Response to Reviewer's Comments

We would like to thank the reviewers for the thorough review and comments on our manuscript. In the revised version, we did our best to incorporate them and we feel that the manuscript has greatly improved as a result. Please see the specific replies to the reviewer comments below.

Anonymous Referee #1

Received and published: 30 August 2018

The manuscript outlines a protocol for comparing models of the impacts of land-use and climate on biodiversity and ecosystem services. Intercomparisons of biodiversity and ecosystem services models and scenarios is much needed, especially for intergovernmental processes such as the IPBES, other policy processes, and conservation interventions. The manuscript outlines a process of comparing 16 spatially-explicit models for past (up to 900 AD), present (2015) and future (up to 2070) based on 3 scenarios (combinations of SSPs and RCPs) and the output variables that can be compared. Overall, biodiversity and ecosystem services model intercomparisons are much needed and this manuscript outlines a protocol for such intercomparisons for the first time.

Thank you for your comments.

Uncertainty is a critical part of models and model intercomparisons as acknowledged in the manuscript (section 7). The section on uncertainties, how uncertainty will be assessed within models and across models is too brief to be helpful. It would be interesting to better understand what the "comprehensive uncertainty analysis based on a variance partitioning approach" would involve. Furthermore, the text states that uncertainty of "the models of biodiversity" (P11) will be assessed, but there is no mention on how ecosystem services model outputs will be assessed for uncertainty. Both types of models will contain uncertainties that require assessment.

We appreciate this comment. In BES-SIM, uncertainties were reported by each modelling team with quantiles, both for biodiversity and ecosystem services where feasible (i.e. models that are able to incorporate uncertainty in their structure). Using the outputs provided, we explored intermodel uncertainty by calculating the mean and standard deviations across all models. The proposed variance partitioning approach is a forward-looking analysis that we aim to produce, but that was not part of the first iteration of BES-SIM. Therefore, we removed it from this section and updated the text accordingly. Please see page 13 (P13L16-24).

The section on other input data (section 3.3) should acknowledge the need for additional parameters within each model, in particular in ecosystem service models. For example, InVEST requires detailed information on parameters/look up tables to allocate the ecosystem service; Madingley has predator-prey relationships encoded. Will the default values be used for the intercomparisons or will models be modified? Which versions of the models will be used? Some of this information is provided in Appendix 1, however more detail could be provided.

In this protocol manuscript, we documented for each model its key components and any particular modifications made for this exercise (Appendix 1 and Table S2). Given the vast amount of technical information for each model and this intermodel comparison, we tried to keep the level of technical details to the extent of readability of the manuscript. Further details on the parameterization of each model, including its default values, can be found in the key publications of each model listed in Appendix 1 of the manuscript and a further set of publications being prepared as a special issue in Global Change Biology detailing each model.

<u>Minor comments</u>

P2L27: ecosystems are a subset of biodiversity as defined by the Convention on Biological Diversity, therefore delete "ecosystems" here.

Corrected. Please see page 2 (P2L29).

P2L31-32: the statement that land-use change has immediate impacts on biodiversity and ecosystem services and impacts of climate change involves time lags is not correct. Both land use and climate changes can have immediate and lagged impacts. There is substantial evidence that climate change can have immediate impacts (e.g. Wellbergen et al. 2008 Proc Roy Soc B 275: 419-425) and land use impacts can be time lagged (e.g. McMichael et al. 2017. Ancient human disturbances may be skewing our understanding of Amazonian forests. PNAS 114: 522-527; Jakovac et al. 2016. Land use as a filter for species composition in Amazonian secondary forests. J. Veg. Sci. 27: 1104-1116; Graham et al. Graham et al. 2017. Implications of afforestation for bird communities: the importance of preceding land-use type. Biodiv. Cons. 26: 3051-3071).

We have used suggested references (Wellbergen et al., 2008; Graham et al., 2017) and revised the sentence as follows on page 3 (P2L32-35):

"Habitat and land-use changes, resulting from past, present and future human activities, as well as climate change, have both immediate and long term impacts on biodiversity and ecosystem services (Graham et al., 2017; Lehsten et al., 2015; Welbergen et al., 2008)."

P3L8 Ferrier et al. 2016 missing from reference list, maybe should be IPBES 2016?

We corrected the reference to IPBES 2016, see for example on page 3 (P3L31).

P5L21 Need to clarify the difference between RCP7.0 which was used for land-use projections and RCP6.0 which is used for other scenario production. Explain why SSP3/RCP7.0 was not used instead of the mixed SSP3/RCP6.0+RCP7.0 for land use. Furthermore, Table 5 does not show the use of RCP7.0 for land use, it is shown as RCP6.0; check this is correct.

The land use dataset used, LUH2, was produced to be consistent with paired RCPs. However, and although the SSP3 is associated with RCP7.0 (SSP3xRCP7.0), currently, climate projections (i.e., time series of precipitation and temperature) are not available for RCP7.0. Therefore, we chose the closest RCP available, which was RCP6.0, and adapted the name of this SSPxRCP combination to SSP3xRCP6.0 to fit our exercise. We now make this clearer in the text on page 5 (P5L17-20):

"The SSP3 is associated with RCP7.0 (SSP3xRCP7.0); however, climate projections (i.e., time series of precipitation and temperature) are currently not available for RCP7.0. Therefore, we chose the closest RCP available, which was RCP6.0, for the standalone use of climate projections and chose SSP3xRCP6.0 for the land use projections from the LUH2. In this paper, we refer to this scenario as SSP3xRCP6.0."

P6L16: spell out ESM at first use.

ESM is spelled out at its first use on page 4 (P4L5).

P7L21: Table 2 shows 13 (and not 12) models requiring climate data. Which is correct, text or table?

Corrected. Please see page 8 (P8L6)

P10L12-15: reword this sentence, not comprehensible.

We have rewritten this sentence to increase clarity as follows on page 12 (P12L2-7):

"The habitat change (H) measures cell-wise changes in available habitat for the species. It is the changes in the suitable habitat extent of each species relative to a baseline, i.e., (Ei,t-Ei,t0)/Ei,t0, where Ei,t is the suitable habitat extent of species i at time t within the unit of analysis. It is reported by averaging across species occurring in each unit of analysis (grid cell, region, or globe), and is provided by the species-level models (i.e., AIM-biodiversity, InSiGHTS, MOL) (Table 4)."

P10L30: "units of the metrics" are not listed in Table 6. Update Table 6 with units, or reword text.

Thank you for noting this. We now state that units are in Table S3 of the Supplement on page 12 (P12L22-23).

P11L3: replace "Additional" with "Additionally"

Corrected. Please see page 12 (P12L26).

P11L4: Table 5 does not show the multiple time points from past to future, this information is provided in Appendix 1 first table. Note tables in Appendix 1 do not have legends or numbers.

Indeed, we now refer to Appendix 1. We have now numbered Appendix 1 table as Appendix 1 Table A1. Please see page 34.

P12L4-5: insert "to" before "the CBD and. . ." and before "other relevant stakeholders"

The paragraph that contained this sentence has been deleted in response to a comment of the second reviewer to avoid the repetition of information from the Introduction.

P14References: some references included "edited by" information for journal articles, e.g. Harfoot et al 2014b, Heinimann et al 2017. Check this is in line with the journal reference guidelines. Several references are submitted or in preparation, hence make it impossible to fully assess this manuscript.

Thanks for noting this. We have now corrected all of the references with editors according to the Copernicus reference style. We have also updated the publishing status of the four references in preparation or submission with a URL link to the preprint where available. Please see for example on page 16 (P16L2-4)

P23-all tables: check carefully throughout. CO2 and m2 should have subscript and superscript "2"s.

Thank you for noting this. We now have subscripts and superscripts correctly placed, see for example of CO_2 *in Table 1 on page 28.*

P23Table1: Information on RCP6.0 is provided, however as RCP7.0 is used for land use projection, some info needs to be provided for RCP7.0 in this table or elsewhere. Information on climate policies is missing for RCP6.0. Table legend should read "Sources of land use and climate input data in BES-SIM" as other input data are used in all models (see later Tables).

Please see our reply to the reviewer's comment P5L21. Further, we added the missing information regarding "climate policies" in RCP6.0 in Table 1 on page 28. We have also modified the caption of Table 2 as suggested on page 29.

P26Table4: better explain "alpha and gamma metrics".

In Section 5 Output metrics, we now provide definitions to alpha (α) and gamma (γ) metrics as follows on page 11 (P11L18-20):

"These metrics were calculated at two scales: local or grid cell (α scale, i.e. the value of the metric within the smallest spatial unit of BES-SIM which is the grid cell) and regional or global (γ scale, i.e. the value of the metric for a set of grid cells comprising a region)."

P32: Scholes et al. 2005 reference is missing in reference list

We added Scholes and Bigg 2005 reference to the list. Thank you for your note.

P34: spell out PFTs at first use (and all other acronyms throughout, e.g. GIS on P36, etc.)

All acronyms are now spelled out at their first use in Appendix 1, see for example on pages 36 and 38.

P37: PCR-GLOBWB is missing from the list of acronyms

We have now added it to the list of acronyms in Appendix 2 on page 43.

P1-37: throughout the text reference is being made to Table S1, S2 etc. (e.g. P7L11), however no tables S1, S2 etc. are included.

We now added a sentence at the end of the manuscript on page 15 (P15L1-2) stating the existence of the Supplement.

Anonymous Referee #2

Received and published: 31 August 2018

Dear authors

The manuscript "A protocol for an intercomparison of biodiversity and ecosystem services models using harmonized land-use and climate scenarios" could be suitable for Geoscientific Model Development. This manuscript explains the framework of BESSIM (inter-comparison study). This model inter-comparison study tries to contribute not only to science communities including earth system modeling, climate science, and ecology, but also the other stakeholders such as policy maker. I fully agreed on the importance of this project to manage the impact on biodiversity and ecosystem services by anthropogenic activities. However, I feel the main manuscript is the lack of content to follow the overall picture of BES-SIM.

From the view to GMD paper, I cannot recommend acceptance for the publication in the current manuscript.

<u>Major comments</u>

Many concerns are as follow;

1. For outside of the ecological area of expertise, the manuscript is not so helpful to understand BES-SIM. For example, there are many outputs related to the biodiversity, however, there are few definition and explanation of each output. At least, this journal's fields is not ecology. So, readers cannot follow even the unit of outputs provided in BES-SIM (e.g., abundance). They should be clearly described in the main manuscript.

   Thank you for your comments. We have now expanded the definitions of each output metric to better guide non-specialists readers throughout the manuscript. Please see Section 4 and Section 5.

2. (I guess) To each SSP (RCP), the narratives (and interpretation) from the view to biodiversity and its social governance should be described in the scenario session. Table 1 provides such kind of information against each factor. The readers want to know these narratives in advance. For example, which one is business as usual to biodiversity? If there are no narratives in biodiversity (it means biodiversity sector is just passive against the other policies), please explain instead. Or, please make the narratives so as to follow the each SSP concept. (Sorry, I wrote this comment before reading the discussion. But, even after the reading discussion, I keep this comment. Also, I apologize that I cannot read Rosa et al. (2017) due to the non-license to read.)

   The SSPs purposely excluded biodiversity in its narratives, except for SSP1 being an environmentally *friendly scenario; thereby potentially the best for biodiversity. We have now added couple of sentences to make it explicit as follows on page 5 (P5L18-21):*

"The SSP scenarios excluded elements that have interaction effects with climate change except for SSP1, which focuses on environmental sustainability. Thus, SSPs describe futures where biodiversity is not affected by climate change to allow for the important estimation of the climate change impact on biodiversity (O'Neill et al., 2014)."

Individual comments

P2L17–19 Please suggest the combination (i.e., SSP1×RCP2.6?) here.

We have inserted the three scenarios combinations in the abstract on page 2 (P2L20).

P3L2 Please clarify "at high levels of climate change".

We have deleted this part from the sentence for clarity on page 3 (P3L4).

P3L5–6 Please suggest how to assess the impacts using the scenario? With empirical or mechanistic model?

We have now refined this by adding the following text on page 3 (P3L8-12):

"Models are used to quantify the biodiversity and ecosystem services impacts of different scenarios, based on climate and land-use projections from General Circulation Models (GCM) and Integrated Assessment Models (IAM) (Pereira et al., 2010)."

P3L6–8 Models are ... Meaning of this sentence is not clear.

We have now refined this by adding the following text on page 3 (P3L12-14):

"These models include empirical dose-response models, species-area relationship models, species distribution models and more mechanistic models such as trophic ecosystem models (Pereira et al., 2010; Akçakaya et al., 2016)."

P3L9 I'm not sure "cross-model harmonization".

We replaced the term with "intermodel comparison" on page 3 (P3L15). Thank you for your note.

P3L9–12 "addressing this issue" <Please add the citation.

We replaced the term "this issue" with "this gap" to make it explicit that we refer to the gap identified in the previous sentence. We also added citations (IPBES, 2016; Leadley et al., 2014) that mention this gap *and clarified the role of this manuscript in addressing this gap as follows on page 3 (P3L14-19):*

"So far, each of these scenario exercises have been based on a single model or a small number of biodiversity and ecosystem service models, and intermodel comparison and uncertainty analysis have been limited (IPBES, 2016; Leadley et al., 2014). The Expert Group on Scenarios and Models of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is addressing this gap by carrying out a biodiversity and ecosystem services model intercomparison with harmonized scenarios, for which this paper lays out the protocol."

P3L21–23 I didn't find Ferrier et al. (2016) said the meaning of this sentence in the discussion. Is this a correct citation?

We corrected the reference to IPBES 2016, see for example on page 3 (P3L31).

P3L25–27 I cannot agree with the sentence "to improve the robustness and comprehensiveness". MIPs (at least without observation data) will not contribute to the improvement of the robustness. Did Warszawski et al. (2014) explain such? (I found they said "process understanding and model development" for ISIMIP.)

Thank you for your comments. We revised the sentence to correct the mention of the robustness, and make clear that MIPs allow for identification of uncertainties associated with scenarios and models. We also added a citation as follows on page 3 (P3L32-34):

"Model intercomparisons bring together different communities of practice for comparable and complementary modelling, in order to improve the comprehensiveness of the subject modelled, and to estimate uncertainties associated with scenarios and models (Frieler et al., 2015)."

P3L28–32 Are there any relationship between ISI-MIP and BES-SIM? If they have, please explain. Else, please remove this sentence.

We added the following sentence to the next paragraph to clarify the relationship between ISI-MIP and BES-SIM as follows on page 4 (P4L12-13):

"Whereas independent of the ISI-MIP, the BES-SIM has been inspired by ISI-MIP and other intercomparison projects and was delivered to address the needs of the global assessment of IPBES."

P4L7 assess -> assessed

Corrected. Please see page 4 (P4L18).

2 Scenario selection It is a little bit obvious that there is no description for bioenergy in SSP1×RCP2.6. Regarding this, there is no information for SSP×RCP scenario matrix in this session.

Therefore, I don't fully understand what is the rationale in the selection of scenario. I believe careful explanation in the scenario selection is helpful to communicate the results.

The SSP and RCP scenarios explore low and high levels of changes in land use and climate. Bioenergy aspects are not prescribed by the storylines in scenarios but it is an endogenous outcome of the models applied on the SSPs in combination with the RCPs. The bioenergy is fairly low in SSP1xRCP 2.6 (highest mitigation) with low emissions of RCP2.6 in a low energy intense and sustainable SSP1 world. It is fairly high in SSP3xRCP 6.0 (little mitigation) even with little mitigation as, for instance, other land based mitigation is not working due to governance failures. SSP5xRCP8.5 (no mitigation) has the lowest bioenergy mainly based on residues. We have now added this information in Table 1 (c) on page 28.

P7L6–7 Please add the citations for all the biodiversity models here. This line is the first appearance of the models in the text.

We have revised the Section 3.3 and Section 4 where the models are introduced, to have the references for the models to appear the first time they are mentioned. Thank you for noting this.

P7L4–11 Please add the citation in the manuscript, even though author remarked the citations.

We have revised the Section 3.3 and added citations in the manuscript.

What is "PREDICTS"?

PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) is the name of one of the biodiversity models included in the BES-SIM exercise. In reality, PREDICTS is a research project (http://www.predicts.org.uk/), in which they create a database of field data (collected from the literature) (Hudson et al. 2017; Hudson et al. 2016) and with which they developed their biodiversity model (Newbold et al., 2016; Purvis et al., 2018). In order to ease the read of the manuscript, which has a large number of acronyms, we kept the model names in acronyms in the text to prevent acronym cluttered sentences which are difficult to follow. The full names of the models can be found both in Appendix 1 and Appendix 2.

CO2 concentrations come from RCP? etc...

To maintain readability, we opted by keeping the text of the manuscript brief with a reference to the table where data sources can be found either in the table itself or in the key publications for each model.

Section 4 Please remark specifically how many species (taxonomic groups?) can simulate in each model.

We have now added the taxonomic groups and the number species modelled in each model in Section 4.

P7L24–25 Please suggest the definitions and units in each variable, if they have (e.g., species, amphibians, organisms).

We have added definitions to the metrics, ecological concepts and methods used in modelling, and taxonomic groups and the number of species modelled in Section 4 to better guide the reader.

P8L6 What is the expert-based model?

We now describe expert-based models and maps as for general comment and clarified it in the sentence as follows on page 8 (P8L25-30):

"Both models rely on IUCN's expert-based range maps as a baseline, which are developed based on expert knowledge of the species habitat preferences and areas known to be absent (Fourcade, 2016). InSiGHTS and MOL used a 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, a model detailing associations between species and habitat types based on expert opinions is used to assess the impacts of land-use in the climate suitable portion of the species range."

P8L7 Please add the brief explanation for BIOMOD2.

We added brief description of the BIOMOD2 model as follows on page 8-9 (P8L30-P9L2):

"BIOMOD2 is an R modelling package that runs up to nine different algorithms (e.g., random forests, logistic regression) of species distribution models using the same data and the same framework. BIOMOD2 included three taxonomic groups (amphibians, birds, mammals) (see section 7. Uncertainties)."

P8L11–21 Please suggest the definitions and units in each variable.

Thank you for your comment. We edited this paragraph with definitions and units where feasible to increase clarity. Please see the new text on page 9 (P9L4-17):

"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 (number of individuals per species), and compositional similarity (pairwise comparison at the species level) relative to a baseline (typically corresponding to a pristine landscape).

Three models in BES-SIM – cSAR-iDiv (Martins and Pereira, 2017), cSAR-IIASA-ETH (Chaudhary et al., 2015), BILBI (Hoskins et al., submitted.; Ferrier et al., 2004, 2007) – rely on versions of the species-area relationship (SAR) to estimate the proportion of species persisting in human-modified habitats relative to native habitat (i.e., number of species in modified landscape divided by number of species in the native *habitat). In its classical form, the SAR describes the relationship between the area of native habitat and the number of species found within that area. The countryside SAR (cSAR) builds on the classic SAR but accounts for the differential use of both human-modified and native habitats by different functional species groups."*

P8L27 What is species-area relationship? species abundance-area relationship?

As noted in the response to the previous comment, we have now added explanations on species area relationship and countryside species area relationship. For each ecological concept introduced and used in models in the manuscript, we now give brief description.

P8L32 "a hierarchical mixed-effects framework to model" -> just "hierarchical mixed effects model"

Corrected. Please see page 10 (P10L5).

P8L33 "global database" <Please add the citation.

We added sources (Hudson et al. 2017; Hudson et al. 2016) for the database as suggested on page 9 (P10L7). Thank you for your note.

P9L20 Please clarify what ecosystem states are in DGVM. Also for functioning and habitat structure.

We have added examples in the sentence as follows on page 10-11 (P10L30-P11L4). In addition, the details of the DGVMs included in BES-SIM are documented in Table S2 of the Supplement, and can also be found in the model specific publications referenced.

"DGVMs can project changes in future ecosystem state (e.g., type of plant functional trait (PFT), relative distribution of each PFT, biomass, height, leaf area index, water stress), ecosystem functioning (e.g., moderation of climate, processing/filtering of waste and toxicants, provision of food and medicines, modulation of productivity, decomposition, biogeochemical and nutrient flows, energy, matter, water), and habitat structure (i.e., amount, composition and arrangement of physical matter that describe an ecosystem within a defined location and time); however, DGVMs 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)."

5 Please add the units in each output (variables).

We added units to output metrics mentioned in the section.

P10L6 "was calculated at two scales: local or grid cell (α)" <Is this correct? The area of grid differs among different latitudinal bands. So, the scale is not unique when the grid cell is used.

All alpha (α) values are proportions calculated relative to an historical baseline in each cell. Therefore, they are not affected by variations of cell area across latitude. The exception is Nα, where absolute changes are calculated relative to an historical baseline. Still, the variations in cell area have limited impact on these absolute changes which are mostly influenced by land-use and climate changes and by the latitudinal gradient in species richness.

P10L10–11 Please describe the definitions of intactness in the text.

We added the definition of abundances and intactness in the text as follows on page 11-12 (P11L30-P12L2):

"The abundance-based intactness (I) measures the mean species abundance in the current community relative to the abundances in a pristine community. This metric is available only for two community-based models, i.e., GLOBIO (where intactness is estimated as the arithmetic mean of the abundance ratios of the individual species, whereby ratios >1 are set to 1), and PREDICTS (where intactness is estimated as the ratios of the sum of species abundances)."

P10L16–17 I'm strongly doubtful whether just one-year baseline is appropriate. But, I'm not sure how large variances in the year to year change are existing in such projected variables.

Biodiversity models in our analysis respond to land-use change and climate change. Land-use changes are relatively smooth over time and there are no large year to year fluctuations. Climate can indeed exhibit large scale annual fluctuations, particularly at the local level, but for historical projections for the year 1900 the biodiversity models assumed no climate impacts on biodiversity metrics. So we believe a single baseline year of 1900 is appropriate here.

P10L18–31 Please add the units for each outputs (e.g., kg-C/m2/year, kg-algae/L etc...).

We added units for each output as suggested. Please see page 12 (P12L10-24).

P11L9 What is "IPBES region"? Please show us the map.

We added references to a map and a dataset showing IPBES regions and subregions (Brooks et al. 2016; UNEP-WCMC, 2015). Please see page 13 (P13L1-2).

P11L17–19 Why? I'm not sure "the gap in climate input".

We revised the sentences as follows on page 13 (P13L9-14):

"When backcasting to 1900, for the models that required continuous climate time-series, random years in the period 1951 to 1960 from the ISIMIP 2a IPSL climate dataset were used to fill the data missing for years 1901 to 1950. Models that used multi-decadal climate averages (i.e., InSiGHTS, BILBI) assumed no

climate impacts for 1900."

P11L24 "different model parameterizations" <I (and readers) cannot follow this meaning. Which parameters? Why they have the uncertainty range. How many simulations are used to get the quantiles of metrics?

We changed it to "based on the parameterizations specific to each model" for clarity on page 13 (P13L18). The way in which each model produced the quantiles depends on the model's internal structure, but in general these arise from varying internal model parameters. For instance, in the cSAR-iDiv model, the uncertainty arises from performing a Monte Carlo/bootstrapping on the affinity values (i.e., sample 100 different values), which leads to slightly different model outputs (i.e., 100 maps of projected extinctions per year). The quantiles are then derived from the distribution of these 100 model outputs (computed using different affinities and the same land use). The details of how uncertainty was provided by each of the models can be found in either their key publications (listed in Appendix 1) or in the Table S2 of the Supplement if this was an improvement made specifically for BES-SIM (e.g., as is the case of cSAR-iDiv).

P11L25 Option 2 seems to assess the uncertainty just for BIOMOD model. This is not inter-comparison among BES-SIM models.

The reviewer is correct. We revised the text as follows to differentiate the two elements of uncertainty analysis – one with quantiles provided by each model and their intercomparison, and another one specifically to climate projections by BIOMOD2, which is independent of the intermodel comparison. We revised the text as follows on page 13 (P13L16-24):

"Reporting uncertainty is a critical component of model intercomparison exercises (IPBES, 2016). Within BES-SIM, uncertainties were explored by each model reporting the mean values of its metrics, and where possible the 25th, 50th, and 75th percentiles based on the parameterizations set specific to each model, which can be found in each model's key manuscripts describing the modelling methods; and when combining the data provided by the different models, the average and the standard deviation of the common metrics were calculated (e.g., intermodel average and standard deviation of $P\gamma$). In a parallel exercise to inform BES-SIM, the BIOMOD2 model was used in assessing the uncertainty in modelling changes in species ranges arising from using different RCP scenarios, different GCMs, a suite of species distribution modelling algorithms (e.g., random forest, logistic regression) and different species dispersal hypotheses."

Section 8 First paragraph seemed to be just repeatment of introduction. Please remove this paragraph.

We removed the paragraph as suggested.

Section 8 In my opinion, the discussion is not essential in this paper, because of nothing results. Instead of discussion, please summarize uncovered topics in the current BES-SIM framework from the view to biodiversity (ESs) projection.

This section is now called "Conclusion" to better reflect the manuscript. Uncovered topics in this BES-SIM framework will be published in a separate manuscript; thus, we kept the remaining text.

P20L20 Please revise the author list in Settele et al.

We added the full author list for the Settele et al. reference.

P33 Appendix1 Please remove "?" in "Three functional groups?" in Madingley model

We corrected this typo.

