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## Challenges in producing policy-relevant global scenarios of biodiversity and ecosystem services



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### ABSTRACT

Scenario-based modelling is a powerful tool to describe relationships between plausible trajectories of drivers, possible policy interventions, and impacts on biodiversity and ecosystem services. Model inter-comparisons are key in quantifying uncertainties and identifying avenues for model improvement but have been missing among the global biodiversity and ecosystem services modelling communities. The biodiversity and ecosystem services scenario-based inter-model comparison (BES-SIM) aims to fill this gap. We used global land-use and climate projections to simulate possible future impacts on terrestrial biodiversity and ecosystem services using a variety of models and a range of harmonized metrics.

The goal of this paper is to reflect on the steps taken in BES-SIM, identify remaining methodological challenges, and suggest pathways for improvement. We identified five major groups of challenges; the need to: 1) better account for the role of nature in future human development storylines; 2) improve the representation of drivers in the scenarios by increasing the resolution (temporal, spatial and thematic) of land-use as key driver of biodiversity change and including additional relevant drivers; 3) explicitly integrate species- and trait-level biodiversity in ecosystem services models; 4) expand the coverage of the multiple dimensions of biodiversity and ecosystem services; and finally, 5) incorporate

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time-series or one-off historical data in the calibration and validation of biodiversity and ecosystem services models.

Addressing these challenges would allow the development of more integrated global projections of biodiversity and ecosystem services, thereby improving their policy relevance in supporting the interlinked international conservation and sustainable development agendas.

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## 1. Introduction

Scenario-based modelling of biodiversity and ecosystem services is a powerful tool to envision how nature might respond to different pathways of future human development and policy choices (IPBES, 2016; Nicholson et al., 2019). The resulting projections are often major components of global biodiversity assessments, such as those carried out by the Convention on Biological Diversity (CBD) and by the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES) (CBD, 2014, 2010; IPBES, 2018). However, their role in informing global policy is still limited (IPBES, 2016), as opposed to the picture in climate research, where scenarios developed and assessed under the auspices of the Intergovernmental Panel on Climate Change (IPCC) have been critical in raising awareness of climate change and associated policy choices, eventually leading to the landmark Paris Agreement (Pachauri and Reisinger, 2007; UN, 2015). The announcement of the UN Sustainable Development Goals (SDGs) highlighted the importance of assessing the role of natural resources in determining human well-being, and hence also the need for integrated scenarios of biodiversity and ecosystem services that could support the interlinked agendas of global conservation and sustainable development.

Model inter-comparison projects, in which multiple models are used to project the consequences of a common set of scenarios, offer a widely accepted means of assessing and highlighting model uncertainties when projecting changes in a given variable of interest (Knutti and Sedláček, 2013). Such ensemble projections, i.e. all individual projections integrated and analyzed together, have been applied in many fields, from environmental change modelling (Forzieri et al., 2013) to species distribution modelling (Elith and Leathwick, 2009; Jones and Cheung, 2014) to climate impacts on forest and marine ecosystems (Bryndum-Buchholz et al., 2019; Bugmann et al., 2019). Yet, to our knowledge, a model inter-comparison with common input scenarios has never been used to compare model outputs from structurally different terrestrial biodiversity and ecosystem services models at global scales.

Previous global-level scenarios for biodiversity and ecosystem services have mostly relied on a single model for biodiversity projections (Carpenter et al., 2005; Ten Brink et al., 2010). In the few cases where the results of multiple models have been compared in biodiversity scenarios assessments, these comparisons have been greatly hindered by the lack of harmonized inputs and easily comparable outputs (IPBES, 2016; Leadley, 2010; Leadley et al., 2014; Pereira et al., 2010), making interpretation and quantification of uncertainties very challenging. In order to fill this gap, the IPBES Expert Group on Scenarios and Models has led a biodiversity and ecosystem services scenario-based model inter-comparison (BES-SIM). In addition to helping to understand and quantify uncertainty in the projections, BES-SIM also contributed to the IPBES Global Assessment (IPBES, 2019) and informed discussions around the post-2020 strategic plan of the CBD.

