Enhancing the use of scenario-based biodiversity information in conservation policy and practice

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*"Science cannot solve the ultimate mystery of nature.
And that is because, in the last analysis, we ourselves are a part of the mystery that we are trying to solve."*
— *Max Planck (1858-1947)*

*"Look deep into nature,
and then you will understand everything better."*
— *Albert Einstein (1879-1955)*

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Appendix II (enclosed as PDF in a CD)

Summary

Humans have used scenarios for developing strategies and informing decisions for a long time in history. Scenarios can be a valuable heuristic for facilitating discourses on plausible futures and advising on the course of action. The overall aim of this dissertation was to contribute to the development of a new scenario and modelling framework being developed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). It also explored the ways to improve the connectivity between the scenarios and the biodiversity data, models and indicators for their enhanced use in conservation policies and practice.

Chapter 2 describes the methods used for Biodiversity and Ecosystem Services Scenarios-based Intercomparison of Models (BES-SIM). This protocol includes descriptions of climate change (Representative Concentration Pathways, RCPs) and socio-economic development (Shared Socioeconomic Pathways, SSPs) scenarios and their data. It describes the nine biodiversity models (AIM-biodiversity, InSIGHTS, MOL, BIOMOD2, cSARs, BILBI, PREDICTS, GLOBIO, MADINGLEY) and six ecosystem services models (LPJ, LPJ-GUESS, CABLE, GLOBIO-ES, InVEST, GLOSP) that joined the model intercomparison, including their modelling methods, assumptions and output metrics. The BES-SIM used harmonized climate and socio-economic scenarios to compare their impact on biodiversity and ecosystem services using common (or commonly categorized) metrics. The protocol was developed based on two workshops with modelling teams and scenarios experts, and this chapter documents its results with rationale on the choices made.

Chapter 3 describes synthesized results of the BES-SIM model intercomparison from Chapter 2 (protocol). We analyzed the impact of three combinations of socio-economic development pathways reflected in land use data alone and combined with greenhouse gas concentration pathways reflected in climate data (SSP1xRCP2.6, SSP3xRCP4.5, SSP5xRCP8.6) from 1900 to 2050. We used three sets of metrics on biodiversity (diversity, intactness, habitat) and ten sets of metrics on ecosystem services (pollination, climate regulation, water regulation, soil protection, hazards/extreme events regulation, pest control, energy production, food and food, materials) at the local (grid), regional and global level. The results suggest that all combinations of RCP and SSP scenarios would lead to continued losses of biodiversity and declines in regulating ecosystem services. This is at the cost of increases in provisioning services, except for in Global Sustainability (SSP1) scenario, the biodiversity loss is slower than the past century with slight increases in regulating services. This study highlights the critical need to explore and integrate different biodiversity and nature-based interventions in socio-economic pathway scenarios to account for their impact on biodiversity, climate change and human well-being.

Chapter 4 describes a new scenarios and modelling framework by IPBES – the Nature Futures Framework (NFF) – its key building blocks and modelling approaches for policy support. Based on a series of stakeholder and expert consultations, analyses, and synthesis, we suggest that the Nature Futures scenarios explore and incorporate diverse value perspectives on nature with stakeholders. These new scenarios capture multiple pathways towards the futures frontier with mutually reinforcing feedbacks that are key to transforming social-ecological systems. We further suggest that these scenarios assess the evolution of these key social-ecological systems using multiple knowledge sources in informing future decisions, including quantitative and qualitative models and indicators. Finally, we describe how the Nature Futures scenarios can be modelled to support conservation and sustainability policy with key challenges to be overcome. This perspective aims to inspire broader applications of the Nature Futures Framework for the development of nature and people positive scenarios.

Chapter 5 applies the Nature Futures Framework in the policy review application proposed in Chapter 4. I assessed the state and trends of biodiversity and ecosystem services in terrestrial protected areas and indigenous land compared to the rest of the land in 2000-2015/18 through the Nature Futures lens. I mapped protected areas and indigenous land to three nature value perspectives as an intervention layer and used five response variables on biodiversity and ecosystem services for spatial and temporal analysis at the global and regional level using national means. We find that nature and its ecological supplies to ecosystem services were at its best state and sustained the most in the Nature for Nature protection regime, then Nature for Society and Nature as Culture, then the least in the Status Quo (unprotected areas). The statistical model results show heterogeneous pattern across variables at final regional scales. This study demonstrates how the Nature Futures Framework can be used with essential biodiversity and ecosystem services variables in diversifying the roles, values, and benefits of nature to retrospectively evaluate the performance of biodiversity interventions. It further suggests the inclusion of indicators beyond the area measure in assessing and improving the impact of protected areas in the implementation of the CBD Post-2020 Global Biodiversity Framework.

This dissertation aspires to contribute to developing and interweaving the recent global initiatives that aim to improve science-based policy design and implementation and enhance the usability of scenarios-based biodiversity information in conservation policies and practice. It suggests the urgent need to bring climate and biodiversity research communities together in developing scenarios that work for both nature and people. It presents the importance of reflecting diverse worldviews and values in developing new scenarios that can engage and inform all societal actors in appreciating nature more and transforming society towards more positive futures. It concludes with concerted efforts required in interweaving science and policy frameworks at each regional scale and across these scales in implementing conservation and sustainability interventions going forward. The Nature Futures scenario and modelling framework and model-based essential variables on biodiversity and ecosystem services bring a unique opportunity to support these ambitions by integrating science in societal decisions for more ecological, livable and just futures with broader stakeholder communities.

Chapter 1

Introduction

1.1 Scenarios and models in the environmental assessments

Scenarios and models have long been used to inform decision-making (ICIS & EEA 2000; MA 2005; Kosow and Gassner 2007; IPBES 2016). In the context of environmental assessments, scenarios are the representation of plausible futures with alternative policy or management options on different drivers that affect nature and people, and models describe these relationships quantitatively or qualitatively (IPBES 2016). Scenarios are optimally developed iteratively, combining qualitative storylines with quantitative modelling (Alcamo *et al.* 2006; Robertson *et al.* 2017). Given the spatial nature and scale dependencies of biodiversity conservation and sustainability issues (Malinga *et al.* 2015), multiscale scenarios are increasingly demanded in science-policy interfaces such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Panel on Climate Change (IPCC) (Obermeister 2019). Multiscale scenarios improve understanding of social-ecological dynamics at different spatial scales and interactions between scales (Kok *et al.* 2007). Previous multiscale efforts include environmental scenarios used in the Millennium Ecosystem Assessment (MA 2005; Carpenter *et al.* 2006) and Shared Socioeconomic Pathway (SSP) scenarios used in the IPCC report (Moss 2010; O'Neill *et al.* 2017).