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

HyeJin Kim[1,2], Isabel M.D. Rosa[1,2], Rob Alkemade[3,4], Paul Leadley[5], George Hurtt[6], Alexander Popp[7], Detlef P van Vuuren[8], Peter Anthoni[9], Almut Arneth[9], Daniele Baisero[10], Emma Caton[11], Rebecca Chaplin-Kramer[12], Louise Chini[6], Adriana De Palma[11], Fulvio Di Fulvio[13], Moreno Di Marco[14], Felipe Espinoza[11], Simon Ferrier[15], Shinichiro Fujimori[16], Ricardo E. Gonzalez[18], Maya Gueguen[29], Carlos Guerra[1,2], Mike Harfoot[19], Thomas D. Harwood[15], Tomoko Hasegawa[17], Vanessa Haverd[20], Petr Havlík[13], Stefanie Hellweg[21], Samantha L. L. Hill[11,19], Akiko Hirata[22], Andrew J. Hoskins[15], Jan H. Janse[3,23], Walter Jetz[24], Justin A. Johnson[25], Andreas Krause[9], David Leclère[13], Ines S. Martins[1,2], Tetsuya Matsui[22], Cory Merow[24], Michael Obersteiner[13], Haruka Ohashi[22], Benjamin Poulter[26], Andy Purvis[11,27], Benjamin Quesada[9,28], Carlo Rondinini[10], Aafke M. Schipper[3,~~28~~29], Richard Sharp[12], Kiyoshi Takahashi[17], Wilfried ~~Thuiller~~[~~29~~]Thuiller[30], Nicolas Titeux[1,~~30~~31], Piero ~~Visconti~~[~~31~~]Visconti[32,~~32~~33], Christopher Ware[15], Florian Wolf[1,2], Henrique M. Pereira[1,2,~~33~~34]

[1]German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena- Leipzig, Deutscher Platz 5e, 04103 Leipzig, Germany
[2]Institute of Biology, Martin Luther University Halle Wittenberg, Am Kirchtor 1, 06108 Halle (Saale), Germany
[3]PBL Netherlands Environmental Assessment Agency, the Hague, the Netherlands
[4]Environmental System Analysis Group, Wageningen University, the Netherlands
[5]Ecologie Systématique Evolution, Univ. Paris-Sud, CNRS, AgroParisTech, Université Paris-Saclay, 91400, Orsay, France
[6]Department of Geographical Sciences, University of Maryland, College Park, MD 20740, USA
[7]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany
[8]Copernicus Institute for Sustainable Development, Utrecht University, Utrecht, the Netherlands
[9]Karlsruhe Institute of Technology, Dept. Meteorology and Climate/Atmospheric Environmental Research, Kreuzeckbahnstr. 19, 82467 Garmisch-Partenkirchen, Germany
[10]C/O Global Mammal Assessment program, Department of Biology and Biotechnologies, Sapienza Università di Roma, Viale dell'Univerisità 32, I-00185, Rome, Italy
[11]Department of Life Sciences, Natural History Museum, London SW7 5BD, U.K.
[12]The Natural Capital Project, Stanford University, 371 Serra Mall, Stanford, CA 94305, USA
[13]International Institute for Applied Systems Analysis, Schlossplatz 1, Laxenburg 2361, Austria
[14]CSIRO Land and Water, GPO Box 2583, Brisbane QLD 4001, Australia
[15]CSIRO Land and Water, GPO Box 1700, Canberra ACT 2601, Australia
[16]Kyoto University, Department of Environmental Engineering, 361, C1-3, Kyoto University Katsura Campus, Nishikyo-ku, Kyoto-city, 615-8540 Japan
[17]Center for Social and Environmental Systems Research, National Institute for Environmental Studies (NIES), 16–2 Onogawa, Tsukuba, Ibaraki 305–8506, Japan
[18]Department of Life Sciences, Imperial College London, Silwood Park, Ascot SL5 7PY, U.K.
[19]UN Environment, World Conservation Monitoring Centre, 219 Huntingdon Road, Cambridge, CB3 0DL, UK.
[20]CSIRO Oceans and Atmosphere, Canberra, 2601, Australia
[21]Institute of Environmental Engineering, ETH Zurich, 8093 Zurich, Switzerland
[22]Forestry and Forest Products Research Institute, Forest Research and Management Organization, 1 Matsunosato, Tsukuba, Ibaraki, 305-8687, Japan
[23]Netherlands Inst. of Ecology NIOO-KNAW, Wageningen, the Netherlands
[24]Ecology and Evolutionary Biology, Yale University, 165 Prospect St, New Haven, CT 06511, USA
[25]Institute on the Environment, University of Minnesota, 1954 Buford Ave. St. Paul, MN 55105, USA
[26]NASA GSFC, Biospheric Science Lab., Greenbelt, MD 20771, USA
[27]Department of Life Sciences, Imperial College London, Silwood Park, Ascot SL5 7PY, U.K.

[28]Universidad del Rosario, Faculty of Natural Sciences and Mathematics, Kr 26 No 63B-48, Bogotá D.C, Colombia
[28]Institute [29]Institute for Water and Wetland Research, PO Box 9010, 6500 GL Nijmegen, the Netherlands
[29]Univ[30]Univ. Grenoble Alpes, CNRS, Univ. Savoie Mont Blanc, Laboratoire d'Écologie Alpine (LECA), F-38000 Grenoble, France
[30]Helmholtz [31]Helmholtz Centre for Environmental Research - UFZ, Department of Community Ecology, Theodor-Lieser-Strasse 4, D-06210 Halle, Germany.
[31]Institute [32]Institute of Zoology, Zoological Society of London, Regent's Park, London, NW1 4RY
[32]Centre [33]Centre for Biodiversity and Environment Research, University College London, Gower Street, London, C1E6BT
[33]CIBIO[34]CIBIO/InBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, Cátedra REFER-Biodiveridade, Universidade do Porto, Campus Agrário de Vairão, R. Padre Armando Quintas, 4485-661 Vairão, Portugal

Correspondence to: Henrique M. Pereira (hpereira@idiv.de)

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's 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) – SSP1xRCP2.6, SSP3xRCP6.0, SSP5xRCP8.6 – 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 (CBD) 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 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 CBD, 2010; Maxwell et al., 2016; Sala, 2000; CBD and UNEP, 2014) with potentially severe impacts on ecosystem services and ultimately human well-being (Cardinale et al., 2012; MA, 2005). Habitat and land-use changes, resulting from past, present and future human activities, as well as climate change, have both immediate and long term impacts on biodiversity and ecosystem services whereas the impacts of climate change have considerable lag times (Lehsten et al., 2015)(Graham et al., 2017; Lehsten et al., 2015; Welbergen et al., 2008). 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 to have direct and indirect impact 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~~to quantify the biodiversity and ecosystem services impacts ~~narratives~~ of different scenarios, based on climate and land-use projections from General Circulation Models (GCM) and Integrated Assessment Models (IAM) ~~using selected and modellable drivers, which describe key components of a system or relationships between them~~ (~~Ferrier et al.~~Pereira et al., 2010 ~~2016~~). These models include empirical dose-response models, species-area relationship models, species distribution models and more mechanistic models such as trophic ecosystem models (Pereira et al., 2010; Akçakaya et al., 2016). So far, each of these scenario~~s~~ ~~analysis~~ exercises ~~have~~ has been based on a single model or a small number of biodiversity and ecosystem service models, and ~~cross-model harmonization~~intermodel comparison and uncertainty analysis have been limited (IPBES, 2016; Leadley et al., 2014). The Expert Group on Scenarios and Models of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is addressing this ~~issue~~ gap by carrying out a biodiversity and ecosystem services model intercomparison with harmonized scenarios, for which this paper lays out the protocol.

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.~~IPBES, 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 associated with scenarios and models (Frieler et al., 2015)~~(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 (ISIMIP) was initiated in 2012 to quantify and synthesize climate change impacts across sectors and scales ~~(Frieler et al., 2015; Rosenzweig et al., 2017)~~(Rosenzweig et al., 2017; Warszawski et al., 2014). The ISIMIP 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). ~~and the data used by , to bridge the climate change and biodiversity and ecosystem services communities,~~

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? Whereas independent of the ISI-MIP, the BES-SIM has been inspired by ISI-MIP and other intercomparison projects and was delivered to address the needs of the global assessment of IPBES. We brought together ten biodiversity models and six ecosystem functions and ecosystem services models to assess impacts of land-use and climate change 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 assessed different classes of ~~dimensions~~ Essential Biodiversity Variables (EBV) ~~of biodiversity~~ including species populations, community composition and ecosystem function~~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 (Pereira et al. 2010; Akçakaya et al., 2016). 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 that are included in the ScenarioMIP protocol as part of CMIP6 (O'Neill et al., 2016), as harmonised data was available for these runs and these form the basis of the CMIP climate simulations. The second criteria implied a selection within the ScenarioMIP set of scenarios with low and high degrees of climate change and different land-use scenarios. Our 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 levels 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, high urbanization, ~~a~~ relatively low demand for animal products~~, a high urbanization rate~~ and ~~a~~ high agricultural productivity. These factors together lead to a decrease in the 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~~ with high population growth, slow economic development, material-intensive consumption and low food demand per capita. Agricultural land intensification is low, especially due to the very limited transfer of new agricultural technologies to developing countries. This scenario has land-use change hardly regulated, with a large land conversion ~~of land to~~for human-dominated uses, and has a relatively high level of climate change with ~~the~~ a 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, high urbanization, ~~a~~ high food demand per capita~~, a high urbanization rate~~ but also ~~a~~ high agricultural productivity. As a result, there is 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). The SSP scenarios excluded elements that have interaction effects with climate change except for SSP1, which focuses on environmental sustainability. Thus, SSPs describe futures where biodiversity is not affected by climate change to allow for the important estimation of the climate change impact on biodiversity (O'Neill et al., 2014).

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 require climate data, we selected the climate projections of the past, present and future from CMIP5 / ISIMIP2a (McSweeney and Jones, 2016) and its downscaled version from the WorldClim (Fick and Hijmans, 2017), as well as MAGICC 6.0 (Meinshausen et al., 2011a, 2011b) from the IMAGE model for GLOBIO models (Table 2). A complete list of input datasets and variables used by the models is documented in Table S1 of the Supplement~~ary 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 – IMAGE for SSP1/RCP2.6, AIM for

SSP3/RCP7.0, and REMIND/MAgPIE for SSP5/RCP8.5 – 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 consistent with the paired RCPs and include biofuel deployment to mitigate climate change. The SSP3 is associated with RCP7.0 (SSP3xRCP7.0); however, climate projections (i.e., time series of precipitation and temperature) are currently not available for RCP7.0. Therefore, we chose the closest RCP available, which was RCP6.0, for the standalone use of climate projections and chose SSP3xRCP6.0 for the land use projections from the LUH2. As there was no land-use projection available for SSP3 with RCP6.0, we chose the available closest simulation SSP3/RCP.0 from the LUH2 datasetsIn this paper, we refer to this scenario as SSP3xRCP6.0.

The land-use projections from each of the IAMs were 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), 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 the 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 Annex Supplementary Methods1 inof the Supplement.

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 Earth Systems Models (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~~In BES-SIM, some models ~~in BES-SIM~~ require continuous time-series data. In order to harmonize the climate data 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 analyses were carried out using a single GCM, the IPSL-CM5A-LR (Dufresne et al., 2013), since it provides ~~data in the~~ mid-range projections across the five GCMs (HadGEM2-ESGFDL-ESM2M, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M) in ISIMIP2a (Warszawski et al., 2014).

The ISIMIP2a output from the IPSL-CM5A-LR provides 12 climate variables on daily time steps from the pre-industrial period 1951 to 2099 at 0.5-degree resolution (McSweeney and Jones, 2016), of which only a subset was used in this exercise (Table S1). The WorldClim downscaled dataset has 19 bioclimatic variables derived from monthly temperature and rainfall from 1960 to 1990 with multi-year averages for specific points in time (e.g., 2050, 2070) up to 2070. Six models in BES-SIM used ISIMIP2a 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~~six of ten biodiversity models ~~(i.e. AIM-biodiversity, MOL, cSAR-iDiv, cSAR-IIASA-ETH, BILBI, InSiGHTS)~~ while ~~some~~ two 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 model (Newbold et al., 2016; Purvis et al., 2018). In three Dynamic Global Vegetation Models (DGVM) models ~~(i.e. LPJ-GUESS, LPJ, CABLE)~~, atmospheric CO_2 concentrations, irrigated fraction, and wood harvest estimates are commonly used, while ~~GLOBIO and GLOSP~~two 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 the availability ~~advancement in~~ of biodiversity data ~~availability~~ and advancement in 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 (Appendix 1, 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 (Appendix 1). All sixteen models are spatially explicit with 15 of them using land-use data as an input, 13~~2~~ of them ~~also~~ requiring climate data. We also used one model, ~~(~~BIOMOD2 (Thuiller, 2004; Thuiller et al., 2009), ~~)~~ to assess the uncertainty of climate range projections without the use of 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 (Ohashi et al., ~~in prep.~~submitted), InSiGHTS (Rondinini et al., 2011; Visconti et al., 2016), MOL (Jetz et al., 2007; Merow et al., 2013), and BIOMOD2 (Appendix 1, 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-biodiversity ~~(Ohashi et al., in prep.)~~ uses Global Biodiversity Information Facility (GBIF) species occurrence data of 9,025 species in five taxonomic groups (amphibians, birds, mammals, plants, reptiles) to train statistical models for current land use and climate to project future species distributions. InSiGHTS uses species' presence records ~~(Rondinini et al., 2011; Visconti et al., 2016)~~ from regular sampling within species' ranges and pseudo-absence records from regular sampling outside of species' ranges on 2,827 species of mammals. ~~and~~ MOL uses species land cover preference information and species presence and absence predictions on 20,833 species of amphibians, birds and mammals. ~~(Jetz et al., 2007; Merow et al., 2013)~~B~~b~~oth models rely on IUCN's expert-based range maps as a baseline, which are developed based on expert knowledge of the species habitat preferences and areas known to be absent (Fourcade, 2016). ~~.~~InSiGHTS and MOL used a 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, a~~n expert-based~~ model detailing associations between species and habitat types based on expert opinion 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)~~ is an R modelling package that runs up to nine different algorithms (e.g., random forests, logistic regression) of species distribution models using the same data and the same framework. ~~was only used to assess uncertainties in climate-envelope-based~~

~~projections,~~ BIOMOD2 included three taxonomic groups (amphibians, birds, mammals)~~and was not included in the model intercomparison with other models incorporating 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 (number of individuals per species), and compositional similarity (pairwise comparison at the species level) relative to a baseline (typically corresponding to a pristine landscape).

Three models in BES-SIM – ~~(~~cSAR-iDiv (Martins and Pereira, 2017), cSAR-IIASA-ETH (Chaudhary et al., 2015), BILBI (Hoskins et al., in prep.; Ferrier et al., 2004, 2007)~~)~~ – rely on versions of the species-area relationship (SAR) to estimate the proportion of species persisting in human-modified habitats relative to native habitat (i.e., number of species in modified landscape divided by number of species in the native habitat). In its classical form, ~~, while three models (PREDICTS, GLOBIO Aquatic, GLOBIO Terrestrial~~~~(Alkemade et al., 2009; Janse et al., 2015; Schipper et al., 2016)~~~~) estimate a range of assemblage-level metrics based on correlative relationships between biodiversity responses and pressure variables (Appendix 1).~~ the SAR describes the relationship between the area of native habitat and the number of species found within that area. The countryside SAR (cSAR) builds on the classic SAR but accounts for the differential use of both human-modified and native habitats by different functional species groups. 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 (cSAR), which use~~use~~s~~ habitat affinities (proportion of area of a~~n~~ habitat type that can be effectively used by a species group) 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. 2017; Hudson et al. 2016) ~~(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 9,853 species for one taxonomic group (birds) in two functional ~~species~~ groups (forest species and non-forest species) ~~for one taxonomic group (birds; N=9853)~~ while the cSAR-IIASA-ETH ~~uses~~ considers a total of 1,911,583 species for five taxonomic groups (amphibians, birds, mammals, plants, and reptiles) by ecoregions (these are however not 1,911,583 unique species as a species present in two ecoregions will be counted twice)~~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 (i.e., change in species), 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 254,145 vascular plant species globally~~)~~.

Three community-based models – PREDICTS, GLOBIO Aquatic and GLOBIO Terrestrial (Alkemade et al., 2009; Janse et al., 2015; Schipper et al., 2016) – estimate a range of assemblage-level metrics based on empirical dose-response relationships between pressure variables (e.g., land-use change and climate change) and biodiversity variables (e.g., species richness or mean species abundance) (Appendix 1). PREDICTS ~~(Newbold et al., 2016; Purvis et al., 2018)~~ uses a hierarchical mixed-effects ~~framework to~~ model to assess 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 in a wide range of taxonomic groups (Hudson et al. 2017; Hudson et al. 2016). 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 on a wide range of taxonomic groups.

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). Madingley uses three functional groups (trophic levels, metabolic pathways, reproductive strategies).

4.4 Models of ecosystem functions and services

In order to measure ecosystem functions and services, three ~~Dynamic Global Vegetation Models (~~DGVM models~~s)~~ – ~~(i.e.,~~ LPJ-GUESS (Lindeskog et al., 2013; Olin et al., 2015; Smith et al., 2014), LPJ (Poulter et al., 2011; Sitch et al., 2003), CABLE (Haverd et al., 2017) – ~~)~~ and three ecosystem services models – ~~(i.e.,~~ InVEST (Sharp et al., 2014), GLOBIO (Alkemade et al., 2009, 2014; Schulp et al., 2012), GLOSP (Guerra et al., 2016)) – 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 (e.g., type of plant functional trait (PFT), relative distribution of each PFT, biomass, height, leaf area index, water stress), ecosystem ~~and~~ functioning (e.g., moderation of climate, processing/filtering of waste and toxicants, provision of food and medicines, modulation of productivity, decomposition, biogeochemical and nutrient flows, energy, matter, water), and habitat structure (i.e., amount, composition and arrangement of physical matter that describe an ecosystem within a defined location and time); however, they DGVMs 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 map and measure the flow and value of ecosystem goods and services across a land or a seascape. They are, based on biophysical processes of the structure and function of ecosystems, accounting and accounts 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, 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 reported over time: extinctions as absolute change in species richness (N, number of species) or as proportional species richness change (P, % species); abundance-based intactness (I, % intactness); and mean proportional change in suitable habitat extent across species (H, % suitable habitat) (Table 4). These metrics were calculated at two scales: local or grid cell (α scale, i.e. the value of the metric within the smallest spatial unit of BES-SIM which is the grid cell) and regional or global (γ scale, i.e. the value of the metric for a set of grid cells comprising a region). For species richness change, some models project the α metrics at the level of the grid cell (e.g., species-based and SAR based community models) while others average the local point values of the metrics across the grid cell weighted by the area of the different habitats in the cell (e.g., PREDICTS, GLOBIO). In addition, some models only provided α values while others provided both α and γ values (Table 4). For the models that can project γ metrics, both regional-γ for each IPBES regions (Table 1 in Brooks et al., 2016, UNEP-WCMC, 2015) and a global-γ were reported.

The species diversity change metrics measured as absolute number or percentage change in species richness shows species persistence and extinction in given time and place. Absolute changes in species richness and proportional species richness change are interrelated and may be calculated from reporting species richness over time, as $N_t=S_t - S_{t0}$ and $P= N_t / S_{t0}$, where S_t is the number of species at time *t*. Most models reported one or both types of species richness metrics (Table 4). IntactnessThe abundance-based intactness, (I) which measures the mean species abundancecan be estimated in several ways, refers to the difference between in the current community composition and the inferred original state in therelative to the abundances in a native vegetationpristine community. This metric is available only for two community-based models, (i.e., GLOBIO (where intactness is estimated as the arithmetic mean of the abundance ratios of the individual species, whereby ratios >1 are set to 1), and PREDICTS (where intactness is estimated as the ratios of the sum of species abundances). The habitat change (H) measures cell-wise changes in available habitat for the species. It ~~was calculated from~~ is ~~averaging across species occurring in the unit of analysis (grid cell, region, or globe)~~ the changes in the suitable habitat extent of each species relative to a baseline, i.e., $(E_{i,t}-E_{i,t0})/E_{i,t0}$, where $E_{i,t}$ is the suitable habitat extent of species *i* at time *t* within the unit of analysis. It is reported by averaging across species occurring in each unit of analysis (grid cell, region, or globe), ~~It~~ and ~~can be reported for~~is provided by the species-level models (i.e., AIM-biodiversity, InSiGHTS, MOL) (Table 4). The baseline year, t_0, used to calculate changes for the extinction and habitat extent metrics, was the first year of the simulation (in most cases t_0=1900, see Table 5).

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, % agricultural area), climate (e.g., vegetation carbon, total carbon uptake and loss, MgC), water quantity (e.g., monthly runoff, Pg/month), water quality (e.g., nitrogen and phosphorus leaching, PgN/s~~algal blooms~~), soil protection (e.g., erosion ~~risk~~protection, 0-100 index), hazards (e.g., costal ~~resilience~~vulnerability, unitless score~~,~~ ; flood risk, number of people affected) and detrimental organisms (e.g., fraction of cropland potentially protected by the natural pest~~,~~ relative to all available cropland, km^2), and material metrics on bioenergy (e.g., bioenergy-crop production, PgC/yr), food and feed (e.g., total crop production, 10^9KCal) and materials (e.g., wood harvest, KgC) (Table 6). Some of these metrics require careful interpretation in the context of NCPs (e.g., an increase in flood risk can be caused by climate change and/or by a reduction of the capacity of ecosystems to reduce flood risk) 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 the disparity of metrics across models within each NCP category, names ~~and units~~ of the metrics are listed in Table 6, ~~with~~and units, definitions and methods are provided in Table S3.

6 Core simulations

The simulations for BES-SIM required a minimum of two outputs from the modelling teams: present (2015) and future (2050). Additionally, a past projection (1900) and a further future projection (2070) were also provided by several modelling teams. Some models projected further into the past and also at multiple time points from the past to the future (~~Table 5~~Appendix 1). 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. The models ran simulations at their original spatial resolutions (Appendix 1), and upscaled results to one-degree grid cells using arithmetic means. In order to provide global or regional averages of the α or grid cell metrics, the arithmetic mean values across the cells of the globe or a region were calculated, as well as percentiles of those metrics. Both, one-degree rasters and a table with values for each IPBES region (Table 1 in Brooks et al., 2016, UNEP-WCMC, 2015) and the globe were provided by each modelling team for each output metric.

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 were run three times: with land-use change only, with climate change only, and with both drivers combined. For instance, to measure the impact of land use alone, the projections into 2050 were obtained while retaining climate data constant from the present (2015) to the future (2050). 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 the present (2015) to the future (2050). 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). When backcasting to 1900, for the models that required continuous climate time-series, ~~used ISIMIP 2a IPSL climate dataset,~~ random years ~~from~~ in the period 1951 to 1960 ~~were~~ from the ISIMIP 2a IPSL climate dataset were used ~~selected~~ to fill ~~the gap~~the data missing for years 1901 to 1950~~in climate input for years 1901 to 1950~~. ~~The models~~Models that used multi-decadal climate averages (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~~assumed no climate impacts for 1900.

7 Uncertainties

Reporting uncertainty is a critical component of model intercomparison exercises (IPBES, 2016). Within BES-SIM, uncertainties were explored ~~in two ways: (1)~~by each model ~~had to report~~reporting the mean values of its metrics, and where possible the 25th, 50th, and 75th percentiles based on ~~different model~~the parameterizations set specific to each model, which can be found in each model's key manuscripts describing the modelling methods; and when combining the data provided by the different models, the average and the standard deviation of the common metrics were calculated (e.g., intermodel average and standard deviation of $P\gamma$).~~;~~ In ~~addition~~a parallel exercise to inform BES-SIM,~~(2)~~ the BIOMOD2 model was used in assessing the uncertainty in modelling changes in species ranges arising from using different RCP scenarios, different GCMs, a suite of species distribution modelling algorithms (e.g., random forest, logistic regression) and different species dispersal hypotheses.

~~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 Conclusion

This manuscript lays out the context, motives, processes, and approaches taken for a scenario-based intercomparison of biodiversity and ecosystem service models (BES-SIM). 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 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 of metrics of ecosystem functions and services (Tables 6, S3) are areas for further 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 scenario (Popp et al., 2017). The gaps identified through BES-SIM and future directions for research and modelling will be published separately as well aswith analyses of the results on the model intercomparison and on individual models.

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 Expert Group on Scenarios and Models, 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 of socio-economic and ecological systems. A future round of BES-SIM could use these biodiversity-centred storylines to project dynamics of biodiversity and ecosystem services and associated consequences for human well-being and socio-economic development and human well-being. This will help policymakers and practitioners to collectively identify pathways for sustainable futures based on alternative biodiversity management approaches and assist researchers in incorporating the role of biodiversity in socio-economic scenarios.

9. Code and data availability

The output data from this model intercomparison will be downloadable from the website of the IPBES Expert Group on Scenarios and Models in the future (https://www.ipbes.net/deliverables/3c-scenarios-and-modelling). 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)

There is a Supplement for this manuscript with Supplementary Methods and Tables S1, S2, S3, which can be found here: https://www.geosci-model-dev-discuss.net/gmd-2018-115/.

Author contributions. All authors co-designed the study under the coordination of Henrique M. Pereira, Rob Alkemade, Paul Leadley and Isabel M.D. Rosa. HyeJin Kim prepared the manuscript with contributions from all co-authors.

Competing interests: The authors declare that they have no conflict of interest.

Acknowledgements

HJK, ISM, FW, CG and HMP are supported by the German Centre for integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, funded by the German Research Foundation (FZT 118). IMDR acknowledges funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 703862. PL is supported by the LabEx BASC supported by the French "Investment d'Avenir" program (grant ANR-11-LABX-0034). GCH and LPC gratefully acknowledge the support of DOE-SciDAC program (DE‑SC0012972). AA, AK, BQ and PA acknowledge support from the Helmholtz Association and its ATMO Programme, and EU FP7 project LUC4C. AP, ADP and SLLH are supported by the Natural Environment Research Council U.K. (grant number NE/M014533/1) and by a DIF grant from the Natural History Museum. RCK and RS are supported by private gifts to the Natural Capital Project. DL, FDF, PH, and MO are supported by the project IS-WEL-Integrated Solutions for Water, Energy and Land funding from Global Environmental Facility, Washington, USA, coordinated by United Nations Industrial Development Organization (UNIDO), UNIDO Project No. 140312. FDF and MO are supported by the ERC SYNERGY grant project IMBALANCE-P-Managing Phosphorous limitation in a nitrogen-saturated Anthropocene, funding from European Commission, European Research Council Executive Agency, grant agreement No. 610028. DL and PH are supported by the project SIGMA- Stimulating Innovation for Global Monitoring of Agriculture and its Impact on the Environment in support of GEOGLAM, funding from the European Union's FP7 research and innovation programme under the Environment area, grant agreement No. 603719. TH, HO, AH, SF, TM and KT are supported by the Global Environmental Research (S-14) of the Ministry of the Environment of Japan. TH, SF and KT are supported by Environment Research and Technology Development Fund 2-1702 of the Environmental Restoration and Conservation Agency of Japan. MH is supported by a KR Rasmussen Foundation grant "Modelling the Biodiversity Planetary Boundary and Embedding Results into Policy" (FP-1503-01714). VH acknowledges support from the Earth Systems and Climate Change Hub, funded by the Australian Government's National Environmental Science Program. CM acknowledges funding from NSF Grant DEB1565046. Finally, we also thank the following organizations for funding the workshops: PBL Netherland Environment Assessment Agency, UNESCO (March 2016), iDiv German Centre for Integrative Biodiversity Research (October 2016, October 2017) and Zoological Society of London (January 2018).