The BES-SIM exercise (see full protocol in Kim et al., 2018) brought together several modeling teams to produce the first global ensemble of projections up to 2050, starting from 1900, of co-occurring changes in terrestrial biodiversity and ecosystem services using harmonized input datasets for future land-use and climate, and producing harmonized model outputs. To strengthen ties between the biodiversity and climate research and assessment communities, BES-SIM inputs were based on the Shared Socio-economic Pathways (SSPs) and the Representative Concentration Pathways (RCPs, Van Vuuren et al., 2014). The SSPs are global trajectories of socio-economic development recently produced for the climate research community (O'Neill et al., 2014), which range from a future more oriented towards sustainability (SSP1) to a future with strong global dependency on fossil fuels (SSP5) (Riahi et al., 2017).

The storylines of the SSPs were used by a range of integrated assessment model (IAMs) to produce spatially-explicit trajectories of drivers of ecosystem change, such as land-use (Popp et al., 2017), which has been harmonized for consistency between past and future (Hurt et al., 2011; Hurt et al., 2016, 2018), and matched with expected trajectories of climate change (the RCPs, Van Vuuren et al., 2014). These represent distinct trajectories of radiative forcing (Van Vuuren et al., 2011), which have been converted into climate (e.g. temperature and precipitation) projections. In BES-SIM, we used a combination of three SSPs x three RCPs, to explore a range of expected future land-use change and climate change, both independently and in combination. The models involved used the same spatially-explicit time-series of land-use and climate data (to the extent possible, see Kim et al., 2018 for details), thus controlling for or reducing among-model discrepancies resulting from differences in input data.

One of the key outcomes of BES-SIM is a much better understanding of the barriers to overcome, and the challenges remaining, to produce policy-relevant global scenarios and models that can better inform the sustainable development agenda and help raising general public awareness for how natural resources ultimately affect human well-being. The objective of this paper is twofold: 1) to highlight the methodological challenges faced in BES-SIM and suggest potential

solutions, based on recent developments; and to thereby 2) suggest potential ways forward for developing the next generation of scenarios that can inform not only global environmental policy (via CBD and IPBES), but also decision-making outside the biodiversity conservation community (e.g. those concerned with human well-being). The emergence of the SDGs and their explicit linkages between nature and human well-being demand improved scenarios that explicitly integrate these aspects. Here, we focus our discussion on the next steps towards producing such scenarios within the biodiversity and ecosystem services modeling communities.

### 1.1. Major outstanding challenges highlighted by BES-SIM

The need for global projections of biodiversity and ecosystem services using harmonized input data was confirmed as BES-SIM results contributed directly to the IPBES Global Assessment (Chapters 2 and 4) and the Summary for Policy Makers (Díaz et al., 2019). Despite major advances, BES-SIM also highlighted various obstacles to further advancing this work, which can be grouped into needs to: 1) better account for the role of nature in future human development trajectories (i.e., scenario storylines such as the SSPs); 2) improve the representation of drivers in the scenarios by increasing the resolution (temporal, spatial and thematic) of land-use (as key driver of biodiversity change) and including additional relevant drivers (e.g., hunting, pollution and invasive species); 3) integrate trait- and species-level biodiversity in ecosystem services models, in accordance with emerging evidence of the importance of biodiversity for service provision (Cardinale et al., 2012; Isbell et al., 2011; Tilman et al., 2014); 4) expand the coverage of the multiple dimensions of biodiversity (e.g., genetic diversity) and ecosystem services (e.g., cultural services); and 5) incorporate time-series observations in the calibration and validation of biodiversity and ecosystem services models.

In the remaining sections of this paper we discuss the progress made by BES-SIM in each of these categories, and pathways for improvement in addressing each of these outstanding challenges, all summarized in Fig. 1. Whilst the first group of challenges relates mostly to scenario storylines, the other four mainly require modeling advances that are needed to better translate these storylines into quantifiable projections of change (IPBES, 2016). It is important to note that this is not an exhaustive list, but rather what we regard – given the emerging scientific literature – as the next logical steps in producing integrated scenarios and projections of biodiversity and ecosystem services. We recognize fully that other challenging aspects also need to be addressed by the wider modeling communities (e.g. different data types, methodological approaches, indicators), if we want scenarios to be used by decision-makers to inform sustainable development agendas.