The IPBES methodological assessment on scenarios and models highlighted several key challenges for improving the use of scenarios in policy processes. They include adopting participatory approaches to scenario development processes, improving the models' representations and linkages across drivers of change, biodiversity, ecosystem functioning and ecosystem services, and integrating social-ecological feedbacks such as critical regime shifts and tipping points (IPBES 2016). Furthermore, scenarios need to better account for human behaviour and decision-making processes particularly at global scales with , despite its difficulties understanding and representing them (Rounsevell *et al.* 2014; Calvin and Bond-Lamberty 2018). Decision-making in global models is commonly defined through economic processes, which is not representative of society (Arneth *et al.* 2014). Furthermore, the role of institutions and governance for land and ocean systems receives little attention, limiting global models from quantifying transformative pathways (Rounsevell *et al.* 2014; Arneth *et al.* 2014). Similar concerns have been raised recently by the climate research community around its Shared Socioeconomic Pathway scenarios (SSPs), providing a unique opportunity for a joint effort to tackle complex biodiversity, climate, and societal challenges together (Elsawah *et al.* 2020; O'Neill *et al.* 2020).

In the last few decades, the modelling techniques have advanced in quantifying the narratives, incorporating a range of societal and economic (e.g. population, economy, energy demand, technology) and environmental (e.g. land productivity and availability, climate change, natural resource, pollution) drivers to inform policy design on climate, agriculture, and energy often at global and regional levels (Stehfest *et al.* 2014; Obersteiner *et al.* 2016; Huppmann *et al.* 2019; Leclère *et al.* 2020). Furthermore, a wide range of biodiversity and ecosystem functions and services models have been developed and used to assess the state of nature to support conservation planning and implementation (Brotons *et al.* 2016; Peterson *et al.* 2016). These models can quantify scenarios by setting different assumptions and goals on policy or management options (e.g. land-use planning, fishery management) based on different environmental trajectories (e.g. changes in temperature or precipitation) to predict their impact on nature and people (Harfoot *et al.* 2014; Sharp *et al.* 2016; Cheung and Oyinlola 2019). These models are increasingly being applied across scale (Cheung *et al.* 2016) with global tools downscaled to national or subnational levels (Murty 2018; Wang *et al.* 2021) and fine-scale spatial data used in global models (Purvis *et al.* 2018; Chaplin-Kramer *et al.* 2019; Pereira *et al.* 2020b).

In 2017, the expert group on scenarios and models of IPBES set itself to develop a new scenario and modelling framework to reposition biodiversity and nature at the centre of policy and governance, recognising their essential role in supporting human well-being and sustainable development (Rosa *et al.* 2017). Over three years, a series of visioning consultations took place with stakeholders and experts from diverse disciplinary and sectoral backgrounds. As a result, the Nature Futures Framework (NFF) emerged for nature-centred, diverse values-reflected, and multiscale scenarios (Pereira *et al.* 2020a). The Nature Futures Framework is a heuristic tool for developing positive scenarios for nature and people by embracing diverse worldviews and values on nature. Previous papers have designed the roadmap (Rosa *et al.* 2017) and presented the participatory visioning process (Pereira *et al.* 2020a) that led to the identification of the three nature value perspectives (Lundquist *et al.* In preparation). In the Nature Futures Framework, Nature for Nature perspective aligns with intrinsic and existential values of nature and prioritizes conserving nature, recognizing its role in sustaining the planet and humanity (Chan *et al.* 2016; O'Connor and Kenter 2019). The Nature for Society perspective aligns with instrumental values and appreciates the benefits nature provides to people (Chan *et al.* 2011; Díaz *et al.* 2018). The Nature as Culture perspective aligns with relational values of nature and embraces co-inhabiting and preserving cultural heritage with nature (Pascual *et al.* 2017; O'Connor and Kenter 2019). This new scenario and modelling framework is envisaged to provide an entry point for articulating and exploring diverse worldviews and values in creating positive futures for nature and people.

1.2 Essential variables and indicators for monitoring biodiversity

In 2008, the Global Earth Observations Biodiversity Observation Network (GEO BON) was established in response to the growing need for improved coordination, production and delivery of biodiversity observations to inform policies for achieving biodiversity conservation and sustainable development (Scholes *et al.* 2012). The Essential Biodiversity Variables (EBVs), inspired by the Essential Climate Variables (ECVs, e.g. temperature, precipitation variables) for the UN Framework Convention on Climate Change, are being developed through the GEO BON network to support policy for the UN Convention on Biological Diversity (CBD, Decision XI/3) and other multilateral environmental agreements. The Essential Biodiversity Variables (Pereira *et al.* 2013) and Essential Ecosystem Services Variables (Balvanera et al. In review) offer a flexible structuring and harmonization of biodiversity and ecosystem service observations with the data-to-indicators workflow that can be applied across the biomes, regions and scale (Turak *et al.* 2017; Kissling *et al.* 2018; Jetz *et al.* 2019).

The EBVs represent multiple dimensions of biodiversity and ecosystems, and they are complementary to one another in analysing the status and trends of nature. EBVs are the intermediate data layer between primary observations and indicators. Therefore, they can adapt to technological advancement in observation systems and evolving demand on indicators (Pereira *et al.* 2013; Fernandez In review). By design, EBVs are biological, scalable, sensitive to change, and feasible to produce. Most of them are produced by predictive models optimising the use of *in-situ* and remote sensing data (Navarro *et al.* 2017). EBVs are defined either at the species level (i.e. species population, species trait, genetic composition) or the ecosystems level (i.e. community composition, ecosystem structure, ecosystem function). Repeated monitoring of the same biological or ecosystem entity at the same locations is vital for detecting and attributing biodiversity change (Pereira *et al.* 2013). Given the vast nature and investment required in measuring and monitoring biodiversity, predictive models become instrumental in detecting and attributing changes in biodiversity, integrating observation and empirical data and advanced statistical tools and methods (Urban *et al.* 2022). Therefore, predicting the response of EBVs to the environmental drivers is necessary in assessing the potential impact of policy and management options on biodiversity and ecosystems (IPBES 2016, 2019). Predictive models at a coarse scale can improve progressively by calibrating models with increasing field-based *in situ* data from the finer spatial scale. EBVs' data-to-indicators workflows have been fleshed out and are currently being operationalized on species populations (Jetz *et al.* 2019), species traits (Kissling *et al.* 2018), and others.