References

Aguirre-Gutiérrez, J., Carvalheiro, L. G., Polce, C., van Loon, E. E., Raes, N., Reemer, M., ~~and~~ Biesmeijer, J. C. and Chapman, M. G. (Eds.): Fit-for-Purpose: Species Distribution Model Performance Depends on Evaluation Criteria – Dutch Hoverflies as a Case Study, ~~edited by M. G. Chapman,~~ PLoS ONE, 8(5), e63708, doi:10.1371/journal.pone.0063708, 2013.

Akçakaya, H. R., Pereira, H. M., Canziani, G. A., Mbow, C., Mori, A., Palomo, M. G., Soberón, J., Thuiller, W., Yachi, S., Ferrier, S., Ninan, K. N., Leadley, P., Alkemade, R., Acosta, L. A., Akçakaya, H. R., Brotons, L., Cheung, W. W. L., Christensen, V., Harhash, K. A., Kabubo- Mariara, J., Lundquist, C., Obersteiner, M., Pereira, H. M., Peterson, G., Pichs-Madruga, R., Ravindranath, N., Rondinini, C. and Wintle, B. A. (Eds.): Improving the rigour and usefulness of scenarios and models through ongoing evaluation and refinement, The methodological assessment report on scenarios and models of biodiversity and ecosystem services. Secretariat of the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services, Bonn, Germany, 2015.

Alkemade, R., van Oorschot, M., Miles, L., Nellemann, C., Bakkenes, M. and ten Brink, B.: GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss, Ecosystems, 12(3), 374–390, doi:10.1007/s10021-009-9229-5, 2009.

Alkemade, R., Burkhard, B., Crossman, N. D., Nedkov, S. and Petz, K.: Quantifying ecosystem services and indicators for science, policy and practice, Ecol. Indic., 37, 161–162, doi:10.1016/j.ecolind.2013.11.014, 2014.

Arkema, K. K., Guannel, G., Verutes, G., Wood, S. A., Guerry, A., Ruckelshaus, M., Kareiva, P., Lacayo, M. and Silver, J. M.: Coastal habitats shield people and property from sea-level rise and storms, Nat. Clim. Change, 3(10), 913–918, doi:10.1038/nclimate1944, 2013.

Arneth, A., Sitch, S., Pongratz, J., Stocker, B. D., Ciais, P., Poulter, B., Bayer, A. D., Bondeau, A., Calle, L., Chini, L. P., Gasser, T., Fader, M., Friedlingstein, P., Kato, E., Li, W., Lindeskog, M., Nabel, J. E. M. S., Pugh, T. A. M., Robertson, E., Viovy, N., Yue, C. and Zaehle, S.: Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed, Nat. Geosci., 10(2), 79–84, doi:10.1038/ngeo2882, 2017.

van Beek, L. P. H., Wada, Y. and Bierkens, M. F. P.: Global monthly water stress: 1. Water balance and water availability: Global Monthly Water Stress, 1, Water Resour. Res., 47(7), doi:10.1029/2010WR009791, 2011.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W. and Courchamp, F.: Impacts of climate change on the future of biodiversity: Biodiversity and climate change, Ecol. Lett., 15(4), 365–377, doi:10.1111/j.1461-0248.2011.01736.x, 2012.

Beusen, A. H. W., Van Beek, L. P. H., Bouwman, A. F., Mogollón, J. M. and Middelburg, J. J.: Coupling global models for hydrology and nutrient loading to simulate nitrogen and phosphorus retention in surface water – description of IMAGE–GNM and analysis of performance, Geosci. Model Dev., 8(12), 4045–4067, doi:10.5194/gmd-8-4045-2015, 2015.

Brooks, T. M., Akçakaya, H. R., Burgess, N. D., Butchart, S. H. M., Hilton-Taylor, C., Hoffmann, M., Juffe-Bignoli, D., Kingston, N., MacSharry, B., Parr, M., Perianin, L., Regan, E. C., Rodrigues, A. S. L., Rondinini, C., Shennan-Farpon, Y. and Young, B. E.: Analysing biodiversity and conservation knowledge products to support regional environmental assessments, Scientific Data, 3, 160007, doi:10.1038/sdata.2016.7, 2016.

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., Narwani, A., Mace, G. M., Tilman, D., Wardle, D. A., Kinzig, A. P., Daily, G. C., Loreau, M., Grace, J. B., Larigauderie, A., Srivastava, D. S. and Naeem, S.: Biodiversity loss and its impact on humanity, Nature, 486(7401), 59–67, doi:10.1038/nature11148, 2012.

Chaplin-Kramer, R., Dombeck, E., Gerber, J., Knuth, K. A., Mueller, N. D., Mueller, M., Ziv, G. and Klein, A.-M.: Global malnutrition overlaps with pollinator-dependent micronutrient production, Proc. R. Soc. B Biol. Sci., 281(1794), 20141799–20141799, doi:10.1098/rspb.2014.1799, 2014.

Chaudhary, A., Verones, F., de Baan, L. and Hellweg, S.: Quantifying Land Use Impacts on Biodiversity: Combining Species–Area Models and Vulnerability Indicators, Environ. Sci. Technol., 49(16), 9987–9995, doi:10.1021/acs.est.5b02507, 2015.

D'Amen, M., Rahbek, C., Zimmermann, N. E. and Guisan, A.: Spatial predictions at the community level: from current approaches to future frameworks: Methods for community-level spatial predictions, Biol. Rev., 92(1), 169–187, doi:10.1111/brv.12222, 2017.

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., Hill, R., Chan, K. M. A., Baste, I. A., Brauman, K. A., Polasky, S., Church, A., Lonsdale, M., Larigauderie, A., Leadley, P. W., van Oudenhoven, A. P. E., van der Plaat, F., Schröter, M., Lavorel, S., Aumeeruddy-Thomas, Y., Bukvareva, E., Davies, K., Demissew, S., Erpul, G., Failler, P., Guerra, C. A., Hewitt, C. L., Keune, H., Lindley, S. and Shirayama, Y.: Assessing nature's contributions to people, Science, 359(6373), 270–272, doi:10.1126/science.aap8826, 2018.

Dufresne, J.-L., Foujols, M.-A., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., de Noblet, N., Duvel, J.-P., Ethé, C., Fairhead, L., Fichefet, T., Flavoni, S., Friedlingstein, P., Grandpeix, J.-Y., Guez, L., Guilyardi, E., Hauglustaine, D., Hourdin, F., Idelkadi, A., Ghattas, J., Joussaume, S., Kageyama, M., Krinner, G., Labetoulle, S., Lahellec, A., Lefebvre, M.-P., Lefevre, F., Levy, C., Li, Z. X., Lloyd, J., Lott, F., Madec, G., Mancip, M., Marchand, M., Masson, S., Meurdesoif, Y., Mignot, J., Musat, I., Parouty, S., Polcher, J., Rio, C., Schulz, M., Swingedouw, D., Szopa, S., Talandier, C., Terray, P., Viovy, N. and Vuichard, N.: Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5, Clim. Dyn., 40(9–10), 2123–2165, doi:10.1007/s00382-012-1636-1, 2013.

Elith, J. and Leathwick, J. R.: Species Distribution Models: Ecological Explanation and Prediction Across Space and Time, Annu. Rev. Ecol. Evol. Syst., 40(1), 677–697, doi:10.1146/annurev.ecolsys.110308.120159, 2009.

Ferrier, S., Powell, G. V. N., Richardson, K. S., Manion, G., Overton, J. M., Allnutt, T. F., Cameron, S. E., Mantle, K., Burgess, N. D., Faith, D. P., Lamoreux, J. F., Kier, G., Hijmans, R. J., Funk, V. A., Cassis, G. A., Fisher, B. L., Flemons, P., Lees, D., Lovett, J. C. and Van Rompaey, R. S. A. R.: Mapping More of Terrestrial Biodiversity for Global Conservation Assessment, BioScience, 54(12), 1101, doi:10.1641/0006-3568(2004)054[1101:MMOTBF]2.0.CO;2, 2004.

Ferrier, S., Manion, G., Elith, J. and Richardson, K.: Using generalized dissimilarity modelling to analyse and predict patterns of beta diversity in regional biodiversity assessment, Divers. Distrib., 13(3), 252–264, doi:10.1111/j.1472-4642.2007.00341.x, 2007.

Fick, S. E. and Hijmans, R. J.: WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas: New climate surface for global land areas, Int. J. Climatol., 37(12), 4302–4315, doi:10.1002/joc.5086, 2017.

Frieler, K., Levermann, A., Elliott, J., Heinke, J., Arneth, A., Bierkens, M. F. P., Ciais, P., Clark, D. B., Deryng, D., Döll, P., Falloon, P., Fekete, B., Folberth, C., Friend, A. D., Gellhorn, C., Gosling, S. N., Haddeland, I., Khabarov, N., Lomas, M., Masaki, Y., Nishina, K., Neumann, K., Oki, T., Pavlick, R., Ruane, A. C., Schmid, E., Schmitz, C., Stacke, T., Stehfest, E., Tang, Q., Wisser, D., Huber, V., Piontek, F., Warszawski, L., Schewe, J., Lotze-Campen, H. and Schellnhuber, H. J.: A framework for the cross-sectoral integration of multi-model impact projections: land use decisions under climate impacts uncertainties, Earth Syst. Dyn., 6(2), 447–460, doi:10.5194/esd-6-447-2015, 2015.

Frieler, K., Lange, S., Piontek, F., Reyer, C. P. O., Schewe, J., Warszawski, L., Zhao, F., Chini, L., Denvil, S., Emanuel, K., Geiger, T., Halladay, K., Hurtt, G., Mengel, M., Murakami, D., Ostberg, S., Popp, A., Riva, R., Stevanovic, M., Suzuki, T., Volkholz, J., Burke, E., Ciais, P., Ebi, K., Eddy, T. D., Elliott, J., Galbraith, E., Gosling, S. N., Hattermann, F., Hickler, T., Hinkel, J., Hof, C., Huber, V., Jägermeyr, J., Krysanova, V., Marcé, R., Müller Schmied, H., Mouratiadou, I., Pierson, D., Tittensor, D. P., Vautard, R., van Vliet, M., Biber, M. F., Betts, R. A., Bodirsky, B. L., Deryng, D., Frolking, S., Jones, C. D., Lotze, H. K., Lotze-Campen, H., Sahajpal, R., Thonicke, K., Tian, H. and Yamagata, Y.: Assessing the impacts of 1.5 °C global warming – simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b), Geosci. Model Dev., 10(12), 4321–4345, doi:10.5194/gmd-10-4321-2017, 2017.

Frischknecht, R., Fantke, P., Tschümperlin, L., Niero, M., Antón, A., Bare, J., Boulay, A.-M., Cherubini, F., Hauschild, M. Z., Henderson, A., Levasseur, A., McKone, T. E., Michelsen, O., i Canals, L. M., Pfister, S., Ridoutt, B., Rosenbaum, R. K., Verones, F., Vigon, B. and Jolliet, O.: Global guidance on environmental life cycle impact assessment indicators: progress and case study, Int. J. Life Cycle Assess., 21(3), 429–442, doi:10.1007/s11367-015-1025-1, 2016.

Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D. S., Dai, H., Hijioka, Y. and Kainuma, M.: SSP3: AIM implementation of Shared Socioeconomic Pathways, Glob. Environ. Change, 42, 268–283, doi:10.1016/j.gloenvcha.2016.06.009, 2017.

Graham, C. T., Wilson, M. W., Gittings, T., Kelly, T. C., Irwin, S., Quinn, J. L. and O'Halloran, J.: Implications of afforestation for bird communities: the importance of preceding land-use type, Biodiversity and Conservation, 26(13), 3051–3071, doi:10.1007/s10531-015-0987-4, 2017.

Guannel, G., Arkema, K., Ruggiero, P., ~~and~~ Verutes, G. and Bianchi, C. N. (Eds.): The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience, ~~edited by C. N. Bianchi,~~ PLOS ONE, 11(7), e0158094, doi:10.1371/journal.pone.0158094, 2016.

Guerra, C. A., Maes, J., Geijzendorffer, I. and Metzger, M. J.: An assessment of soil erosion prevention by vegetation in Mediterranean Europe: Current trends of ecosystem service provision, Ecol. Indic., 60, 213–222, doi:10.1016/j.ecolind.2015.06.043, 2016.

Guisan, A. and Thuiller, W.: Predicting species distribution: offering more than simple habitat models, Ecol. Lett., 8(9), 993–1009, doi:10.1111/j.1461-0248.2005.00792.x, 2005.

Guisan, A. and Zimmermann, N. E.: Predictive habitat distribution models in ecology, Ecol. Model., 135(2–3), 147–186, doi:10.1016/S0304-3800(00)00354-9, 2000.

Harfoot, M., Tittensor, D. P., Newbold, T., McInerny, G., Smith, M. J. and Scharlemann, J. P. W.: Integrated assessment models for ecologists: the present and the future: Integrated assessment models for ecologists, Glob. Ecol. Biogeogr., 23(2), 124–143, doi:10.1111/geb.12100, 2014a.

Harfoot, M. B. J., Newbold, T., Tittensor, D. P., Emmott, S., Hutton, J., Lyutsarev, V., Smith, M. J., Scharlemann, J. P. W., ~~and~~ Purves, D. W. and Loreau, M. (Eds.): Emergent Global Patterns of Ecosystem Structure and Function from a Mechanistic General Ecosystem Model, ~~edited by M. Loreau,~~ PLoS Biol., 12(4), e1001841, doi:10.1371/journal.pbio.1001841, 2014b.

Haverd, V., Smith, B., Nieradzik, L., Briggs, P. R., Woodgate, W., Trudinger, C. M. and Canadell, J. G.: A new version of the CABLE land surface model (Subversion revision r4546), incorporating land use and land cover change, woody vegetation demography and a novel optimisation-based approach to plant coordination of electron transport and carboxylation capacity-limited photosynthesis, Geosci. Model Dev. Discuss., 1–33, doi:10.5194/gmd-2017-265, 2017.

Heinimann, A., Mertz, O., Frolking, S., Egelund Christensen, A., Hurni, K., Sedano, F., Parsons Chini, L., Sahajpal, R., Hansen, M., ~~and~~ Hurtt, G. and Poulter, B. (Eds.): A global view of shifting cultivation: Recent, current, and future extent, ~~,~~ ~~edited by B. Poulter,~~ PLOS ONE, 12(9), e0184479, doi:10.1371/journal.pone.0184479, 2017.

Hempel, S., Frieler, K., Warszawski, L., Schewe, J. and Piontek, F.: A trend-preserving bias correction – the ISI-MIP approach, Earth Syst. Dyn., 4(2), 219–236, doi:10.5194/esd-4-219-2013, 2013.

Hirsch, T. and Secretariat of the Convention on Biological Diversity, Eds.: Global biodiversity outlook 3, Secretariat of the Convention on Biological Diversity, Montreal, Quebec, Canada., 2010.

Hoskins, A.J., Harwood, T.D., Ware, C., Williams, K.J., Perry, J.J., Ota, N., Croft, J.R., Yeates, D.K., Jetz, W., Golebiewski, M., Purvis, A., Ferrier, S., 2018. Supporting global biodiversity assessment through high-resolution macroecological modelling: Methodological underpinnings of the BILBI framework. BioRxiv http://biorxiv.org/cgi/content/short/309377v1. ~~Hoskins, A.J., Harwood, T.D., Ware, C., Williams, K.J., Perry, J.J., Ota, N., Croft, J.R., Yeates, D.K., Jetz, W., Golebiewski, M., Ferrier, S.: BILBI: supporting global biodiversity assessment through high-resolution macroecological modelling.~~ [in prep.]

Hudson, L. N., Newbold, T., Contu, S., Hill, S. L. L., Lysenko, I., De Palma, A., Phillips, H. R. P., Senior, R. A., Bennett, D. J., Booth, H., Choimes, A., Correia, D. L. P., Day, J., Echeverría-Londoño, S., Garon, M., Harrison, M. L. K., Ingram, D. J., Jung, M., Kemp, V., Kirkpatrick, L., Martin, C. D., Pan, Y., White, H. J., Aben, J., Abrahamczyk, S., Adum, G. B., Aguilar-Barquero, V., Aizen, M. A., Ancrenaz, M., Arbeláez-Cortés, E., Armbrecht, I., Azhar, B., Azpiroz, A. B., Baeten, L., Báldi, A., Banks, J. E., Barlow, J., Batáry, P., Bates, A. J., Bayne, E. M., Beja, P., Berg, Å., Berry, N. J., Bicknell, J. E., Bihn, J. H., Böhning-Gaese, K., Boekhout, T., Boutin, C., Bouyer, J., Brearley, F. Q., Brito, I., Brunet, J., Buczkowski, G., Buscardo, E., Cabra-García, J., Calviño-Cancela, M., Cameron, S. A., Cancello, E. M., Carrijo, T. F., Carvalho, A. L., Castro, H., Castro-Luna, A. A., Cerda, R., Cerezo, A., Chauvat, M., Clarke, F. M., Cleary, D. F. R., Connop, S. P., D'Aniello, B., da Silva, P. G., Darvill, B., Dauber, J., Dejean, A., Diekötter, T., Dominguez-Haydar, Y., Dormann, C. F., Dumont, B., Dures, S. G., Dynesius, M., Edenius, L., Elek, Z., Entling, M. H., Farwig, N., Fayle, T. M., Felicioli, A., Felton, A. M., Ficetola, G. F., Filgueiras, B. K. C., Fonte, S. J., Fraser, L. H., Fukuda, D., Furlani, D., Ganzhorn, J. U., Garden, J. G., Gheler-Costa, C., Giordani, P., Giordano, S., Gottschalk, M. S., Goulson, D., et al.: The PREDICTS database: a global database of how local terrestrial biodiversity responds to human impacts, Ecol. Evol., 4(24), 4701–4735, doi:10.1002/ece3.1303, 2014.

Hudson, L. N., Newbold, T., Contu, S., Hill, S. L. L., Lysenko, I., De Palma, A., Phillips, H. R. P., Alhusseini, T. I., Bedford, F. E., Bennett, D. J., Booth, H., Burton, V. J., Chng, C. W. T., Choimes, A., Correia, D. L. P., Day, J., Echeverría-Londoño, S., Emerson, S. R., Gao, D., Garon, M., Harrison, M. L. K., Ingram, D. J., Jung, M., Kemp, V., Kirkpatrick, L., Martin, C. D., Pan, Y., Pask-Hale, G. D., Pynegar, E. L., Robinson, A. N., Sanchez-Ortiz, K., Senior, R. A., Simmons, B. I., White, H. J., Zhang, H., Aben, J., Abrahamczyk, S., Adum, G. B., Aguilar-Barquero, V., Aizen, M. A., Albertos, B., Alcala, E. L., del Mar Alguacil, M., Alignier, A., Ancrenaz, M., Andersen, A. N., Arbeláez-Cortés, E., Armbrecht, I., Arroyo-Rodríguez, V., Aumann, T., Axmacher, J. C., Azhar, B., Azpiroz, A. B., Baeten, L., Bakayoko, A., Báldi, A., Banks, J. E., Baral, S. K., Barlow, J., Barratt, B. I. P., Barrico, L., Bartolommei, P., Barton, D. M., Basset, Y., Batáry, P., Bates, A. J., Baur, B., Bayne, E. M., Beja, P., Benedick, S., Berg, Å., Bernard, H., Berry, N. J., Bhatt, D., Bicknell, J. E., Bihn, J. H., Blake, R. J., Bobo, K. S., Bóçon, R., Boekhout, T., Böhning-Gaese, K., Bonham, K. J., Borges, P. A. V., Borges, S. H., Boutin, C., Bouyer, J., Bragagnolo, C., Brandt, J. S., Brearley, F. Q., Brito, I., Bros, V., Brunet, J., Buczkowski, G., Buddle, C. M., Bugter, R., Buscardo, E., Buse, J., Cabra-García, J., Cáceres, N. C., et al.: The database of the PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) project, Ecology and Evolution, 7(1), 145–188, doi:10.1002/ece3.2579, 2017.

Lawrence N Hudson; Tim Newbold; Sara Contu; Samantha L L Hill; Igor Lysenko; Adriana De Palma; Helen R P Phillips; Tamera I Alhusseini; Felicity E Bedford; Dominic J Bennett; Hollie Booth; Victoria J Burton; Charlotte W T Chng; Argyrios Choimes; David L P Correia; Julie Day; Susy Echeverr\Xeda-Londo\Xf1o; Susan R Emerson; Di Gao; Morgan Garon; Michelle L K Harrison; Daniel J Ingram; Martin Jung; Victoria Kemp; Lucinda Kirkpatrick; Callum D Martin; Yuan Pan; Gwilym D Pask-Hale; Edwin L Pynegar; Alexandra N Robinson; Katia Sanchez-Ortiz; Rebecca A Senior; Benno I Simmons; Hannah J White; Hanbin Zhang; Job Aben; Stefan Abrahamczyk; Gilbert B Adum; Virginia Aguilar-Barquero; Marcelo A Aizen; Bel\Xe9n Albertos; E L Alcala; Maria Del Mar Alguacil; Audrey Alignier; Marc Ancrenaz; Alan N Andersen; Enrique Arbel\Xe1ez-Cort\Xe9s; Inge Armbrecht; V\Xedctor Arroyo-Rodr\Xedguez; Tom Aumann; Jan C Axmacher; Badrul Azhar; Adri\Xe1n B Azpiroz; Lander Baeten; Adama Bakayoko; Andr\Xe1s B\Xe1ldi; John E Banks; Sharad K Baral; Jos Barlow; Barbara I P Barratt; Lurdes Barrico; Paola Bartolommei; Diane M Barton; Yves Basset; P\Xe9ter Bat\Xe1ry; Adam J Bates; Bruno Baur; Erin M Bayne; Pedro Beja; Suzan Benedick; \Xc5ke Berg; Henry Bernard; Nicholas J Berry; Dinesh Bhatt; Jake E Bicknell; Jochen H Bihn; Robin J Blake; Kadiri S Bobo; Roberto B\Xf3\Xe7on; Teun Boekhout; Katrin B\Xf6hning-Gaese; Kevin J Bonham; Paulo A V Borges; S\Xe9rgio H Borges; C\Xe9line Boutin; J\Xe9r\Xe9my Bouyer; Cibele Bragagnolo; Jodi S Brandt; Francis Q Brearley; Isabel Brito; Vicen\Xe7 Bros; J\Xf6rg Brunet; Grzegorz Buczkowski; Christopher M Buddle; Rob Bugter; Erika Buscardo; J\Xf6rn Buse; Jimmy Cabra-Garc\Xeda; Nilton C C\Xe1ceres; Nicolette L Cagle; Mar\Xeda Calvi\Xf1o-Cancela; Sydney A Cameron; Eliana M Cancello; Rut Caparr\Xf3s; Pedro Cardoso; Dan Carpenter; Tiago F Carrijo; Anelena L Carvalho; Camila R Cassano; Helena Castro; Alejandro A Castro-Luna; Rolando Cerda B; Alexis Cerezo; Kim Alan Chapman; Matthieu Chauvat; Morten Christensen; Francis M Clarke; Daniel F R Cleary; Giorgio Colombo; Stuart P Connop; Michael D Craig; Leopoldo Cruz-L\Xf3pez; Saul A Cunningham; Biagio D'Aniello; Neil D'Cruze; Pedro Giov\Xe2ni Da Silva; Martin Dallimer; Emmanuel Danquah; Ben Darvill; Jens Dauber; Adrian L V Davis; Jeff Dawson; Claudio De Sassi; Benoit De Thoisy; Olivier Deheuvels; Alain Dejean; Jean-Louis Devineau; Tim Diek\Xf6tter; Jignasu V Dolia; Erwin Dom\Xednguez; Yamileth Dominguez-Haydar; Silvia Dorn; Isabel Draper; Niels Dreber; Bertrand Dumont; Simon G Dures; Mats Dynesius; Lars Edenius; Paul Eggleton; Felix Eigenbrod; Zolt\Xe1n Elek; Martin H Entling; Karen J Esler; Ricardo F De Lima; Aisyah Faruk; Nina Farwig; Tom M Fayle; Antonio Felicioli; Annika M Felton; Roderick J Fensham; Ignacio C Fernandez; Catarina C Ferreira; Gentile F Ficetola; Cristina Fiera; Bruno K C Filgueiras; H\Xfcseyin K