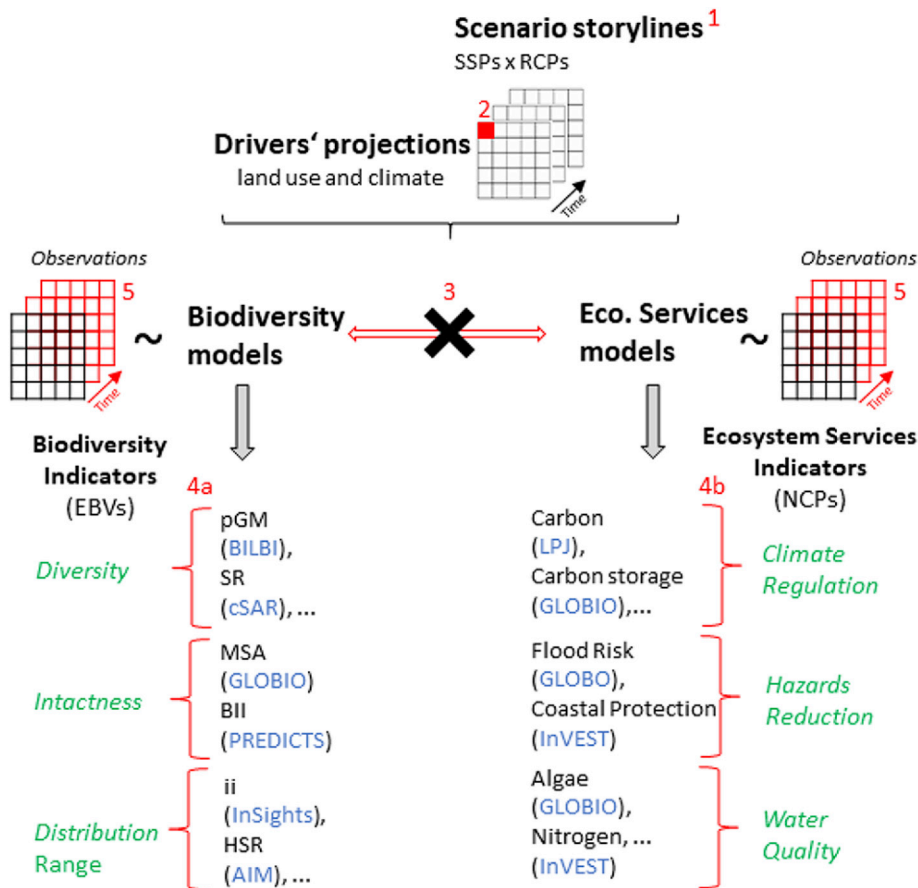
### 1.2. Better accounting for the role of nature in future human development trajectories

The set of scenarios in BES-SIM, drawn from the SSP/RCP framework, was used to describe plausible future trajectories for land-use and climate, as key drivers of biodiversity change (Riahi et al., 2017; Van Vuuren et al., 2014). Despite the level of detail in the SSP storylines, the explicit consideration of nature's role in determining socio-economic development is still limited. For instance, the SSPs storylines used to define the inputs of IAMs were formulated with limited consideration of how biodiversity and ecosystem services feedback to the human system (O'Neill et al., 2014). The consideration of nature in the current global storylines is limited to the role of nature protection, particularly to protected areas.

In addition to the undeniably important role of protected areas in mitigating climate change (Dudley et al., 2010; Popp et al., 2014; Soares-Filho et al., 2010) there are many other aspects of the human-nature interaction that should be considered, especially if we aim to use scenarios to inform decision-making. For instance, particularly under a sustainable development agenda, there is the possibility that societies choose development pathways that are positive for both the future of nature and the benefits that people obtain from nature. In addition, people's different perspectives on and preferences for nature may by themselves lead to alternative socio-economic pathways (Rosa et al., 2017). A simplified version of this preference space recognizes three major perspectives (Schoolenberg et al., 2018): “nature for nature”, where people value nature for itself and includes intrinsic and existence values (independent of cultural/human-centered values); “nature for society”, where people value nature for the direct and indirect benefits it provides (human-centered perspective); and “nature as culture”, where people and nature are connected and the sense of identity derived from cultural landscapes and relational values dominate (still a perspective centered on humans).