The Essential Ecosystem Services Variables (EESVs), developed to complement the Essential Biodiversity Variables, represent core classes of variables to assess key changes in ecosystem services at the interface between nature and human well-being (Balvanera et al. In review). The EESV framework has six classes of essential variables: ecological supply, anthropogenic contribution, demand, use, instrumental value, and relational value. There are two classes on the supply side: *ecological supply*, which measures ecosystems' potential capacity to provide ecosystem services and *anthropogenic contributions* that measures human contributions to the supply of ecosystem services (Schröter *et al.* 2021). There are two classes on the demand side: *demand* that measures the human need for ecosystem services and *use* that measures people's realized appropriation of the ecosystem service (Brauman *et al.* 2020). For the two classes on values, instrumental value relates to meeting material or security needs, while relational value refers to principles embedded or emerging from the interactions between people and nature (Pascual *et al.* 2017; Díaz *et al.* 2018). The EESV framework can be applied flexibly on all types of ecosystem services (e.g. pollination-based crop production, nitrogen-retention-based water regulation, coastal risk reduction from natural habitats) in potentially measuring the stocks and flows of ecosystem services through space and time (Balvanera et al. In review). Therefore, different classes of EESVs can together inform how the conditions of nature are linked to human well-being and the potential unequal distribution of nature's benefits to people (Chaplin-Kramer *et al.* 2019).

Together, the EBVs and EESVs can measure diverse facets, roles, values, and benefits of nature quantitatively through models that integrate multiple knowledge and data sources. Given flexible nature, researchers and practitioners can apply the EBV and EESV frameworks to their data sources as relevant for the context and the place and increase their accessibility, credibility and usability for conservation planning and implementation. It is, for instance, possible to develop strategies for preventing species extinction using the essential variables on species distribution and their area of habitats, together with land use and other environmental pressure maps. Furthermore, a wide range of ecosystem services (e.g. climate regulation, water purification, crop production, coastal risk reduction, nature-based recreation) are being mapped and measured across time and space today, enabling a more comprehensive valuation of material, non-material and relational values of nature. Such information can inform where to place protected areas for conserving biodiversity, where to place cities for human settlement, or which cultural landscape should be maintained for nature and people.

1.3 Objectives of this dissertation

The overall aim of this dissertation was to contribute to the development of new biodiversity-centric scenarios and modelling framework and improve the understanding about their connectivity to biodiversity indicators used in conservation policies and practice. To begin the process, we conducted a global model intercomparison on biodiversity and ecosystem services using the Representative Concentration Pathway (RCP) and Shared Socioeconomic Pathways (SSP) scenarios. We assessed the impact of climate change and socio-economic development on biodiversity and ecosystem services. **Chapter 2** is the methodological protocol on scenarios, data, models, and indicators used in this exercise, and **Chapter 3** is the synthesis of the model intercomparison results. Then to develop a new scenario and modelling framework, we conducted a series of stakeholder and expert consultations with IPBES. **Chapter 4** is a perspective on key building blocks for Nature Futures scenarios with a focus on modelling these new scenarios to inform policy. In **Chapter 5**, employing one of the approaches proposed in Chapter 4, I conducted a retrospective spatio-temporal analyses on the state and trends of biodiversity, ecosystems and nature's contributions in protected areas and indigenous land through the Nature Futures lens using the essential biodiversity and ecosystem services variables.

Chapter 2 describes the methods used for the Biodiversity and Ecosystem Services Scenarios-based Intercomparison of Models (BES-SIM). It includes descriptions of the RCP and SSP scenarios and their climate and land use data, eight biodiversity models and five ecosystem services models with their modelling methods and assumptions, and output metrics used for model intercomparison. The protocol was developed through two workshops jointly with modelling teams and scenarios experts, and this chapter documents the results. The manuscript of Chapter 2, "A protocol for an intercomparison of biodiversity and ecosystem services models using harmonised land-use and climate scenarios", was published in *Geoscientific Model Development 11, 4537–4562.*

Chapter 3 is a synthesis of BES-SIM model intercomparison results using the protocol in Chapter 2. We analysed the impact of socio-economic development scenarios and climate change scenarios on biodiversity and ecosystem services from 1900 to 2050 at the local (grid), regional and global levels. This chapter responds to two main questions: 1) What is the forecasted magnitude of biodiversity and ecosystem services loss from the RCPs (climate) and the SSPs (land use) scenarios between 1900 and 2050? and 2) How much of the variation in projected impacts are attributable to differences in scenarios and models? The manuscript of Chapter 3, "Global trends in biodiversity and ecosystem services from 1900 to 2050", is archived as a pre-print in Bioarxiv and is being prepared for resubmission to a journal.

Chapter 4 describes how Nature Futures scenarios can be developed and modelled to support policy processes. Based on a series of expert and stakeholder consultations, we developed key building blocks to be considered in developing Nature Futures scenarios and present three approaches to modelling them in the review, screening and design phases of policy processes. The chapter responds to two main questions: 1) How can Nature Futures Framework be used in modelling to quantify the impacts of single to multiple policy options in reaching nature and people positive futures? and 2) What modelling advancements can be integrated and what key challenges remain in modelling Nature Futures scenarios? This chapter seeks to facilitate the integration of diverse values of nature in scenarios and models and recommends strengthened modelled linkages across a broader range of drivers, biodiversity, nature's contributions to people and quality of life. The manuscript of Chapter 4, "Towards a better future for biodiversity and people: modelling Nature Futures", is under review in *Global Environmental Change* and is archived as a pre-print in Socarxiv.

Chapter 5 analyses the state and trends of biodiversity, ecosystems, and nature's contributions to people across the Nature Futures protection regime from 2000 to 2015/2018 using the essential variables. Applying one of the approaches proposed in modelling Nature Futures scenarios (Chapter 4), I retrospectively evaluate the state and performance of protected areas and indigenous land through the Nature Futures lens and compare them to unprotected areas. This chapter responds to two main questions: 1) Were protected areas placed where there was a high value of biodiversity and ecosystem services in 2000? 2) Were protected areas effective in conserving biodiversity and ecosystem services compared to non-protected areas over time? This chapter illustrates how the Nature Futures Framework and the essential biodiversity and ecosystem services variables can be used to assess nature's diverse roles, values, and benefits. It also demonstrates how retrospective evaluations can be conducted between targets and goals of the CBD Post-2020 Global Biodiversity Framework. The manuscript presented in Chapter 5, "Performance of terrestrial protected areas under the Nature Futures prism", is currently in preparation for submission to a journal.

In **Chapter 6,** I synthesise the findings of this dissertation with directions for future research and implications for conservation policy and practice.

