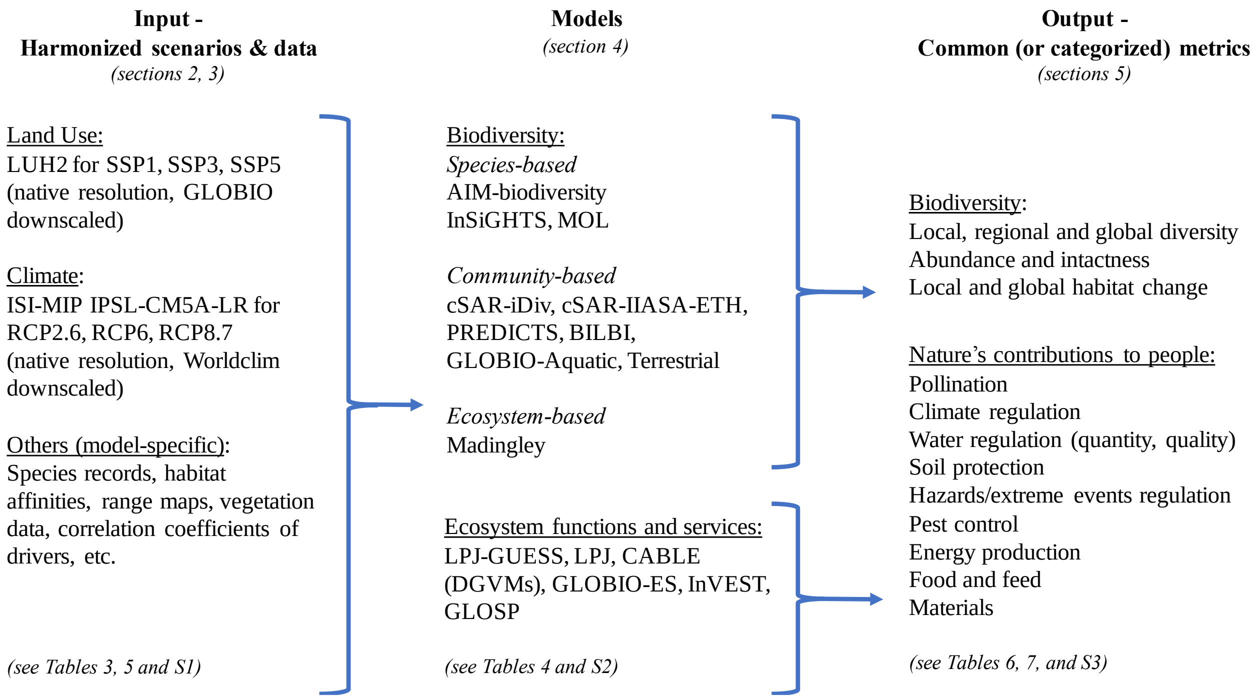
Figure 1: Input-models-output flowchart of BES-SIM



Input -
Harmonized scenarios & data
(sections 2, 3)

Land Use:
LUH2 for SSP1, SSP3, SSP5 (native resolution, GLOBIO downscaled)

Climate:
ISI-MIP IPSL-CM5A-LR for RCP2.6, RCP6, RCP8.7 (native resolution, Worldclim downscaled)

Others (model-specific):
Species records, habitat affinities, range maps, vegetation data, correlation coefficients of drivers, etc.

(see Tables 3, 5 and S1)

Models
(section 4)

Biodiversity:
Species-based
AIM-biodiversity
InSiGHTS, MOL

Community-based
cSAR-iDiv, cSAR-IIASA-ETH, PREDICTS, BILBI, GLOBIO-Aquatic, Terrestrial

Ecosystem-based
Madingley

Ecosystem functions and services:
LPJ-GUESS, LPJ, CABLE (DGVMs), GLOBIO-ES, InVEST, GLOSP

(see Tables 4 and S2)

Output -
Common (or categorized) metrics
(sections 5)

Biodiversity:
Local, regional and global diversity
Abundance and intactness
Local and global habitat change

Nature's contributions to people:
Pollination
Climate regulation
Water regulation (quantity, quality)
Soil protection
Hazards/extreme events regulation
Pest control
Energy production
Food and feed
Materials

(see Tables 6, 7, and S3)

Table 1: Characteristics of (a) SSP and (b) RCP scenarios simulated in BES-SIM (adopted from Moss et al., 2010; O'Neill et al., 2017; Popp et al., 2017; van Vuuren et al., 2011)