Future socio-economic development pathways where one of above mentioned perspectives dominates will very likely lead to different trajectories from the ones explored in the SSPs, with the potential to stimulate thinking towards sustainable futures where the role of nature in driving human well-being is explicitly recognized and accounted for in the subsequent modeling work (Fig. 1, challenge 1). IPBES has called for a new generation of multiscale scenarios that explicitly consider trajectories of development and their dependency on nature (IPBES, 2016). Such scenario framework is being developed by the IPBES expert group on scenarios and models and has been coined Nature Futures (Rosa et al., 2017; Schoolenberg et al., 2018). In this framework, the role of biodiversity in underpinning global socio-economic change (Chapin et al., 2000) is seen as being key to the development of future storylines, capitalizing on the growing knowledge of such relationships.

Empirical evidence suggests that biodiversity is critical to ensure the functioning of ecosystems (Harrison et al., 2014; Isbell et al., 2011; Tilman et al., 2014), thereby impacting climate dynamics at multiple spatial scales, for example, via its impact on biomass and carbon storage potential (Erwin, 2009; Gill et al., 2007; Heller and Zavaleta, 2009), and ultimately human well-being (Haines-Young and Potschin, 2010). These socio-economic relationships with the natural world are particularly important to consider in a connected world (Adger et al., 2009; Marques et al., 2019), where negative impacts



**Fig. 1.** Workflow followed in BES-SIM, highlighting the five groups of barriers and bottlenecks (numbers in red, following the order in the text) that need to be addressed in future exercises to improve global projections of integrated biodiversity and ecosystem services change: 1) better accounting for the role of nature in future human development trajectories; 2) refine land-use projections and broaden the range of drivers in scenarios; 3) integrate biodiversity into ecosystem services models; 4) expand coverage of the multiple dimensions of biodiversity and ecosystem services; 5) incorporate time-series in the calibration and validation of biodiversity and ecosystem services models. *Note:* in blue are the biodiversity and ecosystem services models' names, in black the original metrics outputted by the models and in green the harmonized output metric, based on either Essential Biodiversity Variables (EBVs) or Nature Contributions to People (NCPs). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(e.g., market pressures demanding natural resources) or positive actions (e.g., setting aside land for conservation) may have important consequences elsewhere (Ewers and Rodrigues, 2008; Meyfroidt et al., 2013; Weinzettel et al., 2013). The development of the Nature Futures (new scenario storylines / new set of socio-ecological pathways) has started by identifying positive endpoints for biodiversity and ecosystem services through visioning exercises and stakeholder consultations at global and sub-global scales (Lundquist et al., 2017), integrating the three perspectives discussed above. Ultimately, trajectories for drivers and enabling policies and actions that lead to these endpoints will need to be explored via different modelling approaches (Table 1).

### 1.3. Refine land-use projections and broaden the range of drivers in scenarios

There are two main issues that relate to the representation of drivers of change in the scenarios. Firstly, current land-use projections are too coarse to capture the fine-grain heterogeneity that is characteristic of most land-use patterns (Hoskins et al., 2016; Newbold et al., 2015), and use rather broad class descriptions (e.g. “forested primary land” or “rangeland”) that could be enriched to reflect characteristics more relevant for both biodiversity and ecosystem services, such as intensity of use and habitat structure (Fig. 1, challenge 2). For example, the most recent version of the GLOBIO model includes a land-use allocation routine to downscale coarse-grain land-use data into higher-resolution spatial patterns (Schipper et al., 2019). Yet the need for further refinement of the thematic resolution remains.

Secondly, data on future global environmental change are typically derived from global climate models or IAMs, which currently mainly provide projections for two drivers of biodiversity and ecosystem services change, i.e. land-use and climate, thus failing to represent other important drivers such as infrastructure development, pollution, invasive species and hunting

**Table 1**

List of challenges in producing policy-relevant global scenarios of biodiversity and ecosystem services change addressed by BES-SIM as well as promising avenues moving forward.