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Chapter 2

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

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

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Abstract. To support the assessments of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the IPBES Expert Group on Scenarios and Models is carrying out an intercomparison of biodiversity and ecosystem services models using harmonized scenarios (BES-SIM). The goals of BES-SIM are (1) to project the global impacts of land-use and climate change on biodiversity and ecosystem services (i.e., nature'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 scenario 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 services models used, the core simulations carried out, the harmonization of the model output metrics, and the treatment of uncertainty. The results of this collaborative modeling project will support the ongoing global assessment of IPBES, strengthen ties between IPBES and the Intergovernmental Panel on Climate Change (IPCC) scenarios and modeling 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 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; Secretariat of the CBD and UNEP, 2014), with potentially severe impacts on ecosystem services and ultimately human well-being (Cardinale et al., 2012; MEA, 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 (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 been observed to have direct and indirect impacts on biodiversity and ecosystems, which are projected to intensify by the end of the century, with potentially severe consequences for species and habitats, and, therefore, also for ecosystem functions and services (Pecl et al., 2017; Settele et al., 2015).

Global environmental assessments, such as the Millennium Ecosystem Assessment (MEA, 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 to quantify the biodiversity and ecosystem services impacts of different scenarios, based on climate and land-use projections from general circulation models (GCMs) and integrated assessment models (IAMs) (Pereira et al., 2010). 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., 2015). So far, each of these scenario exercises has been based on a single model or a small number of biodiversity and ecosystem services 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.

Over the past 2 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 throughout 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 Socioeconomic 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 they are being used in a wide range of impact modeling intercomparisons (Rosenzweig et al., 2017; van Vuuren et al., 2014). Therefore, the use of the SSP-RCP framework for modeling the impacts on biodiversity and ecosystem services provides an outstanding opportunity to build bridges between the climate, biodiversity and ecosystem services communities; it has been explicitly recommended as a research priority in the IPBES assessment on scenarios and models (IPBES, 2016).

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

Here, we present the methodology used to carry out a BES-SIM in both 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 land-use and climate future scenarios? (2) What is the magnitude of the uncertainties associated with the projections obtained from different scenarios and models? Although independent of the ISI-MIP, the BES-SIM has been inspired by ISI-MIP and other intercomparison projects and was initiated to address the needs of the global assessment of IPBES. We brought together 10 biodiversity models and six ecosystem functions and services models to assess impacts of land-use and climate change scenarios in the coming decades (up to 2070) and to hindcast changes to the last century (to 1900). The modeling approaches differ in several respects concerning 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 essential biodiversity variables (EBVs), including species populations, community composition, and ecosystem function, 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., 2015). This paper provides an overview of the scenarios, models and metrics used in this intercomparison, and thus a roadmap for further analyses that is envisaged to be integrated into the first global assessment of the IPBES (Fig. 1).

2 Scenario selection

All the models included in BES-SIM used the same set of scenarios with particular combinations of SSPs and RCPs. In the selection of the scenarios, we applied 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 entailed the selection of SSP-RCP combinations that are included in the ScenarioMIP protocol as part of CMIP6 (O'Neill et al., 2016), as harmonized data were available for these runs and they form the basis of the CMIP climate simulations. The second criterion implied a selection of scenarios with low and high degrees of climate change and different land-use scenarios within the ScenarioMIP set. 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 on land use with low and high levels of climate change, we can test these drivers' individual and synergistic impacts on biodiversity and ecosystem services.

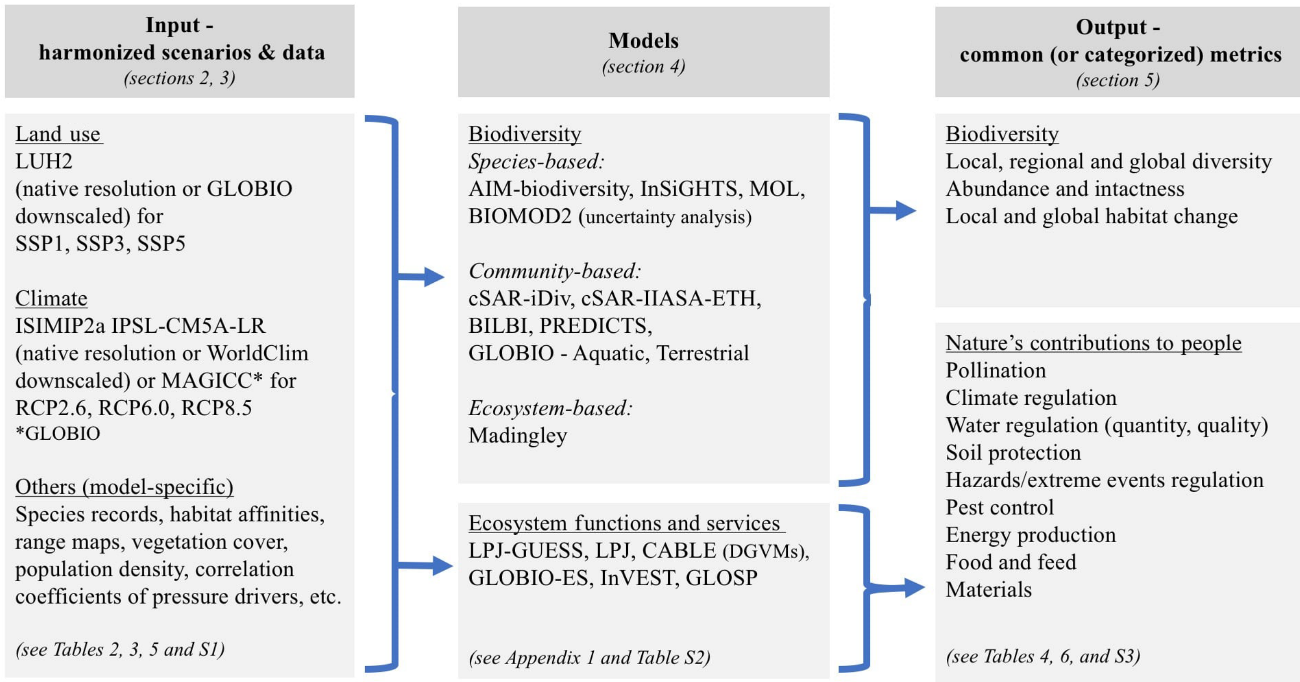

Figure 1. Input–models–output flowchart of BES-SIM.

The first scenario (SSP1xRCP2.6) is characterized by a relatively "environmentally friendly world" with low population growth, high urbanization, relatively low demand for animal products, and 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 characterized by low air pollution, as policies are introduced to limit the increase in greenhouse gases in the atmosphere, leading to an additional forcing of 2.6 $W m^{-2}$ before 2100. The second scenario (SSP3xRCP6.0) is characterized by "regional rivalry", 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 minimal land-use change regulation, with a large land conversion for human-dominated uses, and a relatively high level of climate change with a radiative forcing of 6.0 $W m^{-2}$ by 2100. The third scenario (SSP5xRCP8.5) is a world characterized by "strong economic growth" fuelled by fossil fuels, with low population growth, high urbanization, and high food demand per capita but also 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 provided 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 implemented across the models to the extent possible. All models in BES-SIM used the newly released Land Use Harmonization version 2 dataset (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, b) 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.