F\U0131r\U0131nc\U0131o\U011flu; David Flaspohler; Andreas Floren; Steven J Fonte; Anne Fournier; Robert E Fowler; Markus Franz\Xe9n; Lauchlan H Fraser; Gabriella M Fredriksson; Geraldo B Freire-Jr; Tiago L M Frizzo; Daisuke Fukuda; Dario Furlani; Ren\Xe9 Gaigher; J\Xf6rg U Ganzhorn; Karla P Garc\Xeda; Juan C Garcia-R; Jenni G Garden; Ricardo Garilleti; Bao-Ming Ge; Benoit Gendreau-Berthiaume; Philippa J Gerard; Carla Gheler-Costa; Benjamin Gilbert; Paolo Giordani; Simonetta Giordano; Carly Golodets; Laurens G L Gomes; Rachelle K Gould; Dave Goulson; Aaron D Gove; Laurent Granjon; Ingo Grass; Claudia L Gray; James Grogan; Weibin Gu; Mois\Xe8s Guardiola; Nihara R Gunawardene; Alvaro G Gutierrez; Doris L Guti\Xe9rrez-Lamus; Daniela H Haarmeyer; Mick E Hanley; Thor Hanson; Nor R Hashim; Shombe N Hassan; Richard G Hatfield; Joseph E Hawes; Matt W Hayward; Christian H\Xe9bert; Alvin J Helden; John-Andr\Xe9 Henden; Philipp Henschel; Lionel Hern\Xe1ndez; James P Herrera; Farina Herrmann; Felix Herzog; Diego Higuera-Diaz; Branko Hilje; Hubert H\Xf6fer; Anke Hoffmann; Finbarr G Horgan; Elisabeth Hornung; Roland Horv\Xe1th; Kristoffer Hylander; Paola Isaacs-Cubides; Hiroaki Ishida; Masahiro Ishitani; Carmen T Jacobs; V\Xedctor J Jaramillo; Birgit Jauker; F Jim\Xe9nez Hern\Xe1ndez; McKenzie F Johnson; Virat Jolli; Mats Jonsell; Nur Juliani S; Thomas S Jung; Vena Kapoor; Heike Kappes; Vassiliki Kati; Eric Katovai; Klaus Kellner; Michael Kessler; Kathryn R Kirby; Andrew M Kittle; Mairi E Knight; Eva Knop; Florian Kohler; Matti Koivula; Annette Kolb; Mouhamadou Kone; \Xc1d\Xe1m K\U0151r\Xf6si; Jochen Krauss; Ajith Kumar; Raman Kumar; David J Kurz; Alex S Kutt; Thibault Lachat; Victoria Lantschner; Francisco Lara; Jesse R Lasky; Steven C Latta; William F Laurance; Patrick Lavelle; Violette Le F\Xe9on; Gretchen LeBuhn; Jean-Philippe L\Xe9gar\Xe9; Val\Xe9rie Lehouck; Mar\Xeda V Lencinas; Pia E Lentini; Susan G Letcher; Qi Li; Simon A Litchwark; Nick A Littlewood; Yunhui Liu; Nancy Lo-Man-Hung; Carlos A L\Xf3pez-Quintero; Mounir Louhaichi; Gabor L L\Xf6vei; Manuel Esteban Lucas-Borja; Victor H Luja; Matthew S Luskin; M Cristina MacSwiney G; Kaoru Maeto; Tibor Magura; Neil Aldrin Mallari; Louise A Malone; Patrick K Malonza; Jagoba Malumbres-Olarte; Salvador Mandujano; Inger E M\Xe5ren; Erika Marin-Spiotta; Charles J Marsh; E J P Marshall; Eliana Mart\Xednez; Guillermo Mart\Xednez Pastur; David Moreno Mateos; Margaret M Mayfield; Vicente Mazimpaka; Jennifer L McCarthy; Kyle P McCarthy; Quinn S McFrederick; Sean McNamara; Nagore G Medina; Rafael Medina; Jose L Mena; Estefania Mico; Grzegorz Mikusinski; Jeffrey C Milder; James R Miller; Daniel R Miranda-Esquivel; Melinda L Moir; Carolina L Morales; Mary N Muchane; Muchai Muchane; Sonja Mudri-Stojnic; Nur Munira A; Antonio Mu\Xf1oz-Alonso; B F Munyekenye; Robin Naidoo; A Naithani; Michiko Nakagawa; Akihiro Nakamura; Yoshihiro Nakashima; Shoji Naoe; Guiomar Nates-Parra; Dario A Navarrete Gutierrez; Luis Navarro-Iriarte; Paul K Ndang'ang'a; Eike L Neuschulz; Jacqueline T Ngai; Violaine Nicolas; Sven G Nilsson; Norbertas Noreika; Olivia Norfolk; Jorge Ari Noriega; David A Norton; Nicole M N\Xf6ske; A Justin Nowakowski; Catherine Numa; Niall O'Dea; Patrick J O'Farrell; William Oduro; Sabine Oertli; Caleb Ofori-Boateng; Christopher Omamoke Oke; Vicencio Oostra; Lynne M Osgathorpe; Samuel Eduardo Otavo; Navendu V Page; Juan Paritsis; Alejandro Parra-H; Luke Parry; Guy Pe'er; Peter B Pearman; Nicol\Xe1s Pelegrin; Rapha\Xebl P\Xe9lissier; Carlos A Peres; Pablo L Peri; Anna S Persson; Theodora Petanidou; Marcell K Peters; Rohan S Pethiyagoda; Ben Phalan; T Keith Philips; Finn C Pillsbury; Jimmy Pincheira-Ulbrich; Eduardo Pineda; Joan Pino; Jaime Pizarro-Araya; A J Plumptre; Santiago L Poggio; Natalia Politi; Pere Pons; Katja Poveda; Eileen F Power; Steven J Presley; V\Xe2nia Proen\Xe7a; Marino Quaranta; Carolina Quintero; Romina Rader; B R Ramesh; Martha P Ramirez-Pinilla; Jai Ranganathan; Claus Rasmussen; Nicola A Redpath-Downing; J Leighton Reid; Yana T Reis; Jos\Xe9 M Rey Benayas; Juan Carlos Rey-Velasco; Chevonne Reynolds; Danilo Bandini Ribeiro; Miriam H Richards; Barbara A Richardson; Michael J Richardson; Rodrigo Macip R\Xedos; Richard Robinson; Carolina A Robles; J\Xf6rg R\Xf6mbke; Luz Piedad Romero-Duque; Matthias R\Xf6s; Loreta Rosselli; Stephen J Rossiter; Dana S Roth; T'ai H Roulston; Laurent Rousseau; Andr\Xe9 V Rubio; Jean-Claude Ruel; Jonathan P Sadler; Szabolcs S\Xe1fi\Xe1n; Romeo A Salda\Xf1a-V\Xe1zquez; Katerina Sam; Ulrika Samneg\Xe5rd; Joana Santana; Xavier Santos; Jade Savage; Nancy A Schellhorn; Menno Schilthuizen; Ute Schmiedel; Christine B Schmitt; Nicole L Schon; Christof Sch\Xfcepp; Katharina Schumann; Oliver Schweiger; Dawn M Scott; Kenneth A Scott; Jodi L Sedlock; Steven S Seefeldt; Ghazala Shahabuddin; Graeme Shannon; Douglas Sheil; Frederick H Sheldon; Eyal Shochat; Stefan J Siebert; Fernando A B Silva; Javier A Simonetti; Eleanor M Slade; Jo Smith; Allan H Smith-Pardo; Navjot S Sodhi; Eduardo J Somarriba; Ram\Xf3n A Sosa; Grimaldo Soto Quiroga; Martin-Hugues St-Laurent; Brian M Starzomski; Constanti Stefanescu; Ingolf Steffan-Dewenter; Philip C Stouffer; Jane C Stout; Ayron M Strauch; Matthew J Struebig; Zhimin Su; Marcela Suarez-Rubio; Shinji Sugiura; Keith S Summerville; Yik-Hei Sung; Hari Sutrisno; Jens-Christian Svenning; Tiit Teder; Caragh G Threlfall; Anu Tiitsaar; Jacqui H Todd; Rebecca K Tonietto; Ignasi Torre; B\Xe9la T\Xf3thm\Xe9r\Xe9sz; Teja Tscharntke; Edgar C Turner; Jason M Tylianakis; Marcio Uehara-Prado; Nicolas Urbina-Cardona; Denis Vallan; Adam J Vanbergen; Heraldo L Vasconcelos; Kiril Vassilev; Hans A F Verboven;

Maria Jo\Xe3o Verdasca; Jos\Xe9 R Verd\Xfa; Carlos H Vergara; Pablo M Vergara; Jort Verhulst; Massimiliano Virgilio; Lien Van Vu; Edward M Waite; Tony R Walker; Hua-Feng Wang; Yanping Wang; James I Watling; Britta Weller; Konstans Wells; Catrin Westphal; Edward D Wiafe; Christopher D Williams; Michael R Willig; John C Z Woinarski; Jan H D Wolf; Volkmar Wolters; Ben A Woodcock; Jihua Wu; Joseph M Wunderle, Jr; Yuichi Yamaura; Satoko Yoshikura; Douglas W Yu; Andrey S Zaitsev; Juliane Zeidler; Fasheng Zou; Ben Collen; Rob M Ewers; Georgina M Mace; Drew W Purves; J\Xf6rn P W Scharlemann; Andy Purvis: The 2016 release of the PREDICTS database, , doi:10.5519/0066354, 2016.

Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D. P. and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, Clim. Change, 109(1–2), 117–161, doi:10.1007/s10584-011-0153-2, 2011.

Hurtt, G., Chini, L., Sahajpal, R., Frolking, S., Calvin, K., Fujimori, S., Klein Goldewijk, K., Hasegawa, T., Havlik, P., Lawrence, D., Lawrence, P., Popp, A., Stehfest, E., van Vuuren, D., and Zhang, X.: Harmonization of global land-use change and management for the period 850–2100. [~~submitted~~in prep.]

IPBES: The methodological assessment report on scenarios and models of biodiversity and ecosystem services: S. Ferrier, K. N. Ninan, P. Leadley, R. Alkemade, L. A. Acosta, H. R. Akçakaya, L. Brotons, W. W. L. Cheung, V. Christensen, K. A. Harhash, J. Kabubo-Mariara, C. Lundquist, M. Obersteiner, H. M. Pereira, G. Peterson, R. Pichs-Madruga, N. Ravindranath, C. Rondinini and B. A. Wintle (E~~e~~ds.), Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 348 pages, 2016.

Janse J.H., M. Bakkenes & J. Meijer: Globio-Aquatic, Technical model description v. 1.3: PBL publication 2829, The Hague, PBL Netherlands Environmental Assessment Agency, 2016.

Janse, J. H., Kuiper, J. J., Weijters, M. J., Westerbeek, E. P., Jeuken, M. H. J. L., Bakkenes, M., Alkemade, R., Mooij, W. M. and Verhoeven, J. T. A.: GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems, Environ. Sci. Policy, 48, 99–114, doi:10.1016/j.envsci.2014.12.007, 2015.

Jantz, S. M., Barker, B., Brooks, T. M., Chini, L. P., Huang, Q., Moore, R. M., Noel, J. and Hurtt, G. C.: Future habitat loss and extinctions driven by land-use change in biodiversity hotspots under four scenarios of climate-change mitigation: Future Habitat Loss and Extinctions, Conserv. Biol., 29(4), 1122–1131, doi:10.1111/cobi.12549, 2015.

Jetz, W., Wilcove, D. S., ~~and~~ Dobson, A. P. and Mace, G. M. (Eds.): Projected Impacts of Climate and Land-Use Change on the Global Diversity of Birds, ~~edited by G. M. Mace,~~ PLoS Biol., 5(6), e157, doi:10.1371/journal.pbio.0050157, 2007.

Johnson, J. A., Runge, C. F., Senauer, B., Foley, J. and Polasky, S.: Global agriculture and carbon trade-offs, Proc. Natl. Acad. Sci., 111(34), 12342–12347, doi:10.1073/pnas.1412835111, 2014.

Johnson, J. A., Runge, C. F., Senauer, B. and Polasky, S.: Global Food Demand and Carbon-Preserving Cropland Expansion under Varying Levels of Intensification, Land Econ., 92(4), 579–592, doi:10.3368/le.92.4.579, 2016.

Jungclaus, J. H., Bard, E., Baroni, M., Braconnot, P., Cao, J., Chini, L. P., Egorova, T., Evans, M., González-Rouco, J. F., Goosse, H., Hurtt, G. C., Joos, F., Kaplan, J. O., Khodri, M., Klein Goldewijk, K., Krivova, N., LeGrande, A. N., Lorenz, S. J., Luterbacher, J., Man, W., Maycock, A. C., Meinshausen, M., Moberg, A., Muscheler, R., Nehrbass-Ahles, C., Otto-Bliesner, B. I., Phipps, S. J., Pongratz, J., Rozanov, E., Schmidt, G. A., Schmidt, H., Schmutz, W., Schurer, A., Shapiro, A. I., Sigl, M., Smerdon, J. E., Solanki, S. K., Timmreck, C., Toohey, M., Usoskin, I. G., Wagner, S., Wu, C.-J., Yeo, K. L., Zanchettin, D., Zhang, Q. and Zorita, E.: The PMIP4 contribution to CMIP6 – Part 3: The last millennium, scientific objective, and experimental design for the PMIP4 <i>past1000</i> simulations, Geosci. Model Dev., 10(11), 4005–4033, doi:10.5194/gmd-10-4005-2017, 2017.

Knorr, W., Arneth, A. and Jiang, L.: Demographic controls of future global fire risk, Nat. Clim. Change, 6(8), 781–785, doi:10.1038/nclimate2999, 2016.

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J.-P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., Biewald, A., Bonsch, M., Giannousakis, A., Kreidenweis, U., Müller, C., Rolinski, S., Schultes, A., Schwanitz, J., Stevanovic, M., Calvin, K., Emmerling, J., Fujimori, S. and Edenhofer, O.: Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century, Glob. Environ. Change, 42, 297–315, doi:10.1016/j.gloenvcha.2016.05.015, 2017.

Lawrence, D. M., Hurtt, G. C., Arneth, A., Brovkin, V., Calvin, K. V., Jones, A. D., Jones, C. D., Lawrence, P. J., de Noblet-Ducoudré, N., Pongratz, J., Seneviratne, S. I. and Shevliakova, E.: The Land Use Model Intercomparison Project (LUMIP) contribution to CMIP6: rationale and experimental design, Geosci. Model Dev., 9(9), 2973–2998, doi:10.5194/gmd-9-2973-2016, 2016.

Leadley, P.W., Krug, C.B., Alkemade, R., Pereira, H.M., Sumaila U.R., Walpole, M., Marques, A., Newbold, T., Teh, L.S.L, van Kolck, J., Bellard, C., Januchowski-Hartley, S.R. and Mumby, P.J.: Progress towards the Aichi Biodiversity Targets: An Assessment of Biodiversity Trends, Policy Scenarios and Key Actions. Secretariat of the Convention on Biological Diversity, Montreal, Canada, Technical Series 78, 500 pages, 2014.

Lehsten, V., Sykes, M. T., Scott, A. V., Tzanopoulos, J., Kallimanis, A., Mazaris, A., Verburg, P. H., Schulp, C. J. E., Potts, S. G. and Vogiatzakis, I.: Disentangling the effects of land-use change, climate and CO 2 on projected future European habitat types: Disentangling the drivers of habitat change, Glob. Ecol. Biogeogr., 24(6), 653–663, doi:10.1111/geb.12291, 2015.

Lindeskog, M., Arneth, A., Bondeau, A., Waha, K., Seaquist, J., Olin, S. and Smith, B.: Implications of accounting for land use in simulations of ecosystem carbon cycling in Africa, Earth Syst. Dyn., 4(2), 385–407, doi:10.5194/esd-4-385-2013, 2013.

Martins, I. S. and Pereira, H. M.: Improving extinction projections across scales and habitats using the countryside species-area relationship, Sci. Rep., 7(1), doi:10.1038/s41598-017-13059-y, 2017.

Maxwell, S. L., Fuller, R. A., Brooks, T. M. and Watson, J. E. M.: Biodiversity: The ravages of guns, nets and bulldozers, Nature, 536(7615), 143–145, doi:10.1038/536143a, 2016.

McSweeney, C. F. and Jones, R. G.: How representative is the spread of climate projections from the 5 CMIP5 GCMs used in ISI-MIP?, Clim. Serv., 1, 24–29, doi:10.1016/j.cliser.2016.02.001, 2016.

Meinshausen, M., Wigley, T. M. L. and Raper, S. C. B.: Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 2: Applications, Atmospheric Chem. Phys., 11(4), 1457–1471, doi:10.5194/acp-11-1457-2011, 2011a.

Meinshausen, M., Raper, S. C. B. and Wigley, T. M. L.: Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration, Atmospheric Chem. Phys., 11(4), 1417–1456, doi:10.5194/acp-11-1417-2011, 2011b.

Merow, C., Smith, M. J. and Silander, J. A.: A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter, Ecography, 36(10), 1058–1069, doi:10.1111/j.1600-0587.2013.07872.x, 2013.

Millennium Ecosystem Assessment (Program), Ed.: Ecosystems and human well-being: synthesis, Island Press, Washington, DC., 2005.

Monfreda, C., Ramankutty, N. and Foley, J. A.: Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000: Global crop areas and yields in 2000, Glob. Biogeochem. Cycles, 22(1), n/a-n/a, doi:10.1029/2007GB002947, 2008.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P. and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463(7282), 747–756, doi:10.1038/nature08823, 2010.

Newbold, T., Hudson, L. N., Arnell, A. P., Contu, S., De Palma, A., Ferrier, S., Hill, S. L. L., Hoskins, A. J., Lysenko, I., Phillips, H. R. P., Burton, V. J., Chng, C. W. T., Emerson, S., Gao, D., Pask-Hale, G., Hutton, J., Jung, M., Sanchez-Ortiz, K., Simmons, B. I., Whitmee, S., Zhang, H., Scharlemann, J. P. W. and Purvis, A.: Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment, Science, 353(6296), 288–291, doi:10.1126/science.aaf2201, 2016.

Ohashi, H., Hasegawa, T., Hirata, A., Fujimori, S., Takahashi, K., Tsuyama, I., Nakao, K., Kominami, Y., Tanaka, N., Hijioka, Y., Matsui, T.: Biodiversity can benefit from long-term climate mitigation regardless of land-based measures. [submitted]

Ohashi, H., Hasegawa, T., Hirata, A., Fujimori, S., Takahashi, K., Hijioka, Y., Nakao, K., Tsuyama, I., Kominami, Y., Tanaka, N., Matsui, T.: Long-term climate change impact is more harmful than 2°C climate mitigation land use change. [in prep.]

Olin, S., Schurgers, G., Lindeskog, M., Wårlind, D., Smith, B., Bodin, P., Holmér, J. and Arneth, A.: Modelling the response of yields and tissue C : N to changes in atmospheric CO2 and N management in the main wheat regions of western Europe, Biogeosciences, 12(8), 2489–2515, doi:10.5194/bg-12-2489-2015, 2015.

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K. and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, Geosci. Model Dev., 9(9), 3461–3482, doi:10.5194/gmd-9-3461-2016, 2016.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M. and Solecki, W.: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, Glob. Environ. Change, 42, 169–180, doi:10.1016/j.gloenvcha.2015.01.004, 2017.

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., Lenoir, J., Linnetved, H. I., Martin, V. Y., McCormack, P. C., McDonald, J., Mitchell, N. J., Mustonen, T., Pandolfi, J. M., Pettorelli, N., Popova, E., Robinson, S. A., Scheffers, B. R., Shaw, J. D., Sorte, C. J. B., Strugnell, J. M., Sunday, J. M., Tuanmu, M.-N., Vergés, A., Villanueva, C., Wernberg, T., Wapstra, E. and Williams, S. E.: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being, Science, 355(6332), eaai9214, doi:10.1126/science.aai9214, 2017.

Pereira, H. M., Leadley, P. W., Proenca, V., Alkemade, R., Scharlemann, J. P. W., Fernandez-Manjarres, J. F., Araujo, M. B., Balvanera, P., Biggs, R., Cheung, W. W. L., Chini, L., Cooper, H. D., Gilman, E. L., Guenette, S., Hurtt, G. C., Huntington, H. P., Mace, G. M., Oberdorff, T., Revenga, C., Rodrigues, P., Scholes, R. J., Sumaila, U. R. and Walpole, M.: Scenarios for Global Biodiversity in the 21st Century, Science, 330(6010), 1496–1501, doi:10.1126/science.1196624, 2010.

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B. L., Dietrich, J. P., Doelmann, J. C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H., Waldhoff, S., Weindl, I., Wise, M., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K. and Vuuren, D. P. van: Land-use futures in the shared socio-economic pathways, Glob. Environ. Change, 42, 331–345, doi:10.1016/j.gloenvcha.2016.10.002, 2017.

Poulter, B., Frank, D. C., Hodson, E. L. and Zimmermann, N. E.: Impacts of land cover and climate data selection on understanding terrestrial carbon dynamics and the CO2 airborne fraction, Biogeosciences, 8(8), 2027–2036, doi:10.5194/bg-8-2027-2011, 2011.

Prentice, I. C., Bondeau, A., Cramer, W., Harrison, S. P., Hickler, T., Lucht, W., Sitch, S., Smith, B., ~~and~~ Sykes, M. T., Canadell, J. G., Pataki, D. E. and Pitelka, L. F. (Eds.): Dynamic Global Vegetation Modeling: Quantifying Terrestrial Ecosystem Responses to Large-Scale Environmental Change, in Terrestrial Ecosystems in a Changing World, ~~edited by J. G. Canadell, D. E. Pataki, and L. F. Pitelka,~~ pp. 175–192, Springer Berlin Heidelberg, Berlin, Heidelberg., 2007.

Purvis, A., Newbold, T., De Palma, A., Contu, S., Hill, S. L. L., Sanchez-Ortiz, K., Phillips, H. R. P., Hudson, L. N., Lysenko, I., Börger, L. and Scharlemann, J. P. W.: Modelling and Projecting the Response of Local Terrestrial Biodiversity Worldwide to Land Use and Related Pressures: The PREDICTS Project, in Advances in Ecological Research, vol. 58, pp. 201–241, Elsevier., 2018.

Rabin, S. S., Melton, J. R., Lasslop, G., Bachelet, D., Forrest, M., Hantson, S., Kaplan, J. O., Li, F., Mangeon, S., Ward, D. S., Yue, C., Arora, V. K., Hickler, T., Kloster, S., Knorr, W., Nieradzik, L., Spessa, A., Folberth, G. A., Sheehan, T., Voulgarakis, A., Kelley, D. I., Prentice, I. C., Sitch, S., Harrison, S. and Arneth, A.: The Fire Modeling Intercomparison Project (FireMIP), phase 1: experimental and analytical protocols with detailed model descriptions, Geosci. Model Dev., 10(3), 1175–1197, doi:10.5194/gmd-10-1175-2017, 2017.

Redhead, J. W., May, L., Oliver, T. H., Hamel, P., Sharp, R. and Bullock, J. M.: National scale evaluation of the InVEST nutrient retention model in the United Kingdom, Sci. Total Environ., 610–611, 666–677, doi:10.1016/j.scitotenv.2017.08.092, 2018.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A. and Tavoni, M.: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview, Glob. Environ. Change, 42, 153–168, doi:10.1016/j.gloenvcha.2016.05.009, 2017.

Rondinini, C., Di Marco, M., Chiozza, F., Santulli, G., Baisero, D., Visconti, P., Hoffmann, M., Schipper, J., Stuart, S. N., Tognelli, M. F., Amori, G., Falcucci, A., Maiorano, L. and Boitani, L.: Global habitat suitability models of terrestrial mammals, Philos. Trans. R. Soc. B Biol. Sci., 366(1578), 2633–2641, doi:10.1098/rstb.2011.0113, 2011.

Rosa, I.M.D., Pereira, H.M., Ferrier, S., Alkemade, R., Acosta, L.A., Akcakaya, R., den Belder, E., Fazel, A.M., Fujimori, S., Harfoot, M., Harhash, K.A., Harrison, P.A., Hauck, J., Hendriks, R.J.J., Hernández, G., Jetz, W., Karlsson-Vinkhuyzen, S.I., Kim, H.J., King, N., Kok, M.T.J., Kolomytsev, G.O., Lazarova, T., Leadley, P., Lundquist, C.J., García Márquez, J., Meyer, C., Navarro, L.M., Nesshöver, C., Ngo, H.T., Ninan, K.N., Palomo, M.G., Pereira, L.M., Peterson, G.D., Pichs, R., Popp, A., Purvis, A., Ravera, F., Rondinini, C., Sathyapalan, J., Schipper, A.M., Seppelt, R., Settele, J., Sitas, N., van Vuuren, D.:Rosa, I. M., Pereira, H. M., Ferrier, S., Alkemade, R., Acosta, L. A., Akcakaya, H. R., den Belder, E., Fazel, A. M., Fujimori, S. and Harfoot, M.: Multiscale scenarios for nature futures, Nat. Ecol. Evol., 1(10), 1416, 2017.

Rosenzweig, C., Arnell, N. W., Ebi, K. L., Lotze-Campen, H., Raes, F., Rapley, C., Smith, M. S., Cramer, W., Frieler, K., Reyer, C. P. O., Schewe, J., van Vuuren, D. and Warszawski, L.: Assessing inter-sectoral climate change risks: the role of ISIMIP, Environ. Res. Lett., 12(1), 010301, doi:10.1088/1748-9326/12/1/010301, 2017.

Sala, O. E.: Global Biodiversity Scenarios for the Year 2100 , Science, 287(5459), 1770–1774, doi:10.1126/science.287.5459.1770, 2000.

Schipper, A.M., Bakkenes, M., Meijer, J.R., Alkemade, R., Huijbregts, M.J.: The GLOBIO model. A technical description of version 3.5. PBL publication 2369, The Hague, PBL Netherlands Environmental Assessment Agency, 2016.

Schulp, C. J. E., Alkemade, R., Klein Goldewijk, K. and Petz, K.: Mapping ecosystem functions and services in Eastern Europe using global-scale data sets, Int. J. Biodivers. Sci. Ecosyst. Serv. Manag., 8(1–2), 156–168, doi:10.1080/21513732.2011.645880, 2012.

Secretariat of the Convention on Biological Diversity and United Nations Environment Programme, Eds.: Global biodiversity outlook 4: a mid-term assessment of progress towards the implementation of the strategic plan for biodiversity 2011-2020, Secretariat for the Convention on Biological Diversity, Montreal, Quebec, Canada., 2014.