Challenge	Steps taken	Looking forward
1) better accounting for the role of nature in future human development trajectories	Closer collaboration between global scenarios community (SSPs) and biodiversity and ecosystem services modeling communities.	'Nature Futures' as scenarios that explicitly consider the interaction between socio-economic development and the natural world.
2) refine land-use projections and broaden the range of drivers in scenarios	Improved land-use projections (better spatial resolution through downscaling).	Further improve thematic resolution of land-use and structural aspects of landscapes. Account for other anthropogenic drivers in scenario storylines and projections.
3) integrate biodiversity into ecosystem services models	Accounting for ecosystem-level biodiversity in estimating several ecosystem services.	Improved representation of the role of biological diversity (at ecosystem-, species- and trait-level) in ecosystem services provisioning.
4) expand coverage of the multiple dimensions of biodiversity and ecosystem services	Wide range of biodiversity and ecosystem services models and using EBVs and NCPs as a basis for harmonization of their outputs.	Develop and integrate models covering other dimensions of biodiversity and ecosystem services.
5) incorporate time-series in the calibration and validation of biodiversity and ecosystem services models	Started discussions within BES-SIM.	Improve ability to produce time series of biodiversity and ecosystem services using multiple data sources and integration.

(Benítez-López et al., 2019; Cardinale et al., 2012; Díaz et al., 2006; Doherty et al., 2016; Hölker et al., 2010). The wider range of drivers and how they might vary across space and time should be accounted for in the development of the new scenarios' storylines (e.g., Nature Futures, Schoolenberg et al., 2018). Models should then be improved or developed in order to translate these into quantitative projections that can later be used by biodiversity and ecosystem services models.

At the moment, accurate, relevant and representative global maps of current environmental (pressure) variables can be obtained for example by merging and harmonizing existing (sub)national datasets (Meijer et al., 2018), combining hyperspectral imagery with sophisticated classifications algorithms (i.e. deep learning) and solid ground-truthing data (Chen et al., 2014; Congalton et al., 2014), or high-resolution interpolation of accurate yet scattered measurements, informed by auxiliary data (Barbarossa et al., 2018). However, most advances have focused on land-cover rather than land-use (but see Hoskins et al., 2016) or other drivers of change, which limits their relevance to biodiversity modelling. Improving and expanding the mapping of historical and current drivers is useful not only as a basis to assess the current status of biodiversity (and ecosystem services) globally, but also to inform models of future environmental change. For example, accurate data on recent land-cover change, such as documented for 1992–2015 in ESA's CCI land-cover product (Li et al., 2018), can be used to identify location characteristics that underlie the conversion of natural habitat into agricultural land (a change in cover and use). This information, in turn, can be used to obtain more accurate projections of the locations of future conversion. Similarly, adequate data on present-day road length and transport kilometers can be used to establish prospective models on future roads (Dulac, 2013; Meijer et al., 2018).

#### 1.4. Integrate species-level and trait-level biodiversity in ecosystem services models

BES-SIM provided the opportunity for the biodiversity and ecosystem services modeling communities to come together and discuss integration. Certain ecosystem services projections (e.g., pollination, nitrogen retention and pest control) were produced accounting for the role of biodiversity at the ecosystem-level (Kim et al., 2018). However, these projections relied on biodiversity estimates that were made independently of the biodiversity models. For example, pollinator species richness is included in some of the biodiversity model outputs, but did not directly drive the pollination service models, instead landscape or ecosystem level features drives the species diversity models and the pollination models independently of each other (Tallis and Polasky, 2011).

Likewise, soil erosion and soil protection projections are currently produced depending only on the length of the growing season (Guerra et al., 2014), without consideration of the role of soil biodiversity or plant diversity, for example, in determining such services (Wagg et al., 2014) and the multiple drivers that can impact soil function and diversity (Rillig et al., 2019). Using biodiversity and ecosystem services models independently from each other allowed for the analysis of spatial relationships between biodiversity and ecosystem services to be carried out, but did not allow any direct interaction between these two types of models – i.e. where the output from one model affects the output from the other. There is, therefore, an incomplete representation of the contribution of biodiversity in ecosystem service provisioning (Fig. 1, challenge 3), which could clearly be improved.