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 for modeling land-use scenarios – IMAGE for SSP1/RCP2.6, AIM for SSP3/RCP7.0, and REMIND/MAgPIE for SSP5/RCP8.5 – include different eco-

Table 1. Characteristics of the **(a)** SSP, **(b)** RCP and **(c)** SSPxRCP 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	Limited with continued deforestation	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 and 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 $3\,W\,m^{-2}$ before 2100 and decline	Stabilizes without overshoot pathways to $6\,W\,m^{-2}$ 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)	$>$ 1370 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 policies
(c) SSPxRCP scenarios	SSP1xRCP2.6 Highest mitigation	SSP3xRCP6.0 Limited mitigation	SSP5xRCP8.5 No mitigation
Bioenergy	Low	Highest	Lowest

nomic 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 used land-use scenarios, 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. In 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°), 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

Table 2. Improvements made in the Land Use Harmonization v2 (LUH2) from LUH v1 (sources: Hurtt et al., 2011, 2018).

	LUH v1	LUH v2
Spatial resolution	0.5°	0.25°
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) – C_3 annual crops (c3ann) – C_3 perennial crops (c3per) – C_4 annual crops (c4ann) – C_4 perennial crops (c4per) – C_3 nitrogen-fixing crops (c3nfx)
Future	RCPs (4) – RCP2.6 – RCP4.5 – RCP6.0 – RCP8.5	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)

crops), all with annual time steps. The 12 land states include the separation of primary and secondary natural vegetation into forest and non-forest sub-types, pasture into managed pasture and rangeland, and cropland into multiple crop functional types (C_3 annual, C_3 perennial, C_4 annual, C_4 perennial, and N-fixing crops) (Table 2).

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 arcsec resolution; ~ 300 m) with the land-use allocation routine of the GLOBIO4 model. To that end, urban, cropland, pasture, rangeland, and forestry areas 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 300 m cells with the GLOBIO4 land allocation routine, with specific suitability layers for urban, cropland, pasture, rangeland, and forestry areas. After allocation, cropland was reclassified into three intensity classes (low, medium, high) based on the amount of fertilizer used per grid cell. More details on the downscaling procedure are provided in Supplementary Methods in the Supplement.

3.2 Climate data

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 on 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 system models (GCMs with an 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. In BES-SIM, some models require continuous

Table 3. 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°	LUH2 v2.0 downscaled (GLOBIO) 300 m	ISIMIP2a IPSL-CM5A-LR native resolution 0.5°	ISIMIP2a downscaled IPSL-CM5A-LR (WorldClim) 1 km	IMAGE[1] (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	*		*		

[1] All GLOBIO models use MAGICC climate data from the IMAGE model.

time-series data. In order to harmonize the climate data to be used across biodiversity and ecosystem services 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 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° 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 the ISIMIP2a dataset and three models used the WorldClim dataset. An exception was made for the GLOBIO models, which used MAGICC 6.0 climate data (Meinshausen et al., 2011a, b) in the IMAGE model framework (Stehfest et al., 2014), to which GLOBIO is tightly connected (Table 3). The variables used from the 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 modeling in 6 of 10 biodiversity models, while 2 models 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 (DGVMs), atmospheric CO_2 concentrations, irrigated fraction, and wood harvest estimates are commonly used, while two ecosystem services models rely on topography and soil-type data for soil erosion measures. A full list of model-specific input data is given 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 of biodiversity data and advancement in statistical modeling 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 modeling sufficiently documented and accessible for review (Table S2). Sixteen models were included in BES-SIM (Appendix A, details on modeling methods 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 A). All 16 models are spatially explicit, with 15 of them using land-use data as an input and 13 of them 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 modeled, they can be known as species distribution models, ecological niche models, bioclimatic envelope models, and habitat suitability models (Elith and Leathwick, 2009). Such species-based models 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., 2018), InSiGHTS (Rondinini et al., 2011; Visconti et al., 2016), MOL (Jetz et al., 2007; Merow et al., 2013), and BIOMOD2 (Appendix A, 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 uses Global Biodiversity Information Facility (GBIF) species occurrence data on 9025 species across 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 from regular sampling within species' ranges and pseudo-absence records from regular sampling outside of species' ranges on 2827 species of mammals. MOL uses species land-cover preference information and species presence and absence predictions on 20 833 species of amphibians, birds, and mammals. InSiGHTS and MOL rely on IUCN's range maps as a baseline, which are developed based on expert knowledge of the species habitat preferences and areas of non-occurrence (Fourcade, 2016). Both models use 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 opinion is used to assess the impacts of land use in the climate-suitable portion of the species range. BIOMOD2 is an R modeling 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 Sect. 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), and BILBI (Hoskins et al., 2018; 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., the number of species in the modified landscape divided by the 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. Both the cSAR-iDiv and cSAR-IIASA-ETH models use habitat affinities (proportion of area of a 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, 2016) while the habitat affinities of cSAR-IIASA-ETH come from a previously published database of studies (Chaudhary et al., 2015). The cSAR-iDiv model considers 9853 species for one taxonomic group (birds) in two functional groups (forest species and non-forest species) while cSAR-IIASA-ETH considers a total of 1 911 583 species for five taxonomic groups (amphibians, birds, mammals, plants, reptiles) by ecoregions (these are, however, not 1 911 583 unique species as a species present in two ecoregions will be counted twice). BILBI couples application of the species–area relationship with correlative statistical modeling of continuous spatial turnover patterns 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 for 254 145 vascular plant species globally.

Three community-based models – PREDICTS, GLOBIO Aquatic (Alkemade et al., 2009; Janse et al., 2015), and GLOBIO Terrestrial (Alkemade et al., 2009; 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 A). PREDICTS uses a hierarchical mixed-effects 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 from a wide range of taxonomic groups (Hudson et al., 2017, 2016). GLOBIO is an integrative modeling framework for aquatic and terrestrial biodiversity that builds upon correlative relationships between biodiversity intactness and pressure variables, established with meta-analyses of biodiversity 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 characterized 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, and reproductive strategies).

4.4 Models of ecosystem functions and services

In order to measure ecosystem functions and services, three DGVM models – LPJ-GUESS (Lindeskog et al., 2013; Olin et al., 2015; Smith et al., 2014), LPJ (Poulter et al., 2011; Sitch et al., 2003), and CABLE (Haverd et al., 2018) – and three ecosystem services models – InVEST (Sharp et al., 2016), GLOBIO (Alkemade et al., 2009, 2014; Schulp et al., 2012), and 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 regimes (Prentice et al., 2007). Processes in anthropogenically managed land (cropland, pastures, and managed forests) are also increasingly being accounted for (Arneth et al., 2017). DGVMs can project changes in future ecosystem states (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).