(a) SSP scenarios

	SSP1 Sustainability	SSP3 Regional Rivalry	SSP5 Fossil-fuel Development
Population growth	Relatively low	Low (OECD countries) to high (high fertility countries)	Relatively low
Urbanization	High	Low	High
Equity and social cohesion	High	Low	High
Economic growth	High to medium	Slow	High
International trade and globalization	Moderate	Strongly constrained	High
Land-use regulation	Strong to avoid environmental trade-off	Low with continued deforestation due to agriculture expansion	Medium with slow decline in deforestation
Agricultural productivity	High improvements with diffusion of best practices	Low with slow technology development and restricted trade	Highly managed and resource intensive
Consumption & diet	Low growth in consumption, low-meat	Resource-intensive consumption	Material-intensive consumption, meat-rich diet
Environment	Improving	Serious degradation	Highly successful management
Carbon intensity	Low	High	High
Energy intensity	Low	High	High
Technology development	Rapid	Slow	Rapid
Institution effectiveness	Effective	Weak	Increasingly effective
Policy focus	Sustainable development	Security	Development, free market, human capital
Participation of the land-use sector in mitigation policies	Full	Limited	Full
International cooperation for climate change mitigation	No delay	Heavy delay	Delay

(b) RCP scenarios

	RCP2.6 Low emissions	RCP6.0 Intermediate emissions	RCP8.5 High emissions
Radiative forcing	Peak at 3W/m2 before 2100 and decline	Stabilizes without overshoot pathways to 6W/m2 in 2100	Rising forcing pathways leading to 8.5 W/m2 in 2100
Concentration (p.p.m)	Peak at 490 CO2 equiv. before 2100 and then declines	850 CO2 equiv. (at stabilization after 2100)	>1,370 CO2 equiv. in 2100
Methane emission	Reduced	Stable	Rapid increase
Reliance on fossil fuels	Decline	Heavy	Heavy
Energy intensity	Low	Intermediate	High
Climate policies	Stringent		No implementation

Table 2: Sources of input data in BES-SIM.

BES-SIM model	Land-use data LUH2 v2.0		Climate data		
	Native resolution *0.25 degree*	Downscaled (GLOBIO) *300m*	CMIP5-IPSL Native Resolution *0.5 degree*	CMIP5-IPSL Downscaled (WorldClim) *1km*	IMAGE† (MAGICC 6.0)
Species-based models of biodiversity					
AIM-biodiversity	*		*		
InSiGHTS	*			*	
MOL	*			*	
Community-based models of biodiversity					
cSAR-iDiv	*				
cSAR-IIASA-ETH	*				
BILBI	*			*	
PREDICTS	*				
GLOBIO - Aquatic	*				*
GLOBIO4 - Terrestrial		*			*
Ecosystems-based model of biodiversity					
Madingley	*		*		
Models of ecosystem functions and services					
LPJ-GUESS	*		*		
LPJ	*		*		
CABLE	*		*		
GLOBIO-ES	*				*
InVEST		*		*	
GLOSP	*		*		

†All GLOBIO models use MAGICC climate data from the IMAGE model.

Table 3: Improvements made in the Land Use Harmonization v2 (LUH2) dataset from LUH v1 (Hurtt et al., 2011)

	LUH v1	LUH v2
Spatial resolution	0.5 degree	0.25 degree
Time steps	Annually from 1500 to 2100	Annually from 850 to 2100
Land use categories	5 categories Primary Secondary Pasture Urban Crop	12 categories Forested primary land (primf) Non-forested primary land (primn) Potentially forested secondary land (secdf) Potentially non-forested secondary land (secdn) Managed pasture (pastr) Rangeland (range) Urban land (urban) C3 annual crops (c3ann) C3 perennial crops (c3per) C4 annual crops (c4ann) C4 perennial crops (c4per) C3 nitrogen-fixing crops (c3nfx)
Future	RCPs (4) 2.6 4.5 6.0 8.5	SSPs (6) SSP1-RCP2.6 SSP4-RCP3.4 SSP2-RCP4.5 SSP4-RCP6.0 SSP3-RCP7.0 SSP5-RCP8.5
Land use transitions	<20 per grid cell per year	>100 per grid cell per year
Improvements		- New shifting cultivation algorithm - Landsat F/NF change constraint - Expanded diagnostic package - New historical wood harvest reconstruction - Agricultural management layers: irrigation, fertilizer, biofuel crops, wood harvest product split, crop rotations, flooded (rice)

Table 4: Description of biodiversity and ecosystem functions and services models in BES-SIM.