Given the growing literature linking biological diversity to ecological function (Isbell et al., 2017, 2011; Lefcheck et al., 2015; Tilman et al., 2014), and despite controversy on the direction and magnitude of these links (Dormann et al., 2019; Pillai and Gouhier, 2019), integrating the role of biological diversity, particularly addressing the species-level (and trait/genetic-level) dependency in the provisioning of ecosystem services (Fry et al., 2019; Wang et al., 2018), is crucial to develop integrated understanding of the response of biodiversity and ecosystem services to global change (Table 1). In this

regard, there are promising attempts emerging in the literature that suggest that this integration is well underway (Isbell et al., 2017; Mokany et al., 2016; van Bodegom et al., 2014). However, to achieve the full integration of biodiversity into the key ecosystem services required by the global change modelling to support sustainable development agendas, we need to improve our understanding as to how biodiversity (at ecosystem, species and trait level) regulates a wider range of services such as water, carbon and other nutrient cycles (He et al., 2019; Reichstein et al., 2014), and cultural services.

### 1.5. Expand coverage of the multiple dimensions of biodiversity and ecosystem services

Biodiversity and ecosystem services are multifaceted concepts, with different dimensions responding differently to changes in drivers; hence, a suite of complementary metrics is needed to fully represent such responses in the model projections (Santini et al., 2017, Hill et al., 2016). One of the novelties of BES-SIM is the inclusion of a suite of independently developed, and therefore structurally distinct, biodiversity and ecosystem services models (Kim et al., 2018). The outputs from BES-SIM models addressed very different facets of biodiversity (i.e. species ranges, local species richness, global species extinctions, abundance-based intactness, compositional similarity, abundance of different functional groups), as well as different facets of ecosystem services (e.g., pollination, carbon sequestration, soil erosion, wood production, nutrient export, coastal vulnerability), often with little overlap between different models. It is no surprise that such a wide range of outputs led to a major challenge when producing ensemble projections. To assess the uncertainty around the projected impacts (and their magnitude), we followed a novel approach for biodiversity and ecosystem services model outputs, which we detail below.

#### 1.5.1. Biodiversity

To ensure that we could provide a measure of uncertainty for estimates coming from different models in BES-SIM the original outputs of the biodiversity models were harmonized by being mapped to the Essential Biodiversity Variables (EBVs) framework (Pereira et al., 2013). This resulted in three indicators based on community composition – absolute change in species richness, relative change in species richness, and abundance-based intactness – and one indicator based on changes in species distributions (Fig. 1, challenge 4a). Direct comparison of the outputs of the models was challenging in many cases, as the metrics differed in some technical details even when they represented the same aspect of biodiversity. For instance, the GLOBIO model (Janse et al., 2015; Schipper et al., 2019) outputs a metric called “Mean Species Abundance” (MSA) that represents “the mean abundance of original species in relation to a particular pressure as compared to the mean abundance in an undisturbed reference situation”; likewise the PREDICTS model (Newbold et al., 2015) outputs a metric called “Biodiversity Intactness Index (BII)” that represents “the average abundance of originally present species across a broad range of species, relative to abundance in an undisturbed habitat”. While similar in definition, mathematically they are calculated differently (e.g., the former is the average of abundance ratios while the latter is the ratio of the sums). Similarly, models based on the species-area relationship (Pereira and Daily, 2006), even though they produced similar metrics (absolute and relative change in species richness), refer to different taxa and/or temporal baselines, limiting the meaningfulness of direct comparison. To make comparison across models meaningful, metrics were therefore converted to proportional changes relative to the beginning time of the analysis (i.e.,  $(y_{t1}-y_{t0})/y_{t0}$ ).