The InVEST suite includes 18 models that map and measure the flow and value of ecosystem goods and services across a landscape or a seascape. They are based on biophysical processes of the structure and function of ecosystems, and they account for both supply and demand. The GLOBIO model estimates ecosystem services based on outputs from the IMAGE model (Stehfest et al., 2014), the PCRaster Global Water Balance global hydrological model (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 is a 2-D 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 modeling 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 scale (γ scale, i.e., the value of the metric for a set of grid cells comprising a

Table 4. Selected output indicators for intercomparison 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	Species diversity change at local scale ($P\alpha$ and $N\alpha$)	Species diversity change at subregional and global scale ($P\gamma$ and $N\gamma$)	Abundance-based intactness at local scale ($I\alpha$)	Mean habitat extent change at local and global scale ($H\alpha$ and $H\gamma$)
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			*	

region). For species richness change, some models project the α metrics at the grid cell level (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 show species persistence and extinction in a 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). 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: 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 represents 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), and 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 was 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, $\mathrm{Pg\,month^{-1}}$), water quality (e.g., nitrogen and phosphorus leaching, $\mathrm{PgN\,s^{-1}}$), soil protection (e.g., erosion protection, 0–100 index), hazards (e.g., costal 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, $\mathrm{km^2}$), and material metrics on bioenergy (e.g., bioenergy–crop production, $\mathrm{PgC\,yr^{-1}}$), food and feed (e.g., total crop production, 10^9 KCal) 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)

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

BES-SIM model	Historical	Future land-use change or climate (2050): 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				*

on human well-being and quality of life. Given the disparity of metrics across models within each NCP category, names of the metrics are listed in Table 6, 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 modeling teams: present (2015) and future (2050). Additionally, a past projection (1900) and a further future projection (2070) were also provided by several modeling teams. Some models projected further into the past and also at multiple time points from the past to the future (Appendix A). Models that simulated a continuous time series of climate 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 A), and upscaled results to 1° 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 certain region were calculated, as well as percentiles of those metrics. Both 1° rasters and a table with values for each IPBES region and the globe were provided by each modeling 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 models required continuous climate time-series data to hindcast to 1900, data from years in the time period 1951 to 1960 were randomly selected to fill the data missing for years 1901 to 1950 from the ISIMIP 2a IPSL dataset. Models that used multi-decadal climate averages from WorldClim (i.e., InSiGHTS, BILBI) assumed no climate impacts for 1900.

7 Uncertainties

Reporting uncertainty is a critical component of model intercomparison exercises (IPBES, 2016). Within BES-SIM, un-

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					

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certainties were explored by each model reporting the mean values of its metrics, and where possible the 25th, 50th, and 75th percentiles based on the parameterization set specific to each model, which can be found in each model's key manuscripts describing the modeling methods. When combining the data provided by the different models, the average and the standard deviations 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 modeling changes in species ranges arising from using different RCP scenarios, different GCMs, a suite of species distribution modeling algorithms (e.g., random forest, logistic regression), and different species dispersal hypotheses.

8 Conclusions

The existing SSP and RCP scenarios provide 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 consideration of biodiversity-specific policies in the storylines (only the SSP1 baseline emphasizes 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 also be 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 modeling will be published separately, as well as 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). Catalyzed by the IPBES Expert Group on Scenarios and Models, this new scenario and modeling 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 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 into socio-economic scenarios.

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, last access: 8 November 2018). The LUH2 land-use data used for model runs are available at http://luh.umd.edu/data.shtml (Hurtt et al., 2017). The climate datasets used in BES-SIM can be downloaded from the respective websites (https://www.isimip.org/outputdata/ (Inter-sectoral Impact Model Intercomparison Project Output Data, 2017), http://worldclim.org/version1, Hijmans et al., 2017).

Appendix A

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°	1900, 2015, 2050, 2070	Amphibians, birds, mammals, plants, reptiles	Ohashi et al. (2018)
InSiGHTS	A high-resolution, cell-wise, species-specific hierarchical species distribution model that estimates 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 modeled species and new scenarios for climate and land use.	0.25°	1900, 2015, 2050, 2070	Mammals	Rondinini et al. (2011), Visconti et al. (2016)
MOL (Map of Life)	An expert map-based species distribution model that projects potential losses in species occurrences and geographic range sizes given changes in suitable conditions of climate and land-cover change.	Expert maps for terrestrial amphibians, birds and mammals as a 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 modeling 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°	2015, 2050, 2070	Amphibians, birds, mammals	Jetz et al. (2007), Merow et al. (2013)
BIOMOD2 (BIOdiversity MODelling)	An R package that allows one to run 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, and 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 are used for model calibration, while 30 % are held out for model evaluation). Models are evaluated using various metrics.		100 km	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 with each habitat type. Species richness is calculated by multiplying the proportional species richness by the number of species known to occur in the area. The 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 the PREDICTS database.	0.25°	1900–2010 (10-year interval), 2015, 2050, 2070, 2090	Birds (forest, non-forest, all)	Martins and Pereira (2017)

Table A1. Continued.

BES-SIM model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
cSAR-IIASA-ETH	A countryside species area relationship model that estimates the impact of time series of spatially explicit land-use and land-cover changes on community-level measures of terrestrial biodiversity.	Extends concept of 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°	1500–1900 (100-year interval), 1900–2090 (10-year interval)	Amphibians, birds, mammals, plants, reptiles	Chaudhary et al. (2015), UNEP (2016)
BILBI (Biogeographic modelling Infrastructure for Large-scale Biodiversity Indicators)	A modeling framework that couples application of the species–area relationship with correlative generalized dissimilarity modeling (GDM)-based modeling 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 modeling 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).	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°	900–2100	All	Newbold et al. (2016), Purvis et al. (2018)
GLOBIO (GLObal BIOdiversity) – Aquatic	A modeling 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°	2015, 2050	All	Janse et al. (2015, 2016)

Table A1. Continued.

BES-SIM model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
GLOBIO – Terrestrial	A modeling framework that quantifies the impacts of multiple anthropogenic pressures on local biodiversity (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 arcsec (∼ 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 organization for marine or terrestrial.	Grouped by heterotroph cohorts, organisms are defined by functional traits rather than the taxonomy. Heterotrophs, defined by categorical (trophic group; thermoregulation strategy; reproductive strategy) and quantitative (current body mass; mass at birth; and mass at reproductive maturity) traits, are modeled 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°	1901, 1915–2070 (5-year 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 PFTs are identical within an age cohort. Processes such as photosynthesis, respiration, and 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 modeled recommendations from LUH2.	0.5°	1920, 1950, 1970, 2015, 2050, 2070		Lindeskog et al. (2013), Olin et al. (2015), Smith et al. (2014)

Table A1. Continued.