Settele, J., Scholes, R., Betts, R.A., Bunn, S., Leadley, P., Nepstad, D., Overpeck, J.T., Taboada, M.A., Fischlin, A., Moreno, J.M., Root, T., Musche, M. & Winter, M.Settele, J., Scholes, R., Betts, R. A., Bunn, S., Leadley, P., Nepstad, D., ... Winter, M.: Terrestrial and Inland water systems: in, Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects (pp. 271-360), Cambridge University Press, DOI: 10.1017/CBO9781107415379.009, 2015.

Sharp, R., Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Chaplin-Kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C.K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., Glowinski, K., Chaumont, N., Perelman, A., Lacayo, M. Mandle, L., Hamel, P., Vogl, A.L., Rogers, L., Bierbower, W., Denu, D., and Douglass, J.: InVEST +VERSION+ User's Guide, The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund, 2018.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K. and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Glob. Change Biol., 9(2), 161–185, doi:10.1046/j.1365-2486.2003.00569.x, 2003.

Smith, B., Wårlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J. and Zaehle, S.: Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model, Biogeosciences, 11(7), 2027–2054, doi:10.5194/bg-11-2027-2014, 2014.

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, M., Prins, A.: Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications, The Hague: PBL Netherlands Environmental Assessment Agency, 2014.

Thuiller, W.: Patterns and uncertainties of species' range shifts under climate change, Glob. Change Biol., 10(12), 2020–2027, doi:10.1111/j.1365-2486.2004.00859.x, 2004.

Thuiller, W., Lafourcade, B., Engler, R. and Araújo, M. B.: BIOMOD - a platform for ensemble forecasting of species distributions, Ecography, 32(3), 369–373, doi:10.1111/j.1600-0587.2008.05742.x, 2009.

Thuiller, W., Lavergne, S., Roquet, C., Boulangeat, I., Lafourcade, B. and Araujo, M. B.: Consequences of climate change on the tree of life in Europe, Nature, 470(7335), 531–534, doi:10.1038/nature09705, 2011.

Thuiller, W., Münkemüller, T., Lavergne, S., Mouillot, D., Mouquet, N., Schiffers, K., ~~and~~ Gravel, D. and Holyoak, M. (Eds.): A road map for integrating eco-evolutionary processes into biodiversity models, ~~edited by M. Holyoak,~~ Ecol. Lett., 16, 94–105, doi:10.1111/ele.12104, 2013.

Titeux, N., Henle, K., Mihoub, J.-B., Regos, A., Geijzendorffer, I. R., Cramer, W., Verburg, P. H. and Brotons, L.: Biodiversity scenarios neglect future land-use changes, Glob. Change Biol., 22(7), 2505–2515, doi:10.1111/gcb.13272, 2016.

Titeux, N., Henle, K., Mihoub, J.-B., Regos, A., Geijzendorffer, I. R., Cramer, W., Verburg, P. H., ~~and~~ Brotons, L. and Syphard, A. (Eds.): Global scenarios for biodiversity need to better integrate climate and land use change, ~~edited by A. Syphard,~~ Divers. Distrib., 23(11), 1231–1234, doi:10.1111/ddi.12624, 2017.

United Nations Environment Programme: UNEP-SETAC Life Cycle Initiative: Global Guidance for Life Cycle Impact Assessment Indicators - Volume 1, 2016.

United Nations Environment Programme-World Conservation Monitoring Centre.: Dataset combining Exclusive Economic Zones (EEZ; VLIZ 2014) and terrestrial country boundaries (World Vector Shoreline, 3rd edition, National Geospatial-Intelligence Agency), Cambridge (UK): UNEP World Conservation Monitoring Centre, 2015.

Visconti, P., Bakkenes, M., Baisero, D., Brooks, T., Butchart, S. H. M., Joppa, L., Alkemade, R., Di Marco, M., Santini, L., Hoffmann, M., Maiorano, L., Pressey, R. L., Arponen, A., Boitani, L., Reside, A. E., van Vuuren, D. P. and Rondinini, C.: Projecting Global Biodiversity Indicators under Future Development Scenarios: Projecting biodiversity indicators, Conserv. Lett., 9(1), 5–13, doi:10.1111/conl.12159, 2016.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J. and Rose, S. K.: The representative concentration pathways: an overview, Clim. Change, 109(1–2), 5–31, doi:10.1007/s10584-011-0148-z, 2011.

van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R. and Winkler, H.: A new scenario framework for Climate Change Research: scenario matrix architecture, Clim. Change, 122(3), 373–386, doi:10.1007/s10584-013-0906-1, 2014.

van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., Doelman, J. C., van den Berg, M., Harmsen, M., de Boer, H. S., Bouwman, L. F., Daioglou, V., Edelenbosch, O. Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P. L., van Meijl, H., Müller, C., van Ruijven, B. J., van der Sluis, S. and Tabeau, A.: Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm, Glob. Environ. Change, 42, 237–250, doi:10.1016/j.gloenvcha.2016.05.008, 2017.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O. and Schewe, J.: The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework, Proc. Natl. Acad. Sci., 111(9), 3228–3232, doi:10.1073/pnas.1312330110, 2014.

Welbergen, J. A., Klose, S. M., Markus, N. and Eby, P.: Climate change and the effects of temperature extremes on Australian flying-foxes, Proceedings of the Royal Society B: Biological Sciences, 275(1633), 419–425, doi:10.1098/rspb.2007.1385, 2008.

Zhao, J.: Influencing policymakers: Communication, Nat. Clim. Change, 7(3), 173–174, doi:10.1038/nclimate3215, 2017.

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

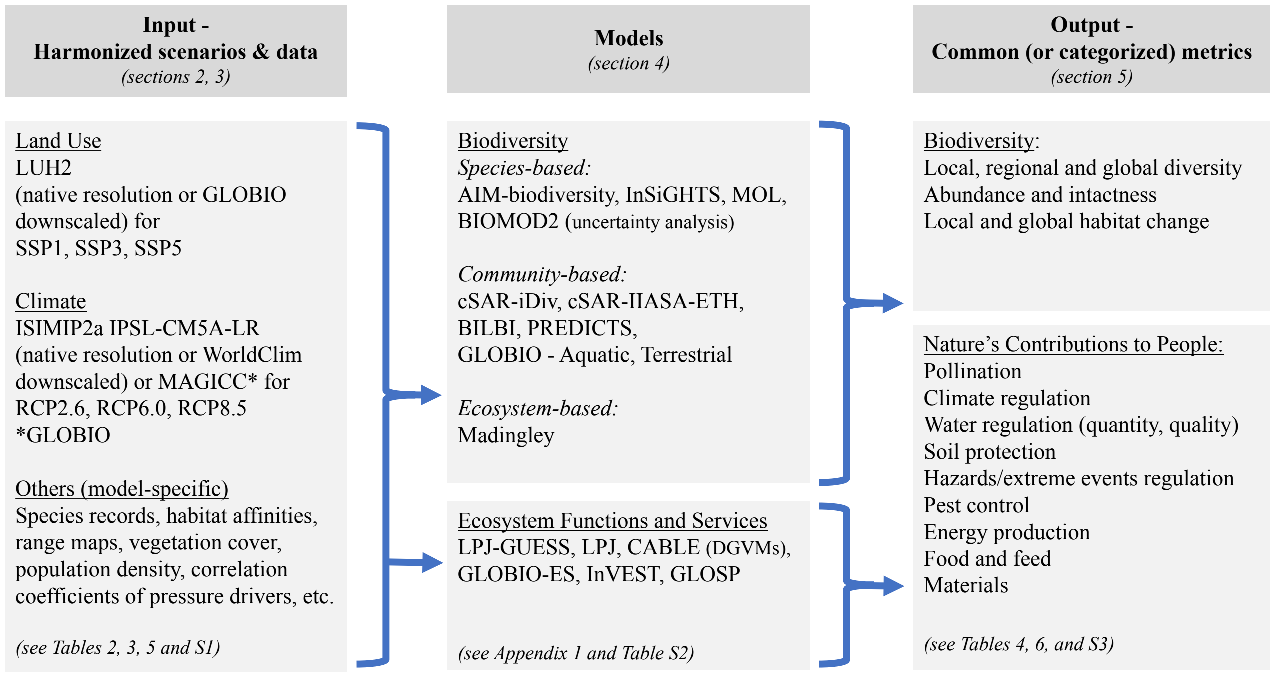

Table 1: Characteristics of (a) SSP and (b) RCP scenarios simulated in BES-SIM (adapted from Moss et al., 2010; O'Neill et al., 2017; Popp et al., 2017; van Vuuren et al., 2011).

(a) SSP scenarios

	SSP1 Sustainability	SSP3 Regional Rivalry	SSP5 Fossil-fueled 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 Limited 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
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
Institution effectiveness	Effective	Weak	Increasingly effective

(b) RCP scenarios

	RCP2.6 Low emissions	RCP6.0 Intermediate emissions	RCP8.5 High emissions
Radiative forcing	Peak at $3W/m^2$ before 2100 and decline	Stabilizes without overshoot pathways to $6W/m^2$ in 2100	Rising forcing pathways leading to $8.5\ W/m^2$ in 2100
Concentration (p.p.m)	Peak at 490 CO_2 equiv. before 2100 and then declines	850 CO_2 equiv. (at stabilization after 2100)	>1,370 CO_2 equiv. in 2100
Methane emission	Reduced	Stable	Rapid increase
Reliance on fossil fuels	Decline	Heavy	Heavy
Energy intensity	Low	Intermediate	High
Climate policies	Stringent	Very modest to almost none	High range of no policiesNo implementation

(c) SSPxRCP scenarios

	SSP1xRCP2.6 Highest mitigation	SSP3xRCP6.0 Limited mitigation	SSP5xRCP8.5 No mitigation
Bioenergy	Low	Highest	Lowest

Table 2: Sources of land use and climate input data in BES-SIM.

BES-SIM model	Land-use data		Climate data		
	LUH2 v2.0 Native resolution *0.25 degree*	LUH2 v2.0 Downscaled (GLOBIO) *300m*	ISIMIP2a IPSL-CM5A-LR Native resolution *0.5 degree*	ISIMIP2a IPSL-CM5A-LR 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) from LUH v1 (sources: Hurtt et al., 2011; Hurtt et al., 2018).

	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 forest/non-forest 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: Selected output indicators for inter~~-~~comparison of biodiversity and ecosystems models. For species diversity change, both proportional changes in species richness (P) and absolute changes (N) are reported. Some models project the α metrics at the level of the grid cell (e.g. species-based and SAR based community models) while others average the local values of the metrics across the grid cell weighted by the area of the different habitats in the cell (e.g. PREDICTS, GLOBIO)**.**

BES-SIM model	~~Local scale~~ S~~s~~pecies diversity change at local scale ~~(~~ (Pα and Nα)	~~Subregional and global scale~~ S~~s~~pecies diversity change at subregional and global scale (Pγ and Nγ)	Abundance-based intactness at local scale (Iα)	~~Local and global~~ M~~m~~ean habitat extent change at local and global scale (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 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 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					

Appendix 1

Table A1: 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., submittedin 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)

BES-SIM Model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
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)
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)
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 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).	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)
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 employ data 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 and Biggs, 2005)~~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, quantified as the mean species abundance (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)
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							
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 plant functional types (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 CO_2 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)
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 Integrated Model to Assess the Global Environment (IMAGE) model and PCRaster Global Water Balance (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)
InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs)	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.	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)

Appendix 2

List of~~.~~ 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
EBV	Essential Biodiversity Variable
ESM	Earth System Models ~~Earth System Models~~
GBIF	Global Biodiversity Information Facility
GBO	Global Biodiversity Outlooks
GCM	~~Global~~ General 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
ISIMIP	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
REMIND	Regionalized Model of Investments and Development
PREDICTS	Projecting Responses of Ecological Diversity In Changing Terrestrial Systems
RCM	Regional Climate Models
RCPs	Representative Concentration Pathways
PCR-GLOBWB	PCRaster Global Water Balance
SAR	Species Area Relationship
SR	Species Richness
SSPs	Shared Socio-economic Pathways

Supplement

Supplementary Methods: Description of the post-processing (downscaling) of LUH2 using GLOBIO 4

GLOBIO 4 discrete land-use allocation routine

The GLOBIO4 land-use allocation procedure requires two main inputs: regionally aggregated totals or demands ('claims') of each land-use type and, for each land-use type, a layer quantifying the suitability of each grid cell for that land-use type (10 arc-seconds resolution; ~300 m). Claims can be derived from national or regional statistics or from models that estimate demands based on socio-economic developments, for example integrated assessment models (IAMs). All claims are expressed in terms of area (km^2). The allocation algorithm then prioritizes candidate grid cells according to their suitability values and allocates the claims of each land-use type in each region starting from the cells with the highest suitability until the total claim is allocated. In the allocation a predefined order is followed, where urban land takes precedence over cropland (Bren d'Amour et al., 2017) and cropland in turn takes precedence over pasture (Hasegawa et al., 2017). If for a given land-use type in a given region there are multiple cells with the same suitability, the allocation is done randomly. Non-allocated areas are assigned the primary vegetation type from a natural land cover map. If the area of land use allocated in a given time step is smaller than the area allocated in the preceding time step, the cells that fall free are assigned secondary vegetation.

Suitability layers

Urban

Urban claims are first allocated to existing urban area, from the centre outward, and then to non-urban area with the probability decreasing with increasing distance from urban areas. We further assume that within protected areas no further urban expansion takes place (beyond the current urban area in PA). To achieve this, the urban suitability layer is calculated as follows, based on the ESA CCI-LC map for 2005:

- For each urban cell (class 190; see Table A2), calculate the Euclidian distance to the nearest other cell (such that cells in the city centres get higher values than cells near the edges). Normalize such that each value ranges between 0 and 1, and add +1 to all values. This gives layer 1.
- For each non-urban cell, calculate the Euclidian distance to the nearest urban cell. Invert the distances (such that cells closer to urban get higher suitability) and normalize such that each value ranges between 0 and 1. Set values within protected areas to zero. This gives layer 2.
- Sum the two layers and normalize again such that each cell gets a value between 0 and 1. This gives a layer where suitability within urban is always higher than beyond urban, and with suitability decreasing from the existing city centres outward.

Cropland

Similar to urban, cropland is first allocated to existing cropland and then with increasing distance to it (based on ESA CCI-LC map for 2005). We assume that homogeneous cropland cells in the ESA CCI-LC map represent more suitable areas than mosaic croplands. We further assume that within protected areas no further cropland expansion takes place (beyond the current cropland within PA). To achieve this, the suitability layer is calculated as follows:

- For each homogeneous cropland cell in the ESA CCI-LC map for 2005 (classes 10, 11, 12 and 20), calculate the Euclidian distance to the nearest other cell (such that cells in the centres of cropland areas get higher values than cells near the edges). Normalize such that each value ranges between 0 and 1, and add +2 to all values. This gives layer 1.
- For each mosaic cropland cell in the ESA CCI-LC map for 2005 (classes 30 and 40), calculate the Euclidian distance to the nearest other cell (such that cells in the centres of cropland areas get higher values than cells near the edges). Normalize such that each value ranges between 0 and 1, and add +1 to all values. This gives layer 2.
- For each non-cropland cell, calculate the Euclidian distance to the nearest cropland cell (classes 10, 11, 12, 20, 30 and 40). Invert the distances (such that cells closer to cropland get higher suitability) and normalize such that each value ranges between 0 and 1. Set values within protected areas to zero. This gives layer 3.
- Sum the three layers and normalize again such that each cell gets a value between 0 and 1. This gives a layer where suitability within cropland is always higher than beyond cropland, with homogeneous cropland being more suitable than mosaic cropland, and with suitability decreasing away from existing cropland.

Pasture and rangeland

For pasture and rangeland, we assume that suitability can be inferred from the density of grazing livestock species, which we retrieve from FAO's gridded livestock of the world (30 arc-seconds). We establish the suitability layer as follows:

- Retrieve the densities (head per km^2) of each of three ruminant livestock species (cattle, goat, sheep) from the FAO's gridded livestock of the world, resolution 30 arc-seconds (https://livestock.geo-wiki.org/download/).
- To correct for differences in body mass among livestock species, convert heads to so-called tropical livestock units (TLU) by assuming that goat/sheep = 0.1 TLU and cattle = 0.6 TLU per individual (Petz et al., 2014).

- Sum the TLUs per grid and normalize the resulting values to achieve suitabilities ranging from 0 to 1.

Forestry
In a recent review it was found that six factors were consistently associated with higher deforestation (roads, urban areas, population, soil suitability, agricultural activity, and proximity to agriculture) (Busch and Ferretti-Gallon, 2017). We assume here that the last five factors primarily reflect deforestation for urban and agricultural development, which is covered in the allocation of urban and cropland, and that forestry/wood harvest is primarily determined by elevation and the proximity to infrastructure needed to transport wood (FAO, 2000). The review further found that protected areas consistently result in lower deforestation. Suitability for forestry (within forest) is therefore calculated as follows:

- Calculate the Euclidian distance to roads from PBL's GRIP database (Meijer *et al.*, accepted) or, in South-America, the distance to either roads or rivers (FAO, 2000), using the Digital Chart of the World (DCW) combined with the Global Lake and Wetland Database (GLWD) to delinate the rivers. Invert and normalize the distances to arrive at suitability values between 0 and 1. This gives layer 1.
- Invert and normalize elevation to arrive at suitability values between 0 and 1. This gives layer 2.
- Multiply the layers and normalize again to arrive at an overall suitability between 0 and 1.

Perform the following post-processing steps:

- Set suitability values within protected areas to zero.
- Clip the global suitability layer to land cover with trees from the ESA CCI-LC map for 2005 (classes 50-110; see Table A2). This contains both closed and open forest, in order to accommodate wood harvest from areas with different tree densities (forested and non-forested in LUH2).

Post-processing LUH2 data with the GLOBIO 4 land allocation routine

Step 1 | Discrete allocation of urban, cropland, pasture and forestry
We use the GLOBIO routine to post-process (downscale) the LUH2 data (http://luh.umd.edu/data.shtml) and refine for cropland, as follows:

1) We aggregated the areas of urban, cropland, pasture, rangeland and forestry across the LUH2 cells to IMAGE region level to obtain the claims. The cropland claim consists of the sum of the five cropland types (c3ann + c3per + c4ann + c4per + c3nfx). The forestry claim is the sum of the wood harvest from forested cells and non-forested cells with primary vegetation (primf_harv + primn_harv), as this is most important for the biodiversity impact. We compiled five sets of claims: three scenarios SSP1-2050, SSP3-2050 and SSP5-2050), the base year (2015), and a starting year (2005) to calculate the initial map.
2) We create an initial land use map by allocating urban, cropland, pasture, rangeland and forestry with GLOBIO 4 land allocation routine, using the claims for 2005 and, for the primary vegetation, the ESA CCI-LC map for the same year. For pasture and rangeland, we use the same suitability layer. By allocating pasture first and rangeland thereafter, the pasture (more intense use) will be allocated to the most suitable areas. Post-process the initial map to remove any remaining urban (class 190) or cropland (classes 10-40) from the ESA CCI-LC map by reclassifying into secondary vegetation.
3) We then allocated the LUH2 'claims' for the years 2015 and 2050 with the GLOBIO 4 allocation routine, using the map from step 2 as initial land use map.

Step 2 | Differentiate cropland
After allocation, we differentiate cropland intensities based on the amount of fertilizer:

1) We created a total fertilizer map layer (0.25 degree resolution; kg N per ha) as weighted average over the crop types: (fertl_c3ann * c3ann + fertl_c4ann * c4ann + fertl_c3per * c3per + fertl_c4per * c4per + fertl_c3nfx * c3nfx)/(c3ann + c4ann + c3per + c4per + c3nfx)
2) We classified intensity per cell: low intensity = 0–100 kg N-input/ha, medium intensity = 100–250 kg N-input/ha and high intensity = >250 kg N-input/ha (Temme and Verburg, 2011).
3) We combined the intensity layer with the map resulting from the discrete allocation to classify cropland based on intensity (post-processing step).

Table S1: Sources and characterization of input data in BES-SIM.

BES-SIM model	Land-use data - re-categorization of LUH2 land-use classes in the model	Climate data - data sources with variables used in the model	Other data
Species-based models of biodiversity			
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-CM5a-LR) - 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 (Rondinini et al., 2011) 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
BIOMOD2		CHELSA (1979-2013 for present, and 2041-2060, 2061-2080 for future) - annual mean temperature, annual temperature range, annual sum of precipitation and precipitation seasonality (coefficient of variation in monthly sum of precipitations)	Expert maps for mammals and amphibians (IUCN) Bird data (Birdlife International)
Community-based models of biodiversity			
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)

BES-SIM model	Land-use data - re-categorization of LUH2 land-use classes in the model	Climate data - data sources with variables used in the model	Other data
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 (Chaudhary et al. 2015; Frischknecht and Jolliet 2016)
BILBI	Primary vegetation (primf, primn) Mature secondary vegetation (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)	WorldClim v1.4 – BIO6 and BIO12 Climate variables derived by 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	Plant species occurrence records (GBIF) Soil attributes: pH, Clay %, Silt %, Bulk Density, Depth (Hengl et al., 2014) 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)		PREDICTS database (Hudson et al., 2014) Human population density (GRUMP v1., HYDE (historical) and the corresponding SSPs as developed by Jones and O'Neill 2016 (future projection)). Agricultural suitability (Zabel et al., 2014)
GLOBIO - Aquatic	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) - daily precipitation and evaporation, monthly precipitation and evaporation. ISIMIP2a (IPSL-CM5a-LR) - water temperature	River flow compared to natural river flow (global hydrological model: PCR-GLOBWB or LPJ) Water temperature (PCR-GLOBWB model) Nutrient loads to aquatic systems (Global Nutrient Model) Drain direction network (Döll and Lehner, 2002) Global map of rivers, lakes and wetlands ((Lehner and Döll, 2004) Lake depths (Kourzeneva, 2010) River dam database (Fekete et al., 2010; Lehner et al., 2011)
GLOBIO - Terrestrial	GLOBIO downscaled LUH2 data (see Annex 1 in Supplementary Materials)	IMAGE model (MAGICC 6.0) - global mean temperature increase (^{o}C)	Nitrogen deposition (IMAGE model) Roads (GRIP dataset, Meijer et al., ~~accepted~~2018)

BES-SIM model	Land-use data - re-categorization of LUH2 land-use classes in the model	Climate data - data sources with variables used in the model	Other data
			Settlements in tropical regions (Humanitarian Data Exchange, Open Street Map)
Ecosystems-based model of biodiversity			
Madingley	*States* Primary (primf, primn) Secondary (secdf, secdn) Grazing (pastr, range) Cropland (c3ann, c4ann, c3per, c4per, c3nfx) Urban (urban) *Transition*s Primary losses (all transitions beginning with primf or primn) Secondary losses (all transitions beginning with secdf or secdn) Secondary gains (all transitions ending with secdf or secdn)	ISIMIP2a (IPSL-CM5a-LR) - temperature, precipitation	Soil characteristics (Smith et al., 2013) Modis Net Primary Productivity (NASA, 2012) Human Appropriation of Net Primary Productivity (Haberl et al., 2007) Human population densities (Jones and O'Neill, 2016; Klein Goldewijk et al., 2016)3
Models of ecosystem functions and services			
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-CM5a-LR) - monthly min/max T, precipitation, shortwave radiation; atmospheric CO_2, 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 (Lamarque et al., 2011)
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-CM5a-LR) - monthly T, precipitation, shortwave radiation or cloudiness; atmospheric CO_2, 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-CM5a-LR) - daily min/max T, precipitation, shortwave radiation, longwave radiation, humidity, windspeed, atmospheric CO_2, N-deposition, land-use transitions (crop, pasture, secondary forest, natural)	Wood harvest estimate (LUH2 dataset) Nitrogen deposition (Lamarque et al., 2011)
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 (Bijl et al., 2016)

BES-SIM model	Land-use data - re-categorization of LUH2 land-use classes in the model	Climate data - data sources with variables used in the model	Other data
InVEST	GLOBIO downscaled LUH2 data (see Annex 1 in Supplementary Materials)	*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 (Jones and O'Neill, 2016) 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 (Monfreda et al., 2008) Nutrient content of 115 crops (table; USDA 2011) Pollination dependence of 115 crops (Klein et al., 2007) Dietary requirements (Allen et al., 2006; BNF, 2016) Demographic population data (GPWv4 Age Dataset – 2018) *Crop production* -Yield raster for 115 crops (Monfreda et al., 2008)
GLOSP	12 original land states in LUH2	ISIMIP2a (IPSL-CM5a-LR) - precipitation	Fractional vegetation cover (Filiponi et al., accepted) Topography (GMTED2010) Soil type and physical properties (Hengl et al., 2014)

Table S2: Model description, modifications and assumptions made to published models in BES-SIM.