BES-SIM Model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
Species-based models of biodiversity							
AIM-biodiversity (Asia-Pacific Integrated Model – Biodiversity)	A species distribution model that estimates biodiversity loss based projected shift of species range under the conditions of land use and climate change.	Distribution of suitable habitat (land) estimated from climate and land-use data using a statistical model on species presence and climate and land-use classifications, calibrated by historical data.	Please see Table S2 for detailed methodology.	0.5 degree	1900, 2015, 2050, 2070	Amphibians, birds, mammals, plants, reptiles	(Ohashi et al., in prep.)
InSiGHTS	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.	Bioclimatic envelope models fitted based on ecologically current reference bioclimatic variables. Species' presence and pseudo-absence records from sampling within and outside of species' ranges. Forecasted layers of land-use/land-cover reclassified according to expert-based species-specific suitability indexes.	Increased number of modelled species, new scenarios for climate and land use.	0.25 degree	1900, 2015, 2050, 2070	Mammals	(Rondinini et al., 2011; Visconti et al., 2016)
MOL (Map of Life)	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.	Expert maps for terrestrial amphibians, birds and mammals as baseline for projections, combined with downscaled layers for current climate. A penalized point process model estimated individual species niche boundaries, which were projected into 2050 and 2070 to estimate range loss. Species habitat preference-informed land cover associations were used to refine the proportion of suitable habitat in climatically suitable cells with present and future land-cover based projections.	Inductive species distribution modelling was built using point process models to delineate niche boundaries. Binary maps of climatically suitable cells were rescaled (to [0,1]) based on the proportion of the cell within a species land cover preference	0.25 degree	2015, 2050, 2070	Amphibians, birds, mammals	(Jetz et al., 2007; Merow et al., 2013)

BES-SIM Model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
BIOMOD2 (BIOdiversity MODelling)	An R-package that allows running up to nine different algorithms of species distribution models using the same data and the same framework. An ensemble could then be produced allowing a full treatment of uncertainties given the data, algorithms, climate models, climate scenarios.	BIOMOD2 is based on species distribution models that link observed or known presence-absence data to environmental variables (e.g. climate). Each model is cross-validated several times (a random subset of 70% of the data is used for model calibration while 30% are hold out for model evaluation). Models are evaluated using various metrics.		100km	2015, 2050, 2070	Amphibians, birds, mammals	(Thuiller, 2004; Thuiller et al., 2009, 2011)
Community-based models of biodiversity							
cSAR (Countryside Species Area Relationship) - iDiv	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.	Proportional species richness of each species group is a power function of the sum of the areas of each habitat in a landscape, weighted by the affinity of each species group to each habitat type. Species richness is calculated by multiplying the proportional species richness by the number of species known to occur in the area. Total number of species in a landscape is the sum of the number of species for each species group.	Two functional groups of bird species: (1) forest birds; (2) non-forest birds. Habitat affinities retrieved from PREDICTS database.	0.25 degree	1900-2010 (10 years interval), 2015, 2050, 2070, 2090	Birds (forest, non-forest, all)	(Martins and Pereira, 2017)

BES-SIM Model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
cSAR- IIASA-ETH	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.	Extends concept the SAR to mainland environment where the habitat size depends not only on the extent of the original pristine habitat, but also on the extent and taxon-specific affinity of the other non-pristine land uses and land covers (LULC) of conversion. Affinities derived from field records. Produces the average habitat suitability, regional species richness, and loss of threatened and endemic species for five taxonomic groups.	Refined link between LULCC and habitat (gross transitions between LULC classes at each time) and better accounting of time dynamics of converted LULC classes.	0.25 degree	1500-1900 (100 years interval), 1900-2090 (10 years interval)	Amphibians, birds, mammals, plants, reptiles	(Chaudhary et al., 2015; UNEP, 2016)
BILBI (Biogeographic modelling Infrastructure for Large-scale Biodiversity Indicators)	A modelling framework that couples application of the species-area relationship with correlative 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).	The potential effects of climate scenarios on beta-diversity patterns are estimated through space-for-time projection of compositional-turnover models fitted to present-day biological and environmental data. These projections are then combined with downscaled land-use scenarios to estimate the proportion of species expected to persist within any given region. This employs an extension of species-area modelling designed to work with biologically-scaled environments varying continuously across space and time.	Please see Table S3 for detailed methodology.	1 km (30 arcsec)	1900, 2015, 2050	Vascular plants	(Ferrier et al., 2004, 2007)