Although BES-SIM covered a broad range of biodiversity metrics, these mainly addressed changes in species distributions (of specific taxa) and community composition, largely leaving out other relevant EBV classes such as genetic composition, species traits, ecosystem structure and ecosystem function. Still, perhaps the most important limitation is that each of the indicators used is reporting a single value for biodiversity change, and the combination of the different indicators still provides a limited capture of the multidimensionality of biodiversity change. For instance, even when no net change in species richness is observed, there may be colonizations and extinctions occurring (Dornelas et al., 2014). More comprehensive descriptions of biodiversity change will need to separately report changes for multiple functional groups (e.g., forest versus open land species) or report multidimensional community composition metrics (Fig. 1, challenge 4a).

#### 1.5.2. Ecosystem services

In BES-SIM, for the first time, we included Dynamic Global Vegetation Models (DGVMs) to provide projections of ecosystem functions alongside fundamentally different models that directly address ecosystem services (InVEST, GLOSP and GLOBIO-ES). For certain metrics, such as carbon sequestration and biomass, the interpretation of metrics is similar, but for other metrics, e.g., pollination, direct comparison was not feasible. For instance, while GLOBIO-ES (De Groot et al., 2010; Schulp et al., 2012) defines pollination services as “the fraction of cropland potentially pollinated, relative to all available cropland”, InVEST (Tallis and Polasky, 2009) defines it as “the proportion of agricultural lands whose pollination needs are met”. Again, although similar in definition, mathematically these were calculated very differently (see Kim et al., 2018 for more detail), making their direct comparison unfeasible. We overcame this challenge by harmonizing the metrics, i.e. mapping them against the Nature Contributions to People (NCPs) framework (Díaz et al., 2018, Fig. 1 challenge 4b), and by determining the proportional changes relative to the beginning time of the analysis, as done for biodiversity.

Despite the fact that models provided outputs for many ecosystem services, including a wide range of regulating and provisioning services (Kim et al., 2018), the need to develop ensemble projections limited the number of metrics BES-SIM could focus on. In addition, many entire classes of ecosystem services were not included in this exercise due to the absence of global models and/or data, still only available for a limited number of services (Chaplin-Kramer et al., 2019). This is particularly true for cultural services, where data is still lacking, and which often evade quantitative or mechanistic modeling,

and coastal and marine ecosystem services, largely due to the lack of marine habitat and species distribution data available historically or in response to scenarios (Fig. 1, challenge 4b).

### 1.6. Incorporate time-series in the calibration and validation of biodiversity and ecosystem services models

Despite the technological advancements of the last couple of decades that vastly increased our ability to collect, process and analyse data, most biological entities are not possible to monitor using remote sensing alone (Ferrier et al., 2017), even if we advance technical capabilities extensively. Therefore, there is a need to develop biodiversity-calibrated models integrating several data sources (in situ observations from permanent monitoring sites, remote observations) (Dornelas et al., 2019; Isaac et al., 2019).

Existing efforts have been hampered by the lack of datasets, particularly at the global scale, that incorporated repeated measurements over time (Fig. 1, challenge 5). Up until now, biodiversity models are typically calibrated for one single time point, using space-for-time substitution (Blois et al., 2013). That is, a relationship between a given biodiversity metric and a selection of predictor variables, for example climate or land-use, is established across space either for a given moment in time, or by compiling observations from different moments in time into a single snapshot of biodiversity for a given location. Models assume that these relationships hold over time, i.e. spatial associations are used as causal predictive relationships. However, spatial associations may be influenced by other variables (e.g., historical contingency) and their projections of how biodiversity in a site changes over time when land-use and climate variables change in that site may not hold (De Palma et al., 2018).

Improving the state-of-the-art in biodiversity modelling calibration and validation could be done in two ways. First, validation of the models should use time series-data for biodiversity when it is available, as species distribution modellers already sometimes do (Araújo et al., 2005). This would allow explicit quantification of error and uncertainties in the projections, which are essential for decision-makers (Parker, 2013). Second, the calibration of the models could also use time-series data (Ferrier et al., 2017) or, in the absence of detailed time series, 'snapshots' of a site or region's biodiversity at some previous point in time. This requires investing on long-term funding for permanent monitoring sites, improving data availability and the development of biodiversity models that use time-series data (Fig. 1, challenge 5).