BES-SIM model	Description
Species-based models of biodiversity	
AIM-biodiversity	The AIM-biodiversity model (Ohashi et al., ~~in prep~~submitted~~.~~) predicts potential shifts of suitable habitat of multiple species caused by the projected climate and land-use change, using the ISI-MIP climate and LUH2 land-use data. The model incorporates distribution of 9,025 species with ≥ 30 refined occurrence data in their native region, which has been assessed by the IUCN Red List. This includes species of the least concern in five major taxonomic groups: vascular plants, amphibians, reptiles, birds, and mammals. Native region of each species was specified by database of the IUCN Red List. The distribution of suitable habitat (land) is estimated from climate and land-use data at 0.5 arc degrees spatial resolution using a statistical model on the relationship between species occurrence and climate and land-use classes. This statistical model is calibrated by Maxent (Phillips et al., 2006) using the occurrence data from the Global Biodiversity Information Facility (GBIF), historical climate (WorldClim database) and land use (Hasegawa et al., 2017) data for 2005. The bias of occurrence data is corrected using bias files for generating a set of background data for a target group of species (Phillips et al., 2009). The shifts in species suitable habitat in 2050 are projected under two common assumptions of dispersal: 'no' (zero) and 'full' (unlimited and instantaneous) migration (Bateman et al., 2013; Midgley et al., 2006). For the past projections, it is assumed that in year 1900 species can distribute in all suitable habitats without any dispersal limitations.
InSiGHTS	The InSiGHTS model (Rondinini et al., 2011; Visconti et al., 2016) forecasts the Extent of Suitable Habitat (ESH) for vertebrates accounting for land and climate suitability, using global mammal habitat suitability models, IUCN range maps, Worldclim climate and LUH land-use data. Bioclimatic envelope models are fitted based on ecologically current reference bioclimatic variables (Visconti et al., 2016). Species' presence records are obtained by regularly sampling within species' ranges, excluding areas outside of known altitudinal limits. Species' pseudo-absence records are obtained by randomly sampling outside of species' ranges, but within the biogeographic realms intersected by the species' range. Presence and pseudo-absence sampling grids match in resolution. Forecasted layers of land use/land cover are reclassified according to expert-based species-specific suitability indexes, which identifies land-wise suitable cells or proportions thereof. The product of the two layers is multiplied by a layer of cell area (e.g., km²) to estimate species-specific cell-wise ESH. InSiGHTS index, which describes the proportional positive and negative contribution of the region (cell to global) to the species' change in ESH compared to a reference year, is calculated. The improvements made to the model since last published methodology (Visconti et al., 2016) include increased number of modelled species and new scenarios used for climate and land use. For both future and past forecasts, the model limits calculations within the current (2011) species range due to the sparsity of historical data – an assumption that the species' ranges remain constant. InSiGHTS index (ii): $$ii_{s,r,t'} = \frac{E_{s,r,t'} - E_{s,r,t}}{\sum_{r=1}^{\vert R \vert} E_{s,r,t}}$$ *E* = ESH s = species *r* = observed region (from cells to global) *R* = set of all regions *t* = reference time (present) *t'* = observed time (future or past)
MOL	The MOL model (Jetz et al., 2007; Merow et al., 2013) projected potential losses in species occurrences and geographic range sizes given changes in suitable conditions (climate only, land-cover only and climate and land-cover), using Worldclim climate data IUCN expert maps, and species land cover preferences. Climatic niches were estimated using penalized Poisson point process models (similar to Maxent) by extracting presence from the expert maps on a quarter degree grid. Niche were projected under future scenarios and binary maps of predicted presence/absence were obtained. These binary values were then rescaled by the proportion of each cell consisting of habitat where the species in known to occur, leading to maps of the proportion of each cell that is suitable

BES-SIM model	Description
	habitat. Species-level losses were aggregated to inform regional trends. For all three projection types – climate only, land-cover only and climate and land-cover – changes in individual species range size and range location were assessed and summarized for different taxonomic and geographic groupings. Species Habitat Index and Red List Index may be projected with modelled results. All modelling was performed as part of a multispecies workflow that automates production and quality control for range models.
BIOMOD2	The BIOMOD2 model (Thuiller, 2004; Thuiller et al., 2009, 2011) is 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 is produced to allow for a full treatment of uncertainties given data, algorithms, climate models and climate scenarios. Based on the 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 data is used for model calibration while 30% is held out for model evaluation). Models are evaluated using various metrics, and produce indicators including change in species range, species loss and gain per pixel, species turnover, functional and phylogenetic diversity.
Community-based models of biodiversity	
cSAR-iDiv	The cSAR-iDiv (Martins and Pereira, 2017; Pereira and Daily, 2006) model assesses the response of biodiversity to land-use change, using LUH2 land use, Birdlife species occurrence and PREDICTS affinities data. It accounts for the persistence of species in human-modified habitats and for the differential use of habitats by species. The model allows to assess the impact of changes in species richness across scenarios of land use in the countryside SAR, the richness of each functional species group *i*, S_i, is given by a function of the area of each habitat *j*, A_j , in the landscape, $$S_i = c_i \left(\sum_{j=1}^{n} h_{ij} A_j \right)^z$$ where n is the number of modified habitats types, h_{ij} is the affinity of species group *i* to habitat *j* and A_j is the area cover by habitat *j*. The parameters *c* and *z* are constants that depend on the taxonomic group and sampling scheme respectively, and will be species group dependent. Species are classified in functional species groups sharing similar habitat preferences using the Birdlife dataset. The h_{ij}, reflecting the relative affinity of a functional species group *i* to a modified habitat type *j* compared to its natural habitat are derived from the PREDICTS dataset. The model calculates the proportion of species of each functional group between two time periods, then multiplies the trend by the actual number of species of the functional group (i.e. as reported by Birdlife) in each sampling unit. Using this approach, the model estimates the trends of local (i.e., grid cells), regional and global species richness of the two functional groups of bird species - forest and non-forest. The improvements made since last published methodology include the use of high-resolution land-use dataset and affinities calculated from the PREDICTS dataset, and application of two functional groups across scales based on habitat types (land classification). For the past projections, the model is applied starting from 1900 with an assumption that the number of species currently present in different areas/sampling units (IUCN/Birdlife data) corresponds to the number of species at the starting point.
cSAR-IIASA-ETH	The IIASA-ETH cSAR model is based on a countryside Species Area Relationship (cSAR) type of model and estimates the impact of time series of spatially explicit land-use and land-cover transitions on community-level measures of terrestrial biodiversity on five taxa (amphibians, birds, mammals, reptiles and plants). It uses LUH2 data and the initial species richness and cSAR model parameters from Chaudhary et al. (2015) and Frischknecht and Jolliet (2016). Regional species loss is weighted by the fraction of range area of all species in every ecoregion and IUCN threat level, to derive an estimate of global extinctions. The original approach of Chaudhary et al. (2015) is not tailored for estimating long-term and large land-use changes because i) it is a linear approximation (contingent to the current land-use patterns) of a non-linear relationship, and ii) although it incorporates a measure of the length of recovery, the approach is not designed to look at the dynamics of LULCC towards a more biodiversity-friendly state. Instead, in the IIASA-ETH-cSAR model the biodiversity impacts of land-use change is estimated directly from the cSAR formula (cSAR relationship and parameters for the model) and applied to the land-use shares for the various LULC classes

BES-SIM model	Description
	considered (their affinity values are derived directly for the local characterization factor database based on field records). The link between LULCC and habitat is more detailed by taking the gross transitions directly as input between LULC classes (instead of net state changes, which ignores the land-use history). The model also accounts for the time dynamics with which a transition generates biodiversity outcomes where the affinity of species for a converted LULC class forgets its origin that is specific to each pair of LULC class. It is typically quick (i.e., lower than one time step) for biodiversity-unfavourable LULC transitions, and long (typically several decades) for biodiversity-favourable LULC transitions. The model is run from 1500 onwards – from the past to into the future – with initial land-use states in year from LUH2 dataset and cumulated transitions from one time step to another.
BILBI	This modelling framework (Hoskins et al., in prep.) couples application of the species-area relationship (SAR) with correlative statistical modelling of continuous patterns of turnover in the species composition of communities as a function of environmental variation (Ferrier et al., 2004, 2007). Generalised dissimilarity modelling (Ferrier et al., 2007) is used to fit models of spatial turnover in vascular-plant composition, based on 52,489,096 occurrence records for 254,145 plant species, extracted from GBIF, and environmental layers covering the entire land surface of the planet at 30-second (~1km) grid-resolution (including climate layers derived from WorldClim; see Table S1). A separate GDM is fitted for each of 61 bio-realms from WWF's ecoregionalisation. In a few cases, data from neighbouring or ecologically-related bio-realms are used to supplement the dataset employed in fitting GDMs for more poorly sampled bio-realms. To accommodate the 'presence-only' nature of much of the biological data assembled from GBIF, GDMs are fitted to observed matches and mismatches in species identity between pairs of individual occurrence records. The modelled probability of a mismatch in species identity is then transformed into the expected compositional similarity between any two cells. Using the approach employed by Blois et al., (2013), Ferrier et al. (2012), Fitzpatrick et al. (2011), Mokany et al. (2012), Prober et al. (2012) and William et al. (2015), space-for-time substitution is applied to the fitted GDMs to project temporal turnover in species composition expected as a result of any given climate scenario based on temperature and precipitation projections for 2050, downscaled by WorldClim. Given that the 'current climate' surfaces from WorldClim, used to fit the GDMs, are averaged over the period 1960-1990, the analysis is effectively projecting the temporal turnover in species composition expected between 1975 (midway between 1960 and 1990) and 2050. This approach allows estimation of temporal turnover for a single location or of spatial-temporal turnover between two different locations. Estimates of the proportional coverage in 2015 of 12 land-use classes within each terrestrial 0.25 degree grid-cell on the planet, from the LUH2, are statistically downscaled to 30-second grid resolution using the approach described by Hoskins et al. (2016) incorporating MODIS Vegetation Continuous Fields, and the Global Human Settlement Population Grid, as additional covariates. Downscaled land use in 2015 is then translated into 'habitat condition' for biodiversity using coefficients fitted in hierarchical mixed-effect modelling undertaken by the PREDICTS project. These coefficients estimate the proportion of local native species richness expected for different land-use classes. This modelling employed the approach described by Newbold et al. (2016b) but with models refitted using the 12 LUH2 land-use classes. Change in habitat condition at 30-second grid resolution is projected for any given LUH2 land-use scenario using a simple delta-downscaling approach of applying the proportional change in habitat condition between 2015 and 2050 to the downscaled 2015 condition values for all 30-second cells within each 0.25 degree cell. The GDM-based modelling of temporal turnover in species composition for the climate scenario of interest, and downscaled habitat condition for the land-use scenario of interest, are used in combination to estimate the proportion of plant species expected to persist over the longer term (i.e. the complement of the proportion of species committed to extinction) employing the SAR. This particular SAR-based approach, as applied recently in two major projects within Australia – the Australian National Outlook (Bryan et al., 2014; Hatfield-Dodds et al., 2015; Brinsmead et al., 2017) and AdaptNRM (Prober et al., 2015) – is an extension of that described originally by Allnutt et al. (2008) and Ferrier et al. (2004). In contrast to more traditional applications of the SAR to estimating levels of species persistence, which work with discrete environmental classes or ecosystem types, this approach views grid-cells as sitting within a continuum of spatial and temporal turnover in biodiversity composition (Allnutt et al., 2008; Ferrier et al., 2004).

BES-SIM model	Description
	The proportion of plant species originally associated with cell *i* which are expected to persist over the longer term, anywhere in their range, as a consequence of a given combination of climate and land-use scenarios is calculated as: $$p_i = \left[\frac{\sum_{j=1}^{n} s_{i_{present}j_{future}} c_{j_{future}}}{\sum_{j=1}^{n} s_{i_{present}j_{present}}}\right]^z$$ where: n = total number of cells on the planet $s_{i_{present}j_{present}}$ = similarity between cells *i* and *j* in the present $s_{i_{present}j_{future}}$ = similarity between cell *i* in the present and cell *j* in the future $c_{j_{future}}$= condition of habitat in cell *j* in the future z = SAR exponent (set to 0.25 for the current study) The proportion of species originally associated with any specified region (reporting unit) expected to persist can then be calculated as a weighted geometric mean of the values for all individual cells in that region: $$p_{region} = \frac{\sum_{i=1}^{m} p_i w_i}{\sum_{i=1}^{m} w_i}$$ where: m = total number of cells in the region (reporting unit) of interest The weights employed are: $$w_i = \frac{1}{\sum_{j=1}^{n} s_{i_{present}j_{present}}}$$ where: n = total number of cells on the planet
PREDICTS	The PREDICTS model (Newbold et al., 2015, 2016b) 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. These models are combined with global data on past, present or future states of the pressures used in modelling, to make global projections of each variable for each desired time point. The modelling uses data from 767 studies, each of which surveyed multiple sites that faced differing land-use and related pressures, for which version 1 has been published (Hudson et al., 2017), with now more data available from over 32,000 sites and over 51,000 species, which is reasonably representative across different biomes and major animal, plant and fungal taxa. Models also use human population density (HYDE, GRUMP v1, Jones and O'Neill, 2016) and LUH2 land-use data. In addition to the LUH2 land-use data, the PREDICTS model uses secondary vegetation age and use intensity classes. Fractional distribution of secondary vegetation age was compiled for each grid cell by tracking conversions using LUH2 transitions data. Secondary vegetation was classified into young, intermediate and mature using the following thresholds: <30y = young, 30y>50y=intermediate, >50y= mature. Use intensity was classified as Minimal, Light or Intense using Global Land Systems data as in Newbold et al. (2015). Linear mixed-effects models (with study- and block-level random effects to accommodate the heterogeneity in the data, and site-level random effects to account for over-dispersion in species richness models) are used to estimate how local (alpha) diversity is affected by land use, land-use intensity and human population density. Model coefficients are combined with maps of the pressure data to make global projections of the estimated values of the response variables. These projections are then combined to yield the variants of the Biodiversity Intactness Index (BII) shown in Newbold et al. (2016; see Scholes and Biggs, 2005 for the original development of BII). Since last published model, sites in the PREDICTS database were re-curated to incorporate the land-use classes present in LUH2 but not used by Hurtt et al. (2011 Climatic Change), i.e., the refinement of agricultural classes. When modelling abundance, the abundance data were rescaled within each study such that the maximum

BES-SIM model	Description
	abundance was the same within each study; this assists with model convergence. The compositional similarity models use the data more fully than previously: whereas previously independent pairwise comparisons were made between sites, the models here are based on the full matrix of pairwise comparisons between sites. This full-matrix approach allows incorporation of human population density in addition to land use (the only pressure variable previously analysed in our models of compositional similarity: (Newbold et al., 2016b, 2016a). Whereas our previous models of compositional similarity used all primary vegetation sites as the baseline condition, expansion of the database has allowed us to restrict the baseline to minimally-used primary vegetation. Previously, human population density (ln(x+1)-transformed) was fitted as a quadratic term in models of abundance and richness but omitted from models of compositional similarity; here we have treated it as a linear term in all models to improve consistency. The study-level mean of ln(human population density + 1) was also added as a control variable into the models of abundance and species-richness, to avoid possible artefacts that could otherwise arise if studies in more densely-populated areas sample more intensively. Agricultural suitability (Zabel et al., 2014) was also used as a control variable (Gray et al., 2016). These control variables are used as additive terms in modelling but not projections. Our previous models of abundance and richness considered proximity to roads as a pressure, but we have omitted roads from these models because of the lack of future and historical estimates; land use, land-use intensity and human population density – all somewhat correlated with proximity to roads – have the potential to explain some of the variance previously explained by roads. PREDICTS also modelled species richness as a function of land use, in order to provide habitat coefficient estimates to other models in BES-SIM. Separate models were run for areas that would naturally be forested and non-forested (data subset using LUH2/fstnf). Human population density was omitted from the model; otherwise, model structure matched that outlined above.
GLOBIO-Aquatic	The GLOBIO-Aquatic model (Janse et al., 2015) quantifies the impacts of multiple anthropogenic pressures in the past, present and future on freshwater biodiversity and its ecosystem services, using climate (IMAGE model), land use (GLOBIO model), river flow (PCR-GLOBWB or LPJ model), water template (PCR-GLOBWB model), nutrient loads to aquatic systems (Global Nutrient Model), global map of rivers, lakes and wetlands (GLWD), and river dam database. The drivers included are land use, eutrophication, climate change and hydrological disturbance. The model comprises a set of mostly correlative relationships between anthropogenic drivers and biodiversity and ecosystem services of rivers, lakes and wetlands. The model produces biodiversity intactness indicator – Mean Species Abundance (MSA) – of lakes, rivers and wetlands as well as the probability of harmful algal blooms as an indicator for freshwater provisioning services.
GLOBIO-Terrestrial	The GLOBIO model for terrestrial biodiversity (Alkemade et al., 2009) quantifies the impacts of multiple anthropogenic pressures on local biodiversity based on the mean species abundance (MSA) metric. MSA represents the mean abundance of original species in relation to a particular pressure as compared to the mean abundance in an undisturbed reference situation. MSA's responses to a particular pressure are quantified based on a meta-analysis of biodiversity monitoring data reported in the literature, whereby abundance ratios of individual species are calculated as $A_{impacted}/A_{reference}$ for $A_{impacted} < A_{reference}$ and $A_{impacted}/A_{reference} = 1$ for $A_{impacted} > A_{reference}$. Changes in biodiversity are quantified by combining georeferenced layers of the pressure variables with the MSA response relationships. Next, the maps with the MSA values per pressure are combined to arrive at an overall MSA. If a particular pressure is assumed to be dominant, the combined impact (MSA) is assumed equal to the impact (MSA) of this dominant pressure. If pressures act independently, the overall MSA value is calculated by multiplying the MSA values corresponding with the individual pressures. Five pressures are currently included (climate change, land use, roads, atmospheric nitrogen deposition and encroachment/hunting). Climate change, nitrogen deposition, and land-use data are derived from the IMAGE model (Stehfest et al., 2014). Land-use data from IMAGE are downscaled to a higher spatial resolution with the GLOBIO land allocation routine. Roads data are taken from the global road inventory project (GRIP) database (Meijer et al., submitted). Settlement data (required to calculate hunting impacts) are retrieved from multiple open-source datasets, including Open Street Map and Humanitarian Data Exchange. Improvements made to the model since the last published methodology include a new high-resolution, discrete land-use allocation routine and improved response relationships for encroachment/hunting (Benítez-López et al., 2017).

BES-SIM model	Description
Ecosystems-based model of biodiversity	
Madingley	The Madingley Model (Harfoot et al., 2014) is a mechanistic, or process-based, model of whole ecosystems developed to synthesize and advance our understanding of ecology, and to enable mechanistic prediction of the structure and function of whole ecosystems at various levels of organisation, whether on land or in water. Using data from ISI-MIP, soil characteristics (Smith et al., 2013), Modis Net Primary Productivity (NASA, 2012), Human Appropriation of Net Primary Productivity (Haberl et al., 2007), and LUH2 (land use), Madingley simulates the dynamics of autotrophs, and all heterotrophs with body masses above 10 µg that feed on living organisms. In the model, organisms are not characterised by species identity but grouped according to a set of categorical functional traits, which determine the types of ecological interactions that modelled organisms are involved in whilst a set of continuous traits determine the rates of each process. Plants are represented by stocks, or pools, of biomass modelled using a terrestrial carbon model. Biomass is added to the stocks though the process of primary production, the seasonality of which is calculated using remotely sensed Net Primary Productivity (Harfoot et al., 2014). This production is allocated to above-ground/below-ground, structural/non-structural, evergreen/deciduous components and Madingley assumes that above-ground, non-structural matter is available for heterotrophic organisms to consume. Biomass is lost from plant stocks through mortality from fire and senescence, as well as through herbivory. Production, allocation and mortality in the plant model are all determined by environmental conditions (temperature, number of frost days, precipitation and the available water capacity of soils). Heterotrophic animals are represented as agents, termed cohorts, which are collections of individual organisms occurring in the same modelled grid cell with identical categorical and continuous functional traits. This approach enables the model to predict emergent ecosystem properties at organisational scales from individuals to the whole ecosystem. Heterotroph dynamics result from five ecological processes: metabolism, eating, reproduction, mortality and dispersal. Predator-prey interactions (including herbivory) are based on a Holling's Type III functional response (Denno et al., 2012), and for predation on a size-based model of predator-prey feeding preferences (Williams et al., 2010). Metabolism is based on empirical relationships between energy consumption and ambient temperature taking into account the body mass of the organism (Brown et al., 2004). Endotherms are assumed in the model to thermoregulate perfectly, and thus are active for 100% of each time step. Ectotherms in the model do not thermoregulate, and thus are only active for the proportion of each time step during which ambient temperature was within their upper and lower activity temperature limits, estimated following (Deutsch et al., 2008). Reproduction can occur once a cohort has achieved its adult body mass and results from the allocation of surplus mass to reproductive potential followed by reproductive events once a threshold ratio of reproductive potential to adult body mass is reached (Harfoot et al., 2014). Mortality (in addition to predation mortality) arises from three causes: a constant background rate, starvation if insufficient food is obtained, and senescence, which increases exponentially after maturity with a functional form similar to the Gompertz model (Pletcher, 1999). Dispersal in the terrestrial realm is either random diffusive dispersal of juvenile organisms or directed dispersal of organisms in response to starvation or low densities of individuals (Harfoot et al., 2014). The model produces total biomass and abundance of above ground heterotrophs, total biomass of autotrophs, total biomass and abundance of functional groups (trophic levels, metabolic pathways, reproductive strategies), trophic and food web structure, biomass structure, age structure, functional diversity (richness, evenness, divergence), functional dissimilarity, net secondary productivity, biomass turnover rates, herbivory, predation, mortality and reproduction rates. The improvements made to the model since last published methodology include incorporation of temporally changing climate as well as natural and human impacted plant stocks to better represent the LUH2 land-use projections and calculation of functional diversity and functional dissimilarity to represent community changes. To make historical reconstructions back to 1900 we first run an ensemble of six simulations from pseudo-random initial conditions for 100 years until it reaches quasi steady state for the year 1901. This spin up used land use and HANPP for 1901, and 100 years of climate randomly recycled from the years 1951 to 1960 of the ISI-MIP IPSL climate reconstruction. The quasi-steady state conditions from these simulations were then ran forward to 2005 using the time series of land use change, climate change (where the period 1901 – 1950 was constructed using randomly recycled years from 1950 – 1961) and HANPP.

BES-SIM model	Description
Models of ecosystem functions and services	
LPJ-GUESS	The LPJ-GUESS model (Lindeskog et al., 2013; Olin et al., 2015; Smith et al., 2014) is a "demography enabled" dynamic global vegetation model using historical and future climate, CO_2, nitrogen deposition and fertilizer, land cover change, irrigated fraction, and wood harvest estimate data. The model computes vegetation and soil state and function, and distribution of vegetation units dynamically in space and time in response to climate change, land-use change, atmospheric CO_2, and N-input. It combines an individual- and patch-based representation of vegetation dynamics with ecosystem biogeochemical cycling from regional to global scales. In LPJ-GUESS, the dynamics of vegetation result from growth and competition for space, light, and soil resources from herbaceous understorey and woody plant individuals in each patch replicated for each simulated grid cell. The suite of simulated patches represents the distribution within a landscape representative of the grid cell as a whole of vegetation stands with different histories of disturbance and stand development (succession). Individuals for woody plant functional types (PFTs; trees and shrubs) are identical within a cohort (age/size class) and patch. Photosynthesis, respiration, stomatal conductance and phenology (leaves and fine roots turnover) are simulated on a daily time step. The net primary production (NPP) accrued at the end of each simulation year is allocated to leaves, fine roots and, for woody PFTs, sapwood, following a set of prescribed allometric relationships for each PFT, resulting in diameter, height, and biomass growth. Population dynamics (establishment and mortality) are represented as stochastic processes, influenced by current resource status, demography and the life-history characteristics of each PFT (text from Smith et al., 2014). The modelled outputs include carbon pools in vegetation, soil, gross primary productivity, heterotrophic respiration, net primary productivity, runoff, leaf area index, crop yields, area burnt, fire emissions, carbon to nitrogen ratios, and nitrogen loss. The improvements made since last published methodology include an upgrade in the fire model and accounting for wood harvest. To provide climate input before 1951 random years out of the period 1951 to 1960 are chosen to generate/recycle the climate data for years 1901 to 1950.
LPJ	LPJ is a big leaf model (Poulter et al., 2011) that simulates the coupled dynamics of biogeography, biogeochemistry and hydrology under varying climate, atmospheric CO_2 concentrations, and land-use land-cover change practices, using historical and future climate, CO_2 level, land cover change transitions, and wood harvest estimate data. LPJ represents demography of grasses and trees in a simplistic manner, where a 'representative individual' is used to scale from individuals to landscapes. Physiological processes are applied to the representative individual and integrated over the landscape, i.e., a grid cell, based on the density of individuals. Land cover change includes explicit representation of deforestation and reforestation, as well as harvesting of managed grasslands. Natural fires are included. The LPJ model has a hierarchical representation of the land surface where within a grid cell, tiles represent primary forest, secondary forest, and managed lands (crops or pasture), and within a tile are either plant functional types (PFTs) or crop functional types (CFTs). On an annual time step, establishment, mortality, fire, carbon allocation, and land cover change are implemented, and on a daily time step, photosynthesis, autotrophic respiration, and heterotrophic respiration are calculated. The carbon cycle is coupled to the hydrologic cycle via stomata, which must be open to assimilate atmospheric CO_2 but simultaneously lose water. Stomatal conductance is determined as the minimum between potential evapotranspiration (demand) and soil plant water availability (supply). Photosynthesis and radiation follows the Farquhar biochemical model and distributes photosynthetic active radiation vertically through the canopy following Beer's Law. The LPJ model is fully prognostic, meaning that PFT distributions, phenology, and carbon dynamics are simulated based on physical principles within a numerical framework. The typical variables of model outputs are (either per grid cell simulated, or per PFT): C pools in veg., soil, GPP, heterotrophic respiration, NPP, runoff, LAI, crop yields, area burnt, and fire emissions. The land cover change and land-use transitions have been upgraded to include the dynamics from the Land Use Harmonization product by George Hurtt and Louise Chini. This development means that LPJ represents the full set of states and transitions represented in LUH v2 and has an improved estimate of carbon fluxes from land-cover change. The model is spun up to pre-industrial equilibrium conditions by using an atmospheric CO_2 concentration of 280 ppm and recycling the first thirty years of meteorological data (1901-1930) for 1000 years.
CABLE	CABLE is a "demography enabled" global terrestrial biosphere model (Haverd et al., 2017) that computes vegetation and soil state and function dynamically in space and time in response to climate change, land-use change and N-input, using historical and future daily climate data downscaled to 3-hourly, annual CO_2 levels in the atmosphere, N-deposition, land-cover change, irrigated faction, and wood harvest area. It combines a patch-based representation of vegetation structural dynamics with ecosystem biogeochemical cycling from regional to