BES-SIM model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
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°	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 C_3 photosynthesis, as an outcome of fitness maximization.		1°	1920, 1950, 1970, 2015, 2050, 2070		Haverd et al. (2018)
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°	2015, 2050, 2070		Alkemade et al. (2009, 2014), Schulp et al. (2012)

Table A1. Continued.

BES-SIM model	Brief model description	Defining features and key processes	Model modification	Spatial resolution	Time steps	Taxonomic or functional scope	Key reference
InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs)	A suite of 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 landscape 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.	300 m and 5 arcmin	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 2-D 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°	2015, 2050		Guerra et al. (2016)

Appendix B: 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
ESMs	Earth system models
GBIF	Global Biodiversity Information Facility
GBO	Global Biodiversity Outlooks
GCMs	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
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
LPJ	Lund-Potsdam-Jena
LPJ-GUESS	Lund-Potsdam-Jena General Ecosystem Simulator
LUH2	Land Use Harmonization Project version 2
MA	Millennium Ecosystem Assessment
MAgPIE	The Model of Agricultural Production and its Impact on the Environment
MIP	Model Intercomparison Project
MOL	Map of Life
NCP	Nature's Contributions to People
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

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Chapter 3

Global trends in biodiversity and ecosystem service from 1900-2050

Global trends in biodiversity and ecosystem services from 1900 to 2050

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Abstract: Despite the scientific consensus on the extinction crisis and its anthropogenic origin, the quantification of historical trends and of future scenarios of biodiversity and ecosystem services has been limited, due to the lack of inter-model comparisons and harmonized scenarios. Here, we present a multi-model analysis to assess the impacts of land-use and climate change from 1900 to 2050. During the 20th century provisioning services increased, but biodiversity and regulating services decreased. Similar trade-offs are projected for the coming decades, but they may be attenuated in a sustainability scenario. Future biodiversity loss from land-use change is projected to keep up with historical rates or reduce slightly, whereas losses due to climate change are projected to increase greatly. Renewed efforts are needed by governments to meet the 2050 vision of the Convention on Biological Diversity.

One Sentence Summary: Development pathways exist that allow for a reduction of the rates of biodiversity loss from land-use change and improvement in regulating services but climate change poses an increasing challenge.

Main Text:

During the last century humans have caused biodiversity loss at rates higher than ever before, with extinction rates for vertebrates of 0.5% to 1% per century, 50 to100 times higher than the mean extinction rates in the Cenozoic fossil record (*1–4*). Although the proximate causes of this loss are multiple, ultimately a growing human population and economy have led to an increasing demand for land and natural resources causing habitat conversion and loss (*5*). Associated increases in the flow of provisioning ecosystem services such as the production of crops and livestock also lead to the widespread degradation of ecosystem's capacity to provide regulating services such as pollination and water quality, raising concerns about the long-term sustainability of recent development trends (*6*). Addressing the biodiversity crisis is increasingly at the center of international policy-making, under multilateral agreements such as the Convention on Biological Diversity. Restoring biodiversity and ecosystem services can actually provide part of the solution to many of the UN Sustainable Development Challenges (*7*, *8*). Therefore, it is key to assess implications of future socio-economic developments for biodiversity and ecosystem services and identify policies that can shift developments towards more sustainable pathways.

Scenario studies examine alternative future socio-economic development pathways and their impacts on direct drivers such as land-use and climate, often using integrated assessment models (*9*). The scenarios consequences for biodiversity and ecosystem services can be assessed using biodiversity and ecosystem function and services models (*10*, *11*). Several studies have explored the future trends of biodiversity and ecosystem services, finding an acceleration of extinction rates 100 to 10 000 times higher than the fossil record, and the continuation of trends of increasing provisioning services with the degradation of some regulation services, although with strong regional variations (*10*, *12–15*). While enlightening on the potential trajectories of biodiversity under global changes, these studies are hardly comparable. Existing scenario studies often use a single model, analyze a single facet of biodiversity, lack integration between biodiversity and ecosystem services impacts, or when comparing multiple models use different projections for future land-use and climate. Therefore, the source of uncertainties in these scenarios is difficult to ascertain (*16*) and an integrated analysis of biodiversity and ecosystem services scenarios has remained elusive.

Here, we present the first multi-model ensemble projections of biodiversity and ecosystem services using a set of harmonized land-use and climate change reconstructions from 1900 to 2015 and three future scenarios from 2015 to 2050. This work was carried out under the auspices of the Expert Group on Scenarios and Models of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) (*17*). We quantified a set of common ecological metrics from the grid cell scale (α-metrics), to the regional (i.e., IPBES subregions) and global scale (γ-metrics) to answer two main questions: (1) What are the global impacts of land-use and climate change on multiple facets of biodiversity and ecosystem services (i.e., Nature's Contributions to People, NCP) over the coming decades, compared to their impacts during the 20th century? (2) How much of the variation in projected impacts can be attributed to differences of development pathways in scenarios and to differences between models (i.e. structural uncertainty)?

We explored a range of plausible futures using the scenario framework of the Shared Socio-Economic Pathways (SSP) and Representative Concentration Pathways (RCP) (*18*). We chose three specific SSP-RCP combinations representing different storylines of population growth, socio-economic development and the level of greenhouse gas emissions (climate policy). These combinations represent contrasting projections of future land-use and climate change (Table S1, Figures S1 and S2): SSP1xRCP2.6 ("global sustainability" with low climate change and low land-use change), SSP3xRCP6.0 ("regional rivalry" with intermediate climate change and high land-use change) and SSP5xRCP8.5 ("fossil-fueled development" with high climate change and intermediate land-use change). For the biodiversity analysis, we consider both the impacts of land-use change alone (maintaining climate constant at historical levels) and of land-use change and climate change combined.

We brought together eight models of biodiversity and five models of ecosystem function and services (Table S2). Depending on the model, up to three biodiversity metrics were calculated (SM): species richness (S), mean species habitat score ($\dot{H}$), and species-abundance based biodiversity intactness (I). For ecosystem functions and services, we classified model outputs into nine classes of Nature's Contributions to People (*19*) (Table S1). We calculated the metrics at the grid cell level (α), at the regional level, and at the global level (γ).