Recent developments in making biodiversity time-series data available at the global level open up a realm of new possibilities. This include the creation of global databases that contain community composition or species populations time-series at multiple sites (e.g., the BIOTIME database [Dornelas et al., 2018], and the Living Planet Index [Collen et al., 2009]), the advent of Darwin Event Core to publish structured biodiversity data to Global Biodiversity Information Facility (GBIF), and the conceptualization of EBVs as space-time-taxa information cubes that can integrate an array of biodiversity data from point occurrences to full community-wide census (Jetz et al., 2019).

However, incorporating time-series in the calibration of biodiversity models, such as those in BES-SIM, remains an open challenge (Table 1). Many of the models in BES-SIM used the PREDICTS database to calculate the changes in community composition after land-use, using a space for time substitution. With biodiversity time series data, it would be possible to not only estimate more accurately the changes in community composition in response to land-use change (Rittenhouse and Rissman, 2012), but also add a temporal component and look at effects such as the relaxation time to a new equilibrium after habitat loss (De Palma et al., 2018; Pereira and Borda-de-Água, 2013). Moreover, models that account for land-use impacts are calibrated with data that reflect historical observations of species distribution and diversity change when habitat conversion (i.e. realised land-use change) takes place, whereas models that account for climate impacts are calibrated based on expected impacts on the distributional range of the species after a shift in climate (i.e. non-realised climate change). Combining static and dynamic variables, including climate and land-use variables, with species distribution models is an area of research receiving increasing attention (Stanton et al., 2012; Voigt et al., 2018).

The challenges noted above for biodiversity are also directly applied to ecosystem services models. There is a substantial body of empirical evidence showing that individual services, bundles of services and their interactions vary across both space and time, driven by policy, biophysical, and socioeconomic characteristics (Renard et al., 2015; Rodríguez et al., 2006). However, apart from the ecosystem services that can be estimated based on land-cover dynamics and thus derived from remote sensing data (Brown, 2013; Naidoo et al., 2008), similar challenges are faced by ecosystem services modellers who often have limited temporally-explicit datasets to work with, especially at the global scale (Chaplin-Kramer et al., 2019). Arguably, this is even a bigger challenge in this community than in the biodiversity modelling community since, apart from some provisioning and regulating ecosystem services like carbon sequestration and nitrogen regulation (Quijas et al., 2019; Watanabe and Ortega, 2014), even single-time model output validation is often lacking (Englund et al., 2017). Including the time dimension into the calibration and validation processes of existing ecosystem service models, although needed, is at the moment seriously limited by the lack of available time series for many services (particularly cultural services, for which even single time-point data is very sparse).

## 2. Conclusion

We have highlighted some of the major advances towards producing global scenarios of biodiversity and ecosystem services (Table 1), based on the BES-SIM inter-model comparison project. This was a novel initiative that brought together research communities developing global socio-economic scenarios, biodiversity impact models and ecosystem-service

impact models to successfully contribute to the IPBES Global Assessment. By forging stronger links between these communities of practice, BES-SIM has also laid the foundation for ongoing development of the modelling dimension of the new Nature Futures scenarios, which explicitly incorporate the two-way dependencies between socio-economic dynamics and biodiversity (Lundquist et al., 2017; Schoolenberg et al., 2018).

Our reflections mainly apply to global scenarios, biodiversity and ecosystem services modeling communities. However, in order to achieve the ambitious and integrative modeling framework set for the Nature Futures scenarios (Rosa et al., 2017), and to best inform international conservation policy and support the sustainable development agenda, these communities now need to broaden their disciplinary focus. This broadening will not only improve the modelling of interactions across biodiversity, ecosystems services, and society, but also better incorporate additional direct (e.g., invasive species, pollution) and indirect drivers (e.g., political decisions on conservation, individual behavioral and perceptual changes) of biodiversity change. The importance of modelling is well reflected in the work plan of the Nature Futures initiative (Schoolenberg et al., 2018), in which scenarios are to be developed through an iterative process of stakeholder consultation, modelling and storyline development. If well-coordinated across international initiatives, countries, scientists and other key actors, the results of scenarios-based modelling can eventually be used to evaluate the effectiveness of policies, and provide projections into the future for policy planning, intervention decisions and resource allocations.

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