BES-SIM model	Description
	global scales. CABLE consists of a 'biophysical' core, the CASA-CNP 'biogeochemistry' module (Wang et al., 2010) and the POP module for woody demography and disturbance-mediated landscape heterogeneity. The biophysical core (sub-diurnal time-step) consists of four components: (1) the radiation module describes radiation transfer and absorption by sunlit and shaded leaves; (2) the canopy micrometeorology module describes the surface roughness length, zero-plane displacement height, and aerodynamic conductance from the reference height to the air within canopy or to the soil surface; (3) the canopy module includes the coupled energy balance, transpiration, stomatal conductance and photosynthesis and respiration of sunlit and shaded leaves; (4) the soil module describes heat and water fluxes within soil (6 vertical layers) and snow (up to 3 vertical layers) and at their respective surfaces. The CASA-CNP biogeochemistry module (daily time-step) inherits daily net photosynthesis from the biophysical code, calculates autotrophic respiration, allocates the resulting net primary production (NPP) to leaves, stems and fine roots, and transfers carbon, nitrogen and phosphorous between plant, litter and soil pools, accounting for losses of each to the atmosphere and by leaching. POP (annual time-step) inherits annual stem NPP from CASA-CNP, and simulates patch-scale woody ecosystem stand dynamics, demography and disturbance-mediated heterogeneity, returning the emergent rate of biomass turnover to CASA-CNP. The model outputs C pools in veg., soil, GPP, heterotrophic respiration, NPP, runoff, LAI, combined crop and pasture yields, wood harvest, C:N ratios, either per grid cell simulated, or per PFT. The land-use and land-cover change module, driven by gross land-use transitions and wood harvest area extend the applicability of CABLE for regional and global carbon-climate simulations, accounting for vegetation response of both biophysical and anthropogenic forcing. Land-use transitions and harvest associated with secondary forest tiles modify the annually-resolved patch age distribution within secondary-vegetated tiles, in turn affecting biomass accumulation and turnover rates and hence the magnitude of the secondary forest sink. CABLE incorporates a novel approach to constraining modelled GPP to be consistent with the Co-ordination Hypothesis, predicted by evolutionary theory, which suggests that electron transport and Rubisco-limited rates adjust seasonally and across biomes to be co-limiting.
GLOBIO-ES	The GLOBIO-ES model (Alkemade et al., 2014; Schulp et al., 2012) simulate the influence of various anthropogenic drivers on ecosystem functions and services at the global scale in past, present and future environments using model outcomes of the IMAGE model on food production, livestock production, carbon balance, land use, and climate (Stehfest et al., 2014), in combination with data on GDP per capita, protected area maps and infrastructure. For ecosystem services related to water, water flow regimes are derived from the PCR-GLOBWB model, and nutrient loading is derived from the IMAGE framework model Global Nutrient Model (see also section on GLOBIO-Aquatic). The model transfers IMAGE model outcomes into a supply – demand concept of ecosystem services and uses causal relationships between environmental variables and ecosystem functions and services (definitions according the cascade model by Haines-Young and Potschin (2010) based on literature reviews). The model quantifies a range of provisioning services (e.g. crop production, grass and fodder production, wild food, water availability), regulating services (e.g. pest control, pollination, erosion risk reduction, carbon sequestration, food risk reduction, harmful algal blooms), and culture services (e.g. nature based tourism) These relationships describe how ecosystem services respond to changing environments. The improvements made since last published methodology include updated relationships between land use and the presence of pollinators and predators using additional peer review papers.
InVEST	*Nutrient Delivery Ratio* The InVEST nutrient delivery ratio model (Redhead et al., 2018) maps nutrient sources from watersheds and their transport to the stream using digital elevation model, land-use land-cover data, nutrient runoff proxy, watersheds layer, and biophysical table. This spatial information can be used to assess the service of nutrient retention by natural vegetation. The retention service is of particular interest for surface water quality issues and can be valued in economic or social terms (e.g. avoided treatment costs, improved water security through access to clean drinking water). The model uses a mass balance approach, describing the movement of mass of nutrient through space. Unlike more sophisticated nutrient models, the model does not represent the details of the nutrient cycle but rather represents the long-term, steady-state flow of nutrients through empirical relationships. Sources of nutrient across the landscape, also called nutrient loads, are determined based on the LULC map and associated loading rates. In a second step, delivery factors are computed for each pixel based on the properties of pixels belonging to the same flow path (in particular their slope and retention efficiency of the land use). At the

BES-SIM model	Description
	watershed/subwatershed outlet, the nutrient export is computed as the sum of the pixel-level contributions. The model outputs total nutrient loads (sources) in the watershed and total nutrient exports from the water shed at the pixel level. Improvements were made to the model to accept load as a raster for certain LULC classes (agriculture) instead of a table value. This was so we could utilize the fertilizer application rates in the management files for each SSP. The nitrogen retention is connected to people by multiplying the per-hectare export by the rural population density in the watershed as a weighting factor of the degree to which water quality impacts rural people (who are typically more vulnerable to declines in water quality because they have fewer or no water treatment options). The model generates its own watersheds (hydrologically complete watersheds that drain to the sea) and added a pit-filling algorithm for DEMs to allow for global routing. A function is added to allow for "continuous" streams, meaning a single pixel (of resolution 300 m) doesn't have to be classified as entirely stream, but can be a value between 0-1, indicating the proportion of the pixel that the stream occupies. *Costal Vulnerability* The InVEST Coastal Vulnerability model (Arkema et al., 2013; Guannel et al., 2016) produces a qualitative index of coastal exposure to erosion and inundation as well as a map of the location and size of human settlements. The model creates the exposure index and coastal population maps using a spatial representation (raster) of population and spatial representations (shapefiles and rasters) of seven bio-geophysical variables (geomorphology, relief, natural habitats (biotic and abiotic), net sea level change, wind exposure, wave exposure, surge potential depth contour) and outputs point shapefile with fields representing base risk, and risk without habitat. The software model was refactored to optimize runtime and memory usage so it was computationally feasible to model global runs. *Pollination* The InVEST Pollination model (Chaplin-Kramer et al., 2014) maps pollination contribution to nutrition based on pollinator-dependent nutrient production, and the dependence of that production on natural habitat around farmland. This nutrition production provided by wild pollinators is then translated to potential number of people fed based on dietary requirements. Pollination sufficiency is based on the area of pollinator habitat around farmland. Agricultural pixels with >30% natural habitat in the 2 km area surrounding the farm are designated as receiving sufficient pollination for pollinator-dependent yields. Pollination-dependence of crops, crop yields, and crop micronutrient content are combined to calculate pollination-dependent nutrient production. Nutrition provided by wild pollinators on each pixel of agricultural land is then calculated according to pollination habitat sufficiency and the pollination-dependent nutrient yields. The model uses yield maps for 115 crops (raster; Monfreda et al., 2008), nutrient content of 115 crops (table; USDA 2011), pollination dependence of 115 crops (raster; Klein et al., 2007), land use (raster; GLOBIO downscaled from LUH2), dietary requirements (WHO), demographic data (GPW4 Age Dataset – 2018), and outputs pollination sufficiency (proportion of agricultural land in a grid cell receiving pollination services sufficient for attaining full pollination-dependent yields), pollination service - nutrient (production of macro/micronutrient per grid cell), people fed - nutrient (potential number of people whose annual dietary requirements are met by nutrition provided by wild pollination), self-sufficiency – nutrient (proportion of nutrition needs of population in a grid cell met by nutrition provided wild pollination in that grid cell). The approach for pollination-dependent nutrient production outlined in Chaplin-Kramer et al. (2014) was extended to include pollination habitat sufficiency. *Crop Production* The crop-production model is based closely on the InVEST Crop Production model (Mueller et al., 2012) with calculation methods for nutritional content from Johnson et al., 2014, 2016. The model was modified by aggregating 175 crops (raster; Monfreda et al., 2008) to the 5 crop-types in LUH2: C3 annual, C3 perennial, C4 annual, C4 perennial and N-fixing crops. Each crop type in the LUH2 states data was resampled (bilinear) to a 5 arc-minute grid-cell to match yield data. Caloric production per hectare on each current and future landscape for each crop type is calculated by aggregating yield data and multiplying it by the proportional extent of the 5 arc-minute grid-cell in each crop-type. To identify crop-type yield for cropland expansion that occurred outside of existing cropland extent (and therefore did not have observed yields available), we used the yield-gap method in (Mueller et al., 2012) to identify the 50^{th}-percentile yield for the grid-cell based on its climate bin (defined with growing-degree days and precipitation). The indicator we report does not include increases in per-area crop yield (e.g. from technological change) and instead isolates simply the increase in food security/food production from

BES-SIM model	Description
	changes in cropland extent under the different scenarios. Yield was expressed in terms of caloric content based on aggregated-versions of the food balance sheets of the Food and Agriculture Organization of the United Nations FAOSTAT database.
GLOSP	GLOSP (Guerra et al., 2016) is a 2D soil erosion model based on the Universal Soil Loss Equation, using climate, land use, vegetation cover, topography, and soil data to estimate global and local soil erosion and protection indicators. 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) [Ps = Pse-Se]. Pse is calculated by the integration of the joint effect of slope length, rainfall erosivity, and soil erodibility. Se is calculated by multiplying Pse by the fractional vegetation cover ($0 \leq$ Fcover ≤ 1). Here soil protection is given by the value of fractional vegetation cover calculated as a function of land use, altitude, precipitation, and soil properties. Global fractional vegetation cover is originally calculated based on a multiple endmembers method described in Filiponi et al. (accepted). This is then resampled to 0.25 degree. To obtain a long temporal distribution of this variable (1900-2099), a spatial explicit polynomial regression function is implemented to calculate monthly Fcover values as a function of land use, altitude, precipitation, and soil properties. For future conditions, vegetation values are calculated based on SSP~RCP correspondences. An assumption is made to the historical projections that the physical processes remain the same through time.

Table S3: Definition of metrics in ecosystem functions and services models in BES-SIM.

Types of services	NCP	Metric	Models	Units	Definitions and formula
Material	Energy	Bioenergy-crop Production	LPJ-GUESS	PgC/yr,kgC/m^2/yr	First generation biofuel crop production (carbon removed during harvest)
Material	Food and feed	Crop Yields	LPJ-GUESS	PgC/yr,kgC/m^2/yr	Harvested carbon in croplands that are used for food production (excluding pastures)
Material	Food and feed	Crop and Pasture Yield	CABLE	PgC/yr;kgC/m^2/yr	Above ground carbon removed from cropland and pastures as a result of harvest and grazing
Material	Food and feed	Crop Production	GLOBIO-ES	10^{9}KCal	The total crop production derived by applying crop productivity of the IMAGE model on the LUH2 crop area estimates, and is derived from the total human demand (including for livestock); production of various crop categories, including wheat, rice, maize, tubers, pulses etc. using estimates of average caloric content the production was translated into Kcal produced.
Material	Food and feed	Grass Production	GLOBIO-ES	Gcal	Grass and fodder production derived by applying grass productivity from the IMAGE model on the LUH2 grassland area estimates; production derived from the total demand of livestock production; largely from pastures and rangelands.
Material	Food and feed	Production of C3Nfx, C3Ann, C3Per, C4Ann, C4Per	InVEST	kcal	Caloric production on the current landscape for each crop type – crop yields based on Monfreda et al. (2008); kcals calculated based on FAO food-balance sheets (FAO 2017)
Material	Materials, companionship and labor	Wood Harvest	LPJ-GUESS, CABLE	KgC, PgC/yr;kgC/m^2/yr	Wood carbon removed from natural vegetation (driven by wood harvest fraction from LUH2)
Regulating	Pollination and dispersal of seeds and other propagules	Pollination: fraction of cropland potentially pollinated, relative to all available cropland	GLOBIO-ES	Proportion	Pollination by natural pollinators assumed to be more effective in cropland situated near natural land; pollination efficiency related to distance from natural elements, based on literature review. A consequence is that pollination increases with the fraction of nature in a cell. We use the relationship between pollination efficiency and the fraction of natural area within a cell 0.5 by 0.5 degrees (Schulp et al., 2012). If NatPerc > 20 and NatPerc < 60, then pollination efficiency = 0.25 * NatPerc + 85, else pollination efficiency = 100 Sum: Total cropland potentially pollinated
Regulating	Pollination and dispersal of seeds and other propagules	Pollination: proportion of agricultural lands whose pollination needs are met	InVEST	Proportion	The model maps pollination contribution to nutrition based on proportion of crop production that is dependent on pollination, and proportion of that production whose pollination needs are met by natural habitat around farmland.

Types of services	NCP	Metric	Models	Units	Definitions and formula
Regulating	Regulation of climate	Total Carbon	LPJ-GUESS, LPJ, CABLE	PgC,kgC/m^2	Sum of vegetation, litter and soil carbon stocks; total carbon pool in the ecosystem, including carbon in stems, branches, leaves, roots, soil and litter
Regulating	Regulation of climate	Total Carbon	GLOBIO-ES	MgC	Total carbon pool in the ecosystem, including carbon in stems, branches, leaves, roots, soil and litter, derived from the IMAGE model (using LPJmL)
Regulating	Regulation of climate	Vegetation Carbon	LPJ-GUESS, LPJ, CABLE	PgC,kg/m^2, PgC,kgC/m^2	Carbon stocks in living wood, roots and leaves
Regulating	Regulation of freshwater quantity, location and timing	Monthly Runoff	LPJ-GUESS, LPJ, CABLE	Pg/s,kg/m^{2}s, Pg/month,kg/m^2 month, Pg/s;kg/m^2/s	Sum of drainage, surface and base waterflow Maximum monthly runoff - monthly combined surface and subsurface runoff summed
Regulating	Regulation of freshwater quantity, location and timing	Total Runoff	CABLE	km^3/yr;mm/yr	Total surface and subsurface runoff summed over the year
Regulating	Regulation of freshwater quantity, location and timing	Water Scarcity Index	GLOBIO-ES		Ratio demand / availability of renewable water, monthly-weighted (0-1) (Wada and Bierkens, 2014)
Regulating	Regulation of freshwater and coastal water quality	Nitrogen Leaching	LPJ-GUESS	PgN/s,kgN/m^2 s	Nitrogen lost from the grid-cell, after subtracting an estimate for gaseous N losses
Regulating	Regulation of freshwater and coastal water quality	Nitrogen in Water	GLOBIO-ES	mgN/l	Total N concentration in the water, i.e. emissions divided by water discharge. The emissions are the sum of urban and diffuse sources, accumulated over the upstream catchment of a cell. The retention in the water network is accounted for Nitrogen concentration in water [mgN/l] per cell, means and quartiles per region.
Regulating	Regulation of freshwater and coastal water quality	Phosphorous in Water	GLOBIO-ES	mgN/l	Total P concentration in the water, i.e. emissions divided by water discharge. The emissions are the sum of urban and diffuse sources, accumulated over the upstream catchment of a cell. The retention in the water network is accounted for Phosphorus concentration in water [mgP/l] per cell, means and quartiles per region.

Types of services	NCP	Metric	Models	Units	Definitions and formula
Regulating	Regulation of freshwater and coastal water quality	Nitrogen Export	InVEST	Tons N/year	The model maps nutrient sources from watersheds and their transport to the stream. This spatial information can be used to assess the service of nutrient retention by natural vegetation. The retention service is of particular interest for surface water quality issues and can be valued in economic or social terms (e.g. avoided treatment costs, improved water security through access to clean drinking water).
Regulating	Regulation of freshwater and coastal water quality	Nitrogen Export*Capita	InVEST	Tons N*people /year	Nitrogen export times rural population, as an indication of where people are most vulnerable to changes in drinking water quality, because rural communities typically have fewer water treatment options or use well-water that may show similar patterns of nitrate leaching.
Regulating	Formation, protection and decontamination of soils and sediments	Erosion Protection: fraction with low risk relative to the area that needs protection	GLOBIO-ES	index (0-100)	Erosion risk calculation for pasture, rangeland, cropland and urban from the USLE as implemented in the IMAGE model. Based on soil characteristics (e.g. texture, depths and slope), climate characteristics (e.g. precipitation) and land-use sensitivity. The risk is calculated as a relative figure between 0 and 100, from high to low risk. Sum: total area with low risk (ER > 80)
Regulating	Formation, protection and decontamination of soils and sediments	Soil Protection	GLOSP	%	The amount of vegetation cover (in %cover) across all pixels within a specific subset (e.g., global, region ‘x’). For each observed year, these values vary between 0 and 1 and for the change index negative values represent the rate of decrease in relation to a reference year.
Regulating	Regulation of hazards and extreme events	Flood Risk: number of people exposed to river flood risk	GLOBIO-ES	people affected	The number of people exposed to river flood risk calculated based on the frequency of daily river discharge exceeding the river’s capacity, the potentially inundated area and the population density in that area. ‘Normal’ predictable yearly flooding is left out. Sum = number of people affected, per region
Regulating	Regulation of hazards and extreme events	Coastal Vulnerability Index	InVEST	unitless score from 1 (min) to 5 (max)	Geophysical and natural habitat characteristics of coastlines are used to compare relative exposure to erosion and flooding in severe weather across space and different scenarios (Arkema et al., 2013).
Regulating	Regulation of hazards and extreme events	Coastal Vulnerability *Capita	InVEST	unitless score*people	Total exposure risk times population within 2km of shore. When overlaid with data on coastal population density, the model’s outputs can be used to identify where humans face higher risks of damage from storm waves and surge.

Types of services	NCP	Metric	Models	Units	Definitions and formula
Regulating	Regulation of detrimental organisms and biological processes	Pest Control: fraction of cropland potentially protected, relative to all available cropland	GLOBIO-ES	km^2	Cropland area that is potentially covered by sufficient pest predators. Pest control by natural predators is assumed to be more effective in cropland situated near natural land. The pest control efficiency is related to distance from natural elements, relation is based on literature review. A consequence is that pollination increases with the fraction of nature in a cell. We use the relationship between pollination efficiency and the fraction of natural area within a cell 0.5 by 0.5 degrees (Schulp et al., 2012). If NatPerc < 35, then pest control = 0.48 * NatPerc + 12,75, else pest control = 0.67 * NatPerc + 7.25 Sum: Total cropland potentially covered by natural predators

References

Alkemade, R., van Oorschot, M., Miles, L., Nellemann, C., Bakkenes, M. and ten Brink, B.: GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss, Ecosystems, 12(3), 374–390, doi:10.1007/s10021-009-9229-5, 2009.

Alkemade, R., Burkhard, B., Crossman, N. D., Nedkov, S. and Petz, K.: Quantifying ecosystem services and indicators for science, policy and practice, Ecol. Indic., 37, 161–162, doi:10.1016/j.ecolind.2013.11.014, 2014.

Allen, L. H., De Benoist, B., Dary, O., Hurrell, R.: World Health Organization: Guidelines on food fortification with micronutrients, 2006.

Allnutt, T. F., Ferrier, S., Manion, G., Powell, G. V. N., Ricketts, T. H., Fisher, B. L., Harper, G. J., Irwin, M. E., Kremen, C., Labat, J.-N., Lees, D. C., Pearce, T. A. and Rakotondrainibe, F.: A method for quantifying biodiversity loss and its application to a 50-year record of deforestation across Madagascar: Extinction estimates in Madagascar from deforestation, Conserv. Lett., 1(4), 173–181, doi:10.1111/j.1755-263X.2008.00027.x, 2008.

Arkema, K. K., Guannel, G., Verutes, G., Wood, S. A., Guerry, A., Ruckelshaus, M., Kareiva, P., Lacayo, M. and Silver, J. M.: Coastal habitats shield people and property from sea-level rise and storms, Nat. Clim. Change, 3(10), 913–918, doi:10.1038/nclimate1944, 2013.

Bateman, B. L., Murphy, H. T., Reside, A. E., Mokany, K., ~~and~~ VanDerWal, J. and Thuiller, W. (Eds.): Appropriateness of full-, partial- and no-dispersal scenarios in climate change impact modelling, ~~edited by W. Thuiller,~~ Divers. Distrib., 19(10), 1224–1234, doi:10.1111/ddi.12107, 2013.

Benítez-López, A., Alkemade, R., Schipper, A. M., Ingram, D. J., Verweij, P. A., Eikelboom, J. A. J. and Huijbregts, M. A. J.: The impact of hunting on tropical mammal and bird populations, Science, 356(6334), 180–183, doi:10.1126/science.aaj1891, 2017.

Bijl, D. L., Bogaart, P. W., Kram, T., de Vries, B. J. M. and van Vuuren, D. P.: Long-term water demand for electricity, industry and households, Environ. Sci. Policy, 55, 75–86, doi:10.1016/j.envsci.2015.09.005, 2016.

Blois, J. L., Williams, J. W., Fitzpatrick, M. C., Jackson, S. T. and Ferrier, S.: Space can substitute for time in predicting climate-change effects on biodiversity, Proc. Natl. Acad. Sci., 110(23), 9374–9379, doi:10.1073/pnas.1220228110, 2013.

Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K.-H., Haberl, H., Creutzig, F. and Seto, K. C.: Future urban land expansion and implications for global croplands, Proc. Natl. Acad. Sci., 114(34), 8939–8944, doi:10.1073/pnas.1606036114, 2017.

Brinsmead, T.S., Smith, K., Hatfield-Dodds, S., Adams, P., Baynes, T., Ferrier, S., Harwood, T., Hayward, J.A., Lennox, J., Marcos Martinez, R., Nolan, M., Qiu, J.: A novel integrated assessment framework for exploring possible futures for Australia: the GNOME.3 suite for the Australian National Outlook, in MODSIM2017 (eds), Syme, G., Hatton MacDonald, D., Fulton, B. and Piantadosi, J., 22nd International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, pp. 1440-1446, 2017.

British Nutrition Foundation: Nutrition requirements, https://www.nutrition.org.uk/attachments/article/234/Nutrition%20Requirements_Revised%20Oct%202016.pdf, last access: January 2018.

Brown, J. H., Gillooly, J. F., Allen, A. P., Savage, V. M. and West, G. B.: TOWARD A METABOLIC THEORY OF ECOLOGY, Ecology, 85(7), 1771–1789, doi:10.1890/03-9000, 2004.

Bryan, B. A., Nolan, M., Harwood, T. D., Connor, J. D., Navarro-Garcia, J., King, D., Summers, D. M., Newth, D., Cai, Y., Grigg, N., Harman, I., Crossman, N. D., Grundy, M. J., Finnigan, J. J., Ferrier, S., Williams, K. J., Wilson, K. A., Law, E. A. and Hatfield-Dodds, S.: Supply of carbon sequestration and biodiversity services from Australia's agricultural land under global change, Glob. Environ. Change, 28, 166–181, doi:10.1016/j.gloenvcha.2014.06.013, 2014.

Busch, J. and Ferretti-Gallon, K.: What Drives Deforestation and What Stops It? A Meta-Analysis, Rev. Environ. Econ. Policy, 11(1), 3–23, doi:10.1093/reep/rew013, 2017.

Chaplin-Kramer, R., Dombeck, E., Gerber, J., Knuth, K. A., Mueller, N. D., Mueller, M., Ziv, G. and Klein, A.-M.: Global malnutrition overlaps with pollinator-dependent micronutrient production, Proc. R. Soc. B Biol. Sci., 281(1794), 20141799–20141799, doi:10.1098/rspb.2014.1799, 2014.

Chaudhary, A., Verones, F., de Baan, L. and Hellweg, S.: Quantifying Land Use Impacts on Biodiversity: Combining Species–Area Models and Vulnerability Indicators, Environ. Sci. Technol., 49(16), 9987–9995, doi:10.1021/acs.est.5b02507, 2015.

Denno, R.F., Lewis, D.: Predator-prey interactions: in, The Princeton guide to ecology, Levin, SA, Carpenter, S.R., Godfray, H.C.J., Kinzig, A.P., Loreau, M., et al., Princeton, NJ: Princeton University Press, pp. 202–212, 2012.

Deutsch, C. A., Tewksbury, J. J., Huey, R. B., Sheldon, K. S., Ghalambor, C. K., Haak, D. C. and Martin, P. R.: Impacts of climate warming on terrestrial ectotherms across latitude, Proc. Natl. Acad. Sci., 105(18), 6668–6672, doi:10.1073/pnas.0709472105, 2008.

Döll, P. and Lehner, B.: Validation of a new global 30-min drainage direction map, J. Hydrol., 258(1–4), 214–231, doi:10.1016/S0022-1694(01)00565-0, 2002.

Fekete, B. M., Wisser, D., Kroeze, C., Mayorga, E., Bouwman, L., Wollheim, W. M. and Vörösmarty, C.: Millennium Ecosystem Assessment scenario drivers (1970-2050): Climate and hydrological alterations: GLOBAL NEWS HYDROLOGY, Glob. Biogeochem. Cycles, 24(4), n/a-n/a, doi:10.1029/2009GB003593, 2010.

Ferrier, S., Harwood, T.D., Williams, K.J.: Assessing refugial potential using compositional-turnover modelling, Pages 51-76, in: Climate change refugia for terrestrial biodiversity: defining areas that promote species persistence and ecosystem resilience in the face of global climate change, National Climate Change Adaptation Research Facility, Gold Coast, 2013.

Ferrier, S., Powell, G. V. N., Richardson, K. S., Manion, G., Overton, J. M., Allnutt, T. F., Cameron, S. E., Mantle, K., Burgess, N. D., Faith, D. P., Lamoreux, J. F., Kier, G., Hijmans, R. J., Funk, V. A., Cassis, G. A., Fisher, B. L., Flemons, P., Lees, D., Lovett, J. C. and Van Rompaey, R. S. A. R.: Mapping More of Terrestrial Biodiversity for Global Conservation Assessment, BioScience, 54(12), 1101, doi:10.1641/0006-3568(2004)054[1101:MMOTBF]2.0.CO;2, 2004.

Ferrier, S., Manion, G., Elith, J. and Richardson, K.: Using generalized dissimilarity modelling to analyse and predict patterns of beta diversity in regional biodiversity assessment, Divers. Distrib., 13(3), 252–264, doi:10.1111/j.1472-4642.2007.00341.x, 2007.

Filipponi F., Valentini E., Xuan A., Guerra C.A., Wolf F., Andrzejak M., Taramelli A.: Global MODIS Fraction of green vegetation Cover for monitoring vegetation abrupt and gradual changes, Remote Sensing. [accepted]

Fitzpatrick, M. C., Sanders, N. J., Ferrier, S., Longino, J. T., Weiser, M. D. and Dunn, R.: Forecasting the future of biodiversity: a test of single- and multi-species models for ants in North America, Ecography, 34(5), 836–847, doi:10.1111/j.1600-0587.2011.06653.x, 2011.