The steep reduction in global species richness that occurred during the 20th century (-0.78% ± 0.30% per century, mean±SE across models) is expected to continue at a slower (global sustainability scenario) or at a similar pace (regional rivalry and fossil-fueled development scenarios) in the next decades when land-use change alone is considered (Figure 1a). However, a much steeper decline is expected when the combined effects of land-use change and climate change are considered (Figure 1b, 1c). The scenario where we are able to stabilize greenhouse gas emissions concentrations and limit climate change to 2°C (global sustainability scenario; Figure S2) has already 40% lower global extinction rates by 2050 than the scenario with no climate mitigation policy (fossil-fueled development), with bigger differences looming for the second half of this century as the contrast between these scenarios continues to increase (*20*). Other biodiversity metrics exhibit similar trends with some interesting differences. Reduction in local species richness are of similar magnitude to global species richness changes, while biodiversity metrics based on global habitat extent across species or abundance-based intactness are up to an order of magnitude more sensitive to land-use change (Figure 1b). The uncertainties due to inter-model variation are large, particularly for the climate change impacts which are based on a smaller subset of models, but the trends are still clear (Figure 1b, 1c).

Global averages mask some even larger species reductions at the level of individual grid-cells (Figure 2). During the 20th century, net reductions in local species richness occurred across much of the world, with pronounced losses in Central America, the Andes, the Southeast of Brazil, West Africa, East Africa, South-East Asia, Eastern Australia and South-West Australia, Central North America, Madagascar, New Zealand and the Caribbean (Figure 2a). In the future, some of these regions, particularly in the tropics, are projected to see further biodiversity losses from land-use change (Figure 2b-d), while some regions start seeing losses for the first time, particularly in the Northern boreal regions as forestry activities increase, and regions in central Africa because of conversion to pasture (Figure S1e). In contrast, some areas in Western Europe and Northeast America have seen modest net gains in local species richness during the last century, as a result of farmland abandonment and decrease of forestry (Figure S1c) This pattern is expected to expand in the future to other temperate areas (Figure 2b-c). However, those regions already incurred extinctions before 1900 and these limited increases are not enough to noticeably improve biodiversity intactness (Figure S3).

The three future scenarios exhibit important regional contrasts of biodiversity change. In the global sustainability scenario further land-use-induced losses are moderate and largely restricted to areas that have already been degraded in the last century (Figure 2b). In the regional rivalry scenario, a more regionalized socio-economic development leads to multiple fronts of biodiversity loss across the world including developed and developing regions (Figure 2c), while in the fossil-fueled development scenario a more globalized world sees biodiversity loss concentrated in Southeast South America, Central Africa, East Africa and South Asia (Figure 2d). When climate is also considered, the losses are further exacerbated: losses occur in much of the world, and especially concentrated in the highly biodiverse areas in the Neotropics and Afrotropics (Figure 2e-g). Spatial patterns are broadly consistent across models, although some disagreement exists, particularly regarding areas where local species richness may increase (Figure S4). When relative changes in species richness are compared with absolute changes (Figure S5), it is apparent that the latter are larger in tropical regions and continents (except Australia), as temperate areas and islands often have lower species richness.

During the 20th century, increases material ecosystem services at the global scale, such as food and timber provisioning, were obtained at the cost of regulating services, such as pollination and nutrient retention (Figure 3). The same overall trends and trade-offs are projected for the next few decades, although much less pronounced in the global sustainability scenario, where limited population growth combined with healthy diets and reduction of food waste, leads to the smallest increases in food, feed and timber demand. This, associated with increases in agricultural productivity and other environmental policies, allows for improvements in some regulating ecosystem services and only moderate declines in others. The global sustainability scenario also has the largest increase in bioenergy production as a component of climate mitigation policies, which leads to land-use change (Figure S1a) and impacts on biodiversity (Figure 2b).

In the two other scenarios, larger rates of increase in food and feed, and timber demand are projected (c. 1% yr^{-1}), although smaller than during the last century (c. 3-4% yr^{-1}) due to decelerating population growth, while decreases are projected for crop pest control, coastal resilience, pollination, soil protection, and nitrogen retention (Figure 3). In contrast with the biodiversity projections, the scenario with highest climate change (fossil fueled development) does not generally have more negative consequences for regulating services than the scenario with intermediate climate change (regional rivalry). The exception is that increasing climate change is likely to play a major role in increasing vulnerability of coastal populations.

Surprisingly, little change in total ecosystem carbon is anticipated between scenarios, probably due to CO_2 fertilization effects in higher climate change scenarios (regional rivalry and fossil fueled development; Figure S6) compensating for the decreases in total forest area (Figure S1a). There is some inter-model variation in the projections of individual ecosystem services. Models for some ecosystem services exhibit strong spatial agreement, such as for ecosystem carbon (Figure S7), while for other ecosystem services, models still exhibit some regions of disagreement, such as for food and feed production (Figure S8). Still, in most cases regional or global variation between scenarios is greater than variation between models (Figure 3 and 4).

As with biodiversity, there is high spatial heterogeneity in future ecosystem service dynamics (Figure S9). In the fossil fueled development and regional rivalry scenarios, some regions - Central Africa, East Africa, Southern Africa, South America and South Asia – are projected to see increases of provisioning ecosystem services at the cost of substantial declines of regulating services and biodiversity (Figure 4b and 4c). Some regions such as Oceania, Mesoamerica and North Africa exhibit much lower declines in regulating services in the fossil fueled development scenario than in the regional rivalry scenario. In the global sustainability scenario, the trade-offs are smaller with some regions even registering increases in both provisioning and regulating services, such as the American regions, Eastern Europe, Southern Africa, Central Africa (Figure 4a). However, regional biodiversity still declines in most regions, as significant climate change still happens, and to a lesser extent, as a consequence of land-use change.

Our results suggest that climate change might become a more important driver of biodiversity loss than land-use change by mid-century, in agreement with recent findings based on single metrics (*14*) and in contrast to an earlier review (*10*). One reason for this finding is that future rates of land-use change are not projected to increase in any of the scenarios examined here relative to the last century rates (Figure

S1a). This contrasts with two of the climate change scenarios, where rates of temperature change will still increase in the future (Figure S2). However, these results need to be interpreted with caution. There are differences in how biodiversity models capture the impacts of climate and land-use change and in the spatial grain of these impacts (*21*). Biodiversity models typically use empirical relationships at the local scale between habitat conversion and biodiversity responses and project those relationships at larger scales (*22*). In contrast, the impacts of climate are based on statistical models relating current climate with coarse species distribution patterns and assume that those relationships will hold in the future (*23*). Thus, projections for land-use change impacts are based on observed local impacts while projections for climate change are inferred from macroecological distribution patterns. In addition, our predictions assumed no species migration from climate change in any of the models, while responses