BES-SIM Model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems)	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.	Models employdata from the PREDICTS database encompassing 767 studies from over 32,000 sites on over 51,000 species. Models assess how alpha diversity is affected by land use, land-use intensity and human population density. Model coefficients are combined with past, present and future maps of the pressure data to make global projections of response variables, which are combined to yield the variants of the Biodiversity Intactness Index (an indicator first proposed by Scholes et al. 2005).	PREDICTS LU classes recurated for LUH2. Abundance rescaled within each study. Baseline of minimally-used primary vegetation. Compositional similarity models included human population. Study-level mean human population and agricultural suitability used as control variables. Proximity to road omitted.	0.25 degree	900-2100	All	(Newbold et al., 2016; Purvis et al., 2018)
GLOBIO (GLObal BIOdiversity) - Aquatic	A modelling framework that quantifies the impacts of land-use, eutrophication, climate change and hydrological disturbance on freshwater biodiversity (MSA) and ecosystem functions/services.	Comprises a set of (mostly correlative) relationships between anthropogenic drivers and biodiversity/ES of rivers, lakes and wetlands. Based on the catchment approach, i.e. the pressures on the aquatic ecosystems are based on what happens in their catchment. Based on the literature.		0.5 degree	2015, 2050	All	(Janse et al., 2015, 2016)

BES-SIM Model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
GLOBIO - Terrestrial	A modelling framework that quantifies the impacts of multiple anthropogenic pressures on local biodiversity, quantified as the mean species abundance (MSA).	Based on a set of correlative relationships between biodiversity (MSA) on the one hand and anthropogenic pressures on the other, quantified based on meta-analyses of biodiversity data reported in the literature. Georeferenced layers of the pressure variables are then combined with the response relationships to quantify changes in biodiversity.	Improved land-use allocation routine, improved response relationships for encroachment (hunting)	10 arc-seconds (~300 m)	2015, 2050	All	(Schipper et al., 2016)
Ecosystems-based model of biodiversity							
Madingley	An integrated process-based, mechanistic, general ecosystem model that uses a unified set of fundamental ecological concepts and processes to predict the structure and function of the ecosystems at various levels of organisation for marine or terrestrial.	Grouped by heterotroph cohorts, organisms are defined by functional traits rather than the taxonomy. Heterotrophs, defined by categorical (trophic group; hermoregulation strategy; reproductive strategy) and quantitative (current body mass; mass at birth; and mass at reproductive maturity) traits are modelled as individuals dynamically. Simulates the autotroph ecological processes of growth and mortality; and heterotroph metabolism, eating, reproduction, growth, mortality, and dispersal. Dispersal is determined by the body mass.	Incorporation of temporally changing climate, and natural and human impacted plant stocks to better represent the LUHv2 land-use projections. Calculation of functional diversity and dissimilarity to represent community changes	1 degree	1901, 1915-2070 (5 years interval)	Three functional groups?	(Harfoot et al., 2014b)
Models of ecosystem functions and services							

BES-SIM Model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator)	A process-based "demography enabled" dynamic global vegetation model that computes vegetation and soil state and function, as well as distribution of vegetation units dynamically in space and time in response to climate change, land-use change and N-input.	. Vegetation dynamics result from growth and competition for light, space and soil resources among woody plant individuals and herbaceous understorey. A suite of simulated patches per grid cell represents stochastic processes of growth and mortality (succession). Individuals for woody PFTs are identical within an age-cohort. Processes such as photosynthesis, respiration, stomatal conductance are simulated daily. Net primary production (NPP) accrued at the end of each simulation year is allocated to leaves, fine roots and, for woody PFTs, sapwood, resulting in height, diameter and biomass growth.	The model version used here has some updates to the fire model compared to Knorr et al. (2016) see also Rabin et al. (2017). Simulations also accounted for wood harvest, using the modelled recommendations from LUH2.	0.5 degree	1920, 1950, 1970, 2015, 2050, 2070		(Lindeskog et al., 2013; Olin et al., 2015; Smith et al., 2014)
LPJ (Lund-Potsdam-Jena)	A big leaf model that simulates the coupled dynamics of biogeography, biogeochemistry and hydrology under varying climate, atmospheric CO2 concentrations, and land-use land cover change practices to represent demography of grasses and trees in a scale from individuals to landscapes.	Hierarchical representation of the land surface - tiles represent land use with various plant or crop functional types. Implements establishment, mortality, fire, carbon allocation, and land cover change on annual time steps, and calculates photosynthesis, autotrophic respiration, and heterotrophic respiration on daily time steps. Fully prognostic, meaning that PFT distributions and phenology are simulated based on physical principles within a numerical framework.	LPJ represents the full set of states and transitions represented in LUHv2 and improved estimate of carbon fluxes from land-cover change.	0.5 degree	1920, 1950, 1970, 2015, 2050, 2070		(Poulter et al., 2011; Sitch et al., 2003)

BES-SIM Model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
CABLE (Community Atmosphere Biosphere Land Exchange)	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 and N-input.	Combines biophysics (coupled photosynthesis, stomatal conductance, canopy energy balance) with daily biogeochemical cycling of carbon and nitrogen (CASA-CNP) and annual patch-based representation of vegetation structural dynamics (POP). Accounts for gross land-use transitions and wood harvest, including effects on patch age distribution in secondary forest. Simulates co-ordination of rate-limiting processes in C3 photosyntheisis, as an outcome of fitness maximisation.		1 degree	1920, 1950, 1970, 2015, 2050, 2070		(Haverd et al., 2017)
GLOBIO-Ecosystem Services	The model simulates the influence of various anthropogenic drivers on ecosystem functions and services.	Quantifies a range of provisioning services (e.g. crop production, grass and fodder production, wild food), regulating services (e.g. pest control, pollination, erosion risk reduction, carbon sequestration), and culture services (e.g. nature based tourism) and other measures (e.g. water availability, food risk reduction, harmful algal blooms). Derived from various models, including the IMAGE model and PCR-GLOBWB, and from empirical studies using meta-analysis.	Relationships between land use and the presence of pollinators and predators updated through additional peer review papers.	0.5 degree	2015, 2050, 2070		(Alkemade et al., 2009, 2014; Schulp et al., 2012)

BES-SIM Model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs)	A suite of GIS based spatially-explicit models used to map and value the ecosystem goods and services in biophysical or economic terms.	18 models for distinct ecosystem services designed for terrestrial, freshwater, marine and coastal ecosystems. Based on production functions that define how changes in an ecosystem's structure and function are likely to affect the flows and values of ecosystem services across a land- or a seascape. Accounts for both service supply and the location and activities of demand. Modular and selectable.	The crop-production model was simplified from 175 crops to the 5 crop-types reported in LUH2. Other models have minor simplifications; see tables S2 and S3 for more detail.	300m and 5 arc-minute	2015, 2050		(Arkema et al., 2013; Chaplin-Kramer et al., 2014; Guannel et al., 2016; Johnson et al., 2014, 2016; Redhead et al., 2018; Sharp et al., 2016)
GLOSP (GLObal Soil Protection)	A 2D soil erosion model based on the Universal Soil Loss Equation that uses climate and land-use projections to estimate global and local soil protection.	Protected soil (Ps) is defined as the amount of soil that is prevented from being eroded (water erosion) by the mitigating effect of available vegetation. Ps is calculated from the difference between soil erosion (Se) and potential soil erosion (Pse) based on the integration of the joint effect of slope length, rainfall erosivity, and soil erodibility. Soil protection is given by the value of fractional vegetation cover calculated as a function of land use, altitude, precipitation, and soil properties.	Please see Table S3 for detailed methodology.	0.25 degree	2015, 2050		(Guerra et al., 2016)

Table 5: Scenario (forcing data) for models in BES-SIM.

		Future Land-Use Change or Climate (2050)		
BES-SIM model	Historical	Land use only, climate held constant at 2015 (SSP1, SSP3, SSP5)	Climate change only, land use held constant at 2015 (RCP2.6, RCP6.0, RCP8.5)	Land use and climate (SSP1xRCP2.6, SSP3xRCP6.0, SSP5xRCP8.5)
Species-based models of biodiversity				
AIM-biodiversity	*	*	*	*
InSiGHTS	*	*	*	*
MOL		*	*	*
Community-based models of biodiversity				
cSAR-iDiv	*	*		
cSAR-IIASA-ETH	*	*		
BILBI	*	*		*
PREDICTS	*	*		
GLOBIO - Aquatic				*
GLOBIO - Terrestrial		*	*	*
Ecosystems-based model of biodiversity				
Madingley	*			*
Models of ecosystem functions and services				
LPJ-GUESS	*	*	*	*
LPJ	*	*	*	*
CABLE	*	*	*	*
GLOBIO-ES				*
InVEST				*
GLOSP				*

Table 6: Selected output indicators for inter-comparison of biodiversity and ecosystems models.

BES-SIM model	Local scale species diversity at pixel level (Pα and Nα)	Subregional and global scale species diversity (Pγ and Nγ)	Species-based intactness and abundance (Iα)	Local and global habitat change (Hα and Hγ)
Species-based models of biodiversity				
AIM-biodiversity	*	*		*
InSiGHTS	*	*		*
MOL	*	*		*
Community-based models of biodiversity				
cSAR-iDiv	*	*		
cSAR-IIASA-ETH	*	*		
BILBI		*		
PREDICTS	*		*	
GLOBIO - Aquatic			*	
GLOBIO - Terrestrial			*	
Ecosystems-based model of biodiversity				
Madingley			*	

Table 7: Selected output indicators for inter-comparison of ecosystem functions and services models, categorized based on the classification of Nature's Contributions to People **(Díaz et al., 2018)**.

BES-SIM model	NCP 2. Pollination and dispersal of seeds and other propagules	NCP 4. Regulation of climate	NCP 6. Regulation of freshwater quantity, location and timing	NCP 7. Regulation of freshwater and coastal water quality	NCP 8. Formation, protection and decontamination of soils and sediments	NCP 9. Regulation of hazards and extreme events	NCP 10. Regulation of detrimental organisms and biological processes	NCP 11. Energy	NCP 12. Food and feed	NCP 13. Materials, companionship and labor
LPJ-GUESS		Total carbon Vegetation carbon	Monthly runoff	Nitrogen leaching				Bioenergy-crop production	Harvested carbon in croplands that are used for food production	Wood harvest (LUH2 extraction)
LPJ		Total carbon Vegetation carbon	Monthly runoff							
CABLE		Total carbon Vegetation carbon	Monthly runoff, Total runoff						Above ground carbon removed from cropland and pastures as a result of harvest and grazing	Wood harvest
GLOBIO-ES	Fraction of cropland potentially pollinated, relative to all available cropland	Total carbon	Water scarcity index	Nitrogen in water Phosphorus in water	Erosion protection: fraction with low risk relative to the area that needs protection	Flood risk: number of people exposed to river flood risk	Pest control: Fraction of cropland potentially protected, relative to all available cropland		Total crop production Total grass production	
InVEST	Proportion of agricultural lands whose pollination needs are met			Nitrogen export Nitrogen export*capita		Coastal vulnerability Coastal vulnerability *capita			Caloric production per hectare on the current landscape for each crop type	
GLOSP					Soil protection					

Table 8. Acronyms

AIM	Asia-pacific Integrated Model
BES-SIM	Biodiversity and Ecosystem Services Scenario-based Intercomparison of Models
BIOMOD	BIOdiversity MODelling
BILBI	Biogeographic modelling Infrastructure for Large-scale Biodiversity Indicators
CABLE	Community Atmosphere Biosphere Land Exchange
CMIP	Climate Model Inter-comparison Project
cSAR	Countryside Species Area Relationship
DGVM	Dynamic Global Vegetation Model
ESM	Earth System Models
GBIF	Global Biodiversity Information Facility
GBO	Global Biodiversity Outlooks
GCM	Global Circulation Models
GEO	Global Environmental Outlook
GLOBIO	GLObal BIOdiversity
GLOSP	GLObal Soil Protection
IAM	Integrated Assessment Models
IMAGE	Integrated Model to Assess the Global Environment
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPSL-CM5A-LR	Institut Pierre-Simon Laplace-Climate Model 5A-Low Resolution
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
LPJ	Lund-Potsdam-Jena
LPJ-GUESS	Lund-Potsdam-Jena General Ecosystem Simulator
LUH2	Land Use Harmonization Project version 2
MA	Millennium Ecosystem Assessment
MAgPIE	The Model of Agricultural Production and its Impact on the Environment
MIP	Model Intercomparison Project
MOL	Map of Life
NCP	Nature’s Contributions to People
PREDICTS	Projecting Responses of Ecological Diversity In Changing Terrestrial Systems
RCM	Regional Climate Models
RCPs	Representative Concentration Pathways
SAR	Species Area Relationship
SR	Species Richness
SSPs	Shared Socio-economic Pathways