Frischknecht R., Jolliet O. (eds): Global Guidance for Life Cycle Impact Assessment Indicators, vol 1, United Nations Environment Programme, 2016.

Food and Agriculture Organization of the United Nations: Food balance sheets, Rome, http://www.fao.org/economic/ess/fbs/en, 2017.

Food and Agriculture Organization of the United Nations: Global Forest Resources Assessment 2000, Rome, FAO Forestry Department, 2000.

Gray, C. L., Hill, S. L. L., Newbold, T., Hudson, L. N., Börger, L., Contu, S., Hoskins, A. J., Ferrier, S., Purvis, A. and Scharlemann, J. P. W.: Local biodiversity is higher inside than outside terrestrial protected areas worldwide, Nat. Commun., 7, 12306, doi:10.1038/ncomms12306, 2016.

Guannel, G., Arkema, K., Ruggiero, P., ~~and~~ Verutes, G. and Bianchi, C. N. (Eds.): The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience, ~~edited by C. N. Bianchi,~~ PLOS ONE, 11(7), e0158094, doi:10.1371/journal.pone.0158094, 2016.

Guerra, C. A., Maes, J., Geijzendorffer, I. and Metzger, M. J.: An assessment of soil erosion prevention by vegetation in Mediterranean Europe: Current trends of ecosystem service provision, Ecol. Indic., 60, 213–222, doi:10.1016/j.ecolind.2015.06.043, 2016.

Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W. and Fischer-Kowalski, M.: Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems, Proc. Natl. Acad. Sci., 104(31), 12942–12947, doi:10.1073/pnas.0704243104, 2007.

Haines-Young, R., Potschin, M.: The links between biodiversity, ecosystem services and human well-being, Ch 7: in, Ecosystem Ecology: A New Synthesis (eds.), Raffaelli, D., Frid, C., BES Ecological Reviews Series, CUP, Cambridge, in press, 2010.

Harfoot, M. B. J., Newbold, T., Tittensor, D. P., Emmott, S., Hutton, J., Lyutsarev, V., Smith, M. J., Scharlemann, J. P. W., ~~and~~ Purves, D. W., Loreau, M. (Eds.): Emergent Global Patterns of Ecosystem Structure and Function from a Mechanistic General Ecosystem Model, ~~edited by M. Loreau,~~ PLoS Biol., 12(4), e1001841, doi:10.1371/journal.pbio.1001841, 2014.

Hasegawa, T., Fujimori, S., Ito, A., Takahashi, K. and Masui, T.: Global land-use allocation model linked to an integrated assessment model, Sci. Total Environ., 580, 787–796, doi:10.1016/j.scitotenv.2016.12.025, 2017.

Hatfield-Dodds, S., Schandl, H., Adams, P. D., Baynes, T. M., Brinsmead, T. S., Bryan, B. A., Chiew, F. H. S., Graham, P. W., Grundy, M., Harwood, T., McCallum, R., McCrea, R., McKellar, L. E., Newth, D., Nolan, M., Prosser, I. and Wonhas, A.: Australia is 'free to choose' economic growth and falling environmental pressures, Nature, 527(7576), 49–53, doi:10.1038/nature16065, 2015.

Haverd, V., Smith, B., Nieradzik, L., Briggs, P. R., Woodgate, W., Trudinger, C. M. and Canadell, J. G.: A new version of the CABLE land surface model (Subversion revision r4546), incorporating land use and land cover change, woody vegetation demography and a novel optimisation-based approach to plant coordination of electron transport and carboxylation capacity-limited photosynthesis, Geosci. Model Dev. Discuss., 1–33, doi:10.5194/gmd-2017-265, 2017.

Hengl, T., de Jesus, J. M., MacMillan, R. A., Batjes, N. H., Heuvelink, G. B. M., Ribeiro, E., Samuel-Rosa, A., Kempen, B., Leenaars, J. G. B., Walsh, M. G., ~~and~~ Gonzalez, M. R. and Bond-Lamberty, B. (Eds.): SoilGrids1km — Global Soil Information Based on Automated Mapping, ~~edited by B. Bond-Lamberty,~~ PLoS ONE, 9(8), e105992, doi:10.1371/journal.pone.0105992, 2014.

Hoskins, A. J., Bush, A., Gilmore, J., Harwood, T., Hudson, L. N., Ware, C., Williams, K. J. and Ferrier, S.: Downscaling land-use data to provide global 30″ estimates of five land-use classes, Ecol. Evol., 6(9), 3040–3055, doi:10.1002/ece3.2104, 2016.

Hoskins, A.J., Harwood, T.D., Ware, C., Williams, K.J., Perry, J.J., Ota, N., Croft, J.R., Yeates, D.K., Jetz, W., Golebiewski, M., Purvis, A., Ferrier, S., 2018. Supporting global biodiversity assessment through high-resolution macroecological modelling: Methodological underpinnings of the BILBI framework. BioRxiv http://biorxiv.org/cgi/content/short/309377v1. [in prep.]

~~Hoskins, A. J., Harwood, T.D., Ware, C., Williams, K.J., Perry, J.J., Ota, N., Croft, J.R., Yeates, D.K., Jetz, W., Golebiewski, M., Ferrier, S.: BILBI: supporting global biodiversity assessment through high-resolution macroecological modelling. [in prep.]~~

Hudson, L. N., Newbold, T., Contu, S., Hill, S. L. L., Lysenko, I., De Palma, A., Phillips, H. R. P., Senior, R. A., Bennett, D. J., Booth, H., Choimes, A., Correia, D. L. P., Day, J., Echeverría-Londoño, S., Garon, M., Harrison, M. L. K., Ingram, D. J., Jung, M., Kemp, V., Kirkpatrick, L., Martin, C. D., Pan, Y., White, H. J., Aben, J., Abrahamczyk, S., Adum, G. B., Aguilar-Barquero, V., Aizen, M. A., Ancrenaz, M., Arbeláez-Cortés, E., Armbrecht, I., Azhar, B., Azpiroz, A. B., Baeten, L., Báldi, A., Banks, J. E., Barlow, J., Batáry, P., Bates, A. J., Bayne, E. M., Beja, P., Berg, Å., Berry, N. J., Bicknell, J. E., Bihn, J. H., Böhning-Gaese, K., Boekhout, T., Boutin, C., Bouyer, J., Brearley, F. Q., Brito, I., Brunet, J., Buczkowski, G., Buscardo, E., Cabra-García, J., Calviño-Cancela, M., Cameron, S. A., Cancello, E. M., Carrijo, T. F., Carvalho, A. L., Castro, H., Castro-Luna, A. A., Cerda, R., Cerezo, A., Chauvat, M., Clarke, F. M., Cleary, D. F. R., Connop, S. P., D'Aniello, B., da Silva, P. G., Darvill, B., Dauber, J., Dejean, A., Diekötter, T., Dominguez-Haydar, Y., Dormann, C. F., Dumont, B., Dures, S. G., Dynesius, M., Edenius, L., Elek, Z., Entling, M. H., Farwig, N., Fayle, T. M., Felicioli, A., Felton, A. M., Ficetola, G. F., Filgueiras, B. K. C., Fonte, S. J., Fraser, L. H., Fukuda, D., Furlani, D., Ganzhorn, J. U., Garden, J. G., Gheler-Costa, C., Giordani, P., Giordano, S., Gottschalk, M. S., Goulson, D., et al.: The PREDICTS database: a global database of how local terrestrial biodiversity responds to human impacts, Ecol. Evol., 4(24), 4701–4735, doi:10.1002/ece3.1303, 2014.

Hudson, L. N., Newbold, T., Contu, S., Hill, S. L. L., Lysenko, I., et al.: Dataset: The 2016 release of the PREDICTS database, http://dx.doi.org/10.5519/0066354, 2016.

Hudson, L. N., Newbold, T., Contu, S., Hill, S. L. L., Lysenko, I., De Palma, A., Phillips, H. R. P., Alhusseini, T. I., Bedford, F. E., Bennett, D. J., Booth, H., Burton, V. J., Chng, C. W. T., Choimes, A., Correia, D. L. P., Day, J., Echeverría-Londoño, S., Emerson, S. R., Gao, D., Garon, M., Harrison, M. L. K., Ingram, D. J., Jung, M., Kemp, V., Kirkpatrick, L., Martin, C. D., Pan, Y., Pask-Hale, G. D., Pynegar, E. L., Robinson, A. N., Sanchez-Ortiz, K., Senior, R. A., Simmons, B. I., White, H. J., Zhang, H., Aben, J., Abrahamczyk, S., Adum, G. B., Aguilar-Barquero, V., Aizen, M. A., Albertos, B., Alcala, E. L., del Mar Alguacil, M., Alignier, A., Ancrenaz, M., Andersen, A. N., Arbeláez-Cortés, E., Armbrecht, I., Arroyo-Rodríguez, V., Aumann, T., Axmacher, J. C., Azhar, B., Azpiroz, A. B., Baeten, L., Bakayoko, A., Báldi, A., Banks, J. E., Baral, S. K., Barlow, J., Barratt, B. I. P., Barrico, L., Bartolommei, P., Barton, D. M., Basset, Y., Batáry, P., Bates, A. J., Baur, B., Bayne, E. M., Beja, P., Benedick, S., Berg, Å., Bernard, H., Berry, N. J., Bhatt, D., Bicknell, J. E., Bihn, J. H., Blake, R. J., Bobo, K. S., Bóçon, R., Boekhout, T., Böhning-Gaese, K., Bonham, K. J., Borges, P. A. V., Borges, S. H., Boutin, C., Bouyer, J., Bragagnolo, C., Brandt, J. S., Brearley, F. Q., Brito, I., Bros, V., Brunet, J., Buczkowski, G., Buddle, C. M., Bugter, R., Buscardo, E., Buse, J., Cabra-García, J., Cáceres, N. C., et al.: The database of the PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) project, Ecol. Evol., 7(1), 145–188, doi:10.1002/ece3.2579, 2017.

Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D. P. and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, Clim. Change, 109(1–2), 117–161, doi:10.1007/s10584-011-0153-2, 2011.

Hurtt, G., Chini, L., Sahajpal, R., Frolking, S., Calvin, K., Fujimori, S., Klein Goldewijk, K., Hasegawa, T., Havlik, P., Lawrence, D., Lawrence, P., Popp, A., Stehfest, E., van Vuuren, D., and Zhang, X.: Harmonization of global land-use change and management for the period 850–2100. [submitted]

Janse, J. H., Bakkenes, M. & Meijer, J.: Globio-Aquatic, Technical model description v. 1.3: PBL publication 2829, The Hague, PBL Netherlands Environmental Assessment Agency, 2016.

Janse, J. H., Kuiper, J. J., Weijters, M. J., Westerbeek, E. P., Jeuken, M. H. J. L., Bakkenes, M., Alkemade, R., Mooij, W. M. and Verhoeven, J. T. A.: GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems, Environ. Sci. Policy, 48, 99–114, doi:10.1016/j.envsci.2014.12.007, 2015.

Jetz, W., Wilcove, D. S., ~~and~~ Dobson, A. P. and Mace, G. M. (Eds.): Projected Impacts of Climate and Land-Use Change on the Global Diversity of Birds, ~~edited by G. M. Mace,~~ PLoS Biol., 5(6), e157, doi:10.1371/journal.pbio.0050157, 2007.

Johnson, J. A., Runge, C. F., Senauer, B., Foley, J. and Polasky, S.: Global agriculture and carbon trade-offs, Proc. Natl. Acad. Sci., 111(34), 12342–12347, doi:10.1073/pnas.1412835111, 2014.

Johnson, J. A., Runge, C. F., Senauer, B. and Polasky, S.: Global Food Demand and Carbon-Preserving Cropland Expansion under Varying Levels of Intensification, Land Econ., 92(4), 579–592, doi:10.3368/le.92.4.579, 2016.

Jones, B. and O'Neill, B. C.: Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways, Environ. Res. Lett., 11(8), 084003, doi:10.1088/1748-9326/11/8/084003, 2016.

Klein, A.-M., Vaissiere, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C. and Tscharntke, T.: Importance of pollinators in changing landscapes for world crops, Proc. R. Soc. B Biol. Sci., 274(1608), 303–313, doi:10.1098/rspb.2006.3721, 2007.

Klein Goldewijk, K., Beusen, A., Doelman, J. and Stehfest, E.: New anthropogenic land use estimates for the Holocene; HYDE 3.2, Earth Syst. Sci. Data Discuss., 1–40, doi:10.5194/essd-2016-58, 2016.

Kourzeneva, E.: External data for lake parameterization in Numerical Weather Prediction and climate modelling, Boreal Environment Research, 15: 165-177, 2010.

Lamarque, J.-F., Kyle, G. P., Meinshausen, M., Riahi, K., Smith, S. J., van Vuuren, D. P., Conley, A. J. and Vitt, F.: Global and regional evolution of short-lived radiatively-active gases and aerosols in the Representative Concentration Pathways, Clim. Change, 109(1–2), 191–212, doi:10.1007/s10584-011-0155-0, 2011.

Lehner, B. and Döll, P.: Development and validation of a global database of lakes, reservoirs and wetlands, J. Hydrol., 296(1–4), 1–22, doi:10.1016/j.jhydrol.2004.03.028, 2004.

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J. C., Rödel, R., Sindorf, N. and Wisser, D.: High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management, Front. Ecol. Environ., 9(9), 494–502, doi:10.1890/100125, 2011.

Lindeskog, M., Arneth, A., Bondeau, A., Waha, K., Seaquist, J., Olin, S. and Smith, B.: Implications of accounting for land use in simulations of ecosystem carbon cycling in Africa, Earth Syst. Dyn., 4(2), 385–407, doi:10.5194/esd-4-385-2013, 2013.

Martins, I. S. and Pereira, H. M.: Improving extinction projections across scales and habitats using the countryside species-area relationship, Sci. Rep., 7(1), doi:10.1038/s41598-017-13059-y, 2017.

Meijer, J. R., Huijbregts, M. A. J., Schotten, K. C. G. J. and Schipper, A. M.: Global patterns of current and future road infrastructure, Environmental Research Letters, 13(6), 064006, doi:10.1088/1748-9326/aabd42, 2018.

~~Meijer, J.R., Huijbregts, M.A.J., Schotten, C.G.J., Schipper, A.M.: Global patterns of current and future road infrastructure, Environmental Research Letters. [accepted]~~

Merow, C., Smith, M. J. and Silander, J. A.: A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter, Ecography, 36(10), 1058–1069, doi:10.1111/j.1600-0587.2013.07872.x, 2013.

Midgley, G. F., Hughes, G. O., Thuiller, W. and Rebelo, A. G.: Migration rate limitations on climate change-induced range shifts in Cape Proteaceae, Divers. Htmlent Glyphamp Asciiamp Distrib., 12(5), 555–562, doi:10.1111/j.1366-9516.2006.00273.x, 2006.

Mokany, K., Harwood, T. D., Williams, K. J. and Ferrier, S.: Dynamic macroecology and the future for biodiversity, Glob. Change Biol., 18(10), 3149–3159, doi:10.1111/j.1365-2486.2012.02760.x, 2012.

Monfreda, C., Ramankutty, N. and Foley, J. A.: Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000: GLOBAL CROP AREAS AND YIELDS IN 2000, Glob. Biogeochem. Cycles, 22(1), n/a-n/a, doi:10.1029/2007GB002947, 2008.

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N. and Foley, J. A.: Closing yield gaps through nutrient and water management, Nature, 490(7419), 254–257, doi:10.1038/nature11420, 2012.

Newbold, T., Hudson, L. N., Hill, S. L. L., Contu, S., Lysenko, I., Senior, R. A., Börger, L., Bennett, D. J., Choimes, A., Collen, B., Day, J., De Palma, A., Díaz, S., Echeverria-Londoño, S., Edgar, M. J., Feldman, A., Garon, M., Harrison, M. L. K., Alhusseini, T., Ingram, D. J., Itescu, Y., Kattge, J., Kemp, V., Kirkpatrick, L., Kleyer, M., Correia, D. L. P., Martin, C. D., Meiri, S., Novosolov, M., Pan, Y., Phillips, H. R. P., Purves, D. W., Robinson, A., Simpson, J., Tuck, S. L., Weiher, E., White, H. J., Ewers, R. M., Mace, G. M., Scharlemann, J. P. W. and Purvis, A.: Global effects of land use on local terrestrial biodiversity, Nature, 520(7545), 45–50, doi:10.1038/nature14324, 2015.

Newbold, T., Hudson, L. N., Hill, S. L. L., Contu, S., Gray, C. L., Scharlemann, J. P. W., Börger, L., Phillips, H. R. P., Sheil, D., Lysenko, I. and Purvis, A.: Global patterns of terrestrial assemblage turnover within and among land uses, Ecography, 39(12), 1151–1163, doi:10.1111/ecog.01932, 2016a.

Newbold, T., Hudson, L. N., Arnell, A. P., Contu, S., De Palma, A., Ferrier, S., Hill, S. L. L., Hoskins, A. J., Lysenko, I., Phillips, H. R. P., Burton, V. J., Chng, C. W. T., Emerson, S., Gao, D., Pask-Hale, G., Hutton, J., Jung, M., Sanchez-Ortiz, K., Simmons, B. I., Whitmee, S., Zhang, H., Scharlemann, J. P. W. and Purvis, A.: Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment, Science, 353(6296), 288–291, doi:10.1126/science.aaf2201, 2016b.

Ohashi, H., Hasegawa, T., Hirata, A., Fujimori, S., Takahashi, K., Tsuyama, I., Nakao, K., Kominami, Y., Tanaka, N., Hijioka, Y., Matsui, T.: Biodiversity can benefit from long-term climate mitigation regardless of land-based measures. [submitted]

Ohashi, H., Hasegawa, T., Hirata, A., Fujimori, S., Takahashi, K., Hijioka, Y., Nakao, K., Tsuyama, I., Kominami, Y., Tanaka, N., Matsui, T.: Long-term climate change impact is more harmful than 2°C climate mitigation land use change. [in prep.]

Olin, S., Schurgers, G., Lindeskog, M., Wårlind, D., Smith, B., Bodin, P., Holmér, J. and Arneth, A.: Modelling the response of yields and tissue C : N to changes in atmospheric CO_2 and N management in the main wheat regions of western Europe, Biogeosciences, 12(8), 2489–2515, doi:10.5194/bg-12-2489-2015, 2015.

Pereira, H. M. and Daily, G. C.: Modelling biodiversity dynamics in countryside landscapes, Ecology, 87(8), 1877–1885, doi:10.1890/0012-9658(2006)87[1877:MBDICL]2.0.CO;2, 2006.

Petz, K., Alkemade, R., Bakkenes, M., Schulp, C. J. E., van der Velde, M. and Leemans, R.: Mapping and modelling trade-offs and synergies between grazing intensity and ecosystem services in rangelands using global-scale datasets and models, Glob. Environ. Change, 29, 223–234, doi:10.1016/j.gloenvcha.2014.08.007, 2014.

Phillips, S. J., Anderson, R. P. and Schapire, R. E.: Maximum entropy modeling of species geographic distributions, Ecol. Model., 190(3–4), 231–259, doi:10.1016/j.ecolmodel.2005.03.026, 2006.

Phillips, S. J., Dudík, M., Elith, J., Graham, C. H., Lehmann, A., Leathwick, J. and Ferrier, S.: Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data, Ecol. Appl., 19(1), 181–197, doi:10.1890/07-2153.1, 2009.

Pletcher: Model fitting and hypothesis testing for age-specific mortality data, J. Evol. Biol., 12(3), 430–439, doi:10.1046/j.1420-9101.1999.00058.x, 1999.

Poulter, B., Frank, D. C., Hodson, E. L. and Zimmermann, N. E.: Impacts of land cover and climate data selection on understanding terrestrial carbon dynamics and the CO_2 airborne fraction, Biogeosciences, 8(8), 2027–2036, doi:10.5194/bg-8-2027-2011, 2011.

Prober, S. M., Hilbert, D. W., Ferrier, S., Dunlop, M. and Gobbett, D.: Combining community-level spatial modelling and expert knowledge to inform climate adaptation in temperate grassy eucalypt woodlands and related grasslands, Biodivers. Conserv., 21(7), 1627–1650, doi:10.1007/s10531-012-0268-4, 2012.

Prober, S.M., Williams, K.J., Harwood, T.D., Doerr, V.A.J., Jeanneret, T., Manion, G., Ferrier, S.: *Helping biodiversity adapt: Supporting climate-adaptation planning using a community-level modelling approach,* CSIRO Land and Water Flagship, 2015.

Redhead, J. W., May, L., Oliver, T. H., Hamel, P., Sharp, R. and Bullock, J. M.: National scale evaluation of the InVEST nutrient retention model in the United Kingdom, Sci. Total Environ., 610–611, 666–677, doi:10.1016/j.scitotenv.2017.08.092, 2018.

Rondinini, C., Di Marco, M., Chiozza, F., Santulli, G., Baisero, D., Visconti, P., Hoffmann, M., Schipper, J., Stuart, S. N., Tognelli, M. F., Amori, G., Falcucci, A., Maiorano, L. and Boitani, L.: Global habitat suitability models of terrestrial mammals, Philos. Trans. R. Soc. B Biol. Sci., 366(1578), 2633–2641, doi:10.1098/rstb.2011.0113, 2011.

Schipper, A.M., Bakkenes, M., Meijer, J.R., Alkemade, R., Huijbregts, M.J.: The GLOBIO model. A technical description of version 3.5. PBL publication 2369, The Hague, PBL Netherlands Environmental Assessment Agency, 2016.

Scholes, R. J. and Biggs, R.: A biodiversity intactness index, Nature, 434(7029), 45, 2005.

Schulp, C. J. E., Alkemade, R., Klein Goldewijk, K. and Petz, K.: Mapping ecosystem functions and services in Eastern Europe using global-scale data sets, Int. J. Biodivers. Sci. Ecosyst. Serv. Manag., 8(1–2), 156–168, doi:10.1080/21513732.2011.645880, 2012.

Sharp, R., Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Chaplin-Kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C.K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., Glowinski, K., Chaumont, N., Perelman, A., Lacayo, M. Mandle, L., Hamel, P., Vogl, A.L., Rogers, L., Bierbower, W., Denu, D., and Douglass, J.: InVEST +VERSION+ User's Guide, The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund, 2018.

Smith, B., Wårlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J. and Zaehle, S.: Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model, Biogeosciences, 11(7), 2027–2054, doi:10.5194/bg-11-2027-2014, 2014.

Smith, M. J., Purves, D. W., Vanderwel, M. C., Lyutsarev, V. and Emmott, S.: The climate dependence of the terrestrial carbon cycle, including parameter and structural uncertainties, Biogeosciences, 10(1), 583–606, doi:10.5194/bg-10-583-2013, 2013.

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, M., Prins, A.: Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications, The Hague: PBL Netherlands Environmental Assessment Agency, 2014.

Temme, A. J. A. M. and Verburg, P. H.: Mapping and modelling of changes in agricultural intensity in Europe, Agric. Ecosyst. Environ., 140(1–2), 46–56, doi:10.1016/j.agee.2010.11.010, 2011.

Thuiller, W.: Patterns and uncertainties of species' range shifts under climate change, Glob. Change Biol., 10(12), 2020–2027, doi:10.1111/j.1365-2486.2004.00859.x, 2004.

Thuiller, W., Lafourcade, B., Engler, R. and Araújo, M. B.: BIOMOD - a platform for ensemble forecasting of species distributions, Ecography, 32(3), 369–373, doi:10.1111/j.1600-0587.2008.05742.x, 2009.

Thuiller, W., Lavergne, S., Roquet, C., Boulangeat, I., Lafourcade, B. and Araujo, M. B.: Consequences of climate change on the tree of life in Europe, Nature, 470(7335), 531–534, doi:10.1038/nature09705, 2011.

Tolman, H.L.: User Manual and System Documentation of WAVEWATCH III version 3.14 Technical Note, US Department of Commerce, National Oceanographic and Atmospheric Administration, National Weather Service, National Centers for Environmental Predictions, 2009.

Visconti, P., Bakkenes, M., Baisero, D., Brooks, T., Butchart, S. H. M., Joppa, L., Alkemade, R., Di Marco, M., Santini, L., Hoffmann, M., Maiorano, L., Pressey, R. L., Arponen, A., Boitani, L., Reside, A. E., van Vuuren, D. P. and Rondinini, C.: Projecting Global Biodiversity Indicators under Future Development Scenarios: Projecting biodiversity indicators, Conserv. Lett., 9(1), 5–13, doi:10.1111/conl.12159, 2016.

Wang, Y. P., Law, R. M. and Pak, B.: A global model of carbon, nitrogen and phosphorus cycles for the terrestrial biosphere, Biogeosciences, 7(7), 2261–2282, doi:10.5194/bg-7-2261-2010, 2010.

Williams, K.J., Prober, S.M., Harwood, T.D., Doerr, V.A.J., Jeanneret, T., Manion, G., Ferrier, S.: *Implications of climate change for biodiversity: A community-level modelling approach.* CSIRO Land and Water Flagship, http://adaptnrm.csiro.au/wp-content/uploads/2014/12/biodiversity-implications-tech-guide.pdf, 2015.

Williams, R. J., Anandanadesan, A., ~~and~~ Purves, D. and Bersier, L.-F. (Eds.): The Probabilistic Niche Model Reveals the Niche Structure and Role of Body Size in a Complex Food Web, ~~edited by L. F. Bersier,~~ PLoS ONE, 5(8), e12092, doi:10.1371/journal.pone.0012092, 2010.

Zabel, F., Putzenlechner, B., ~~and~~ Mauser, W. and Kropp, J. P. (Eds.): Global Agricultural Land Resources – A High Resolution Suitability Evaluation and Its Perspectives until 2100 under Climate Change Conditions, ~~edited by J. P. Kropp,~~ PLoS ONE, 9(9), e107522, doi:10.1371/journal.pone.0107522, 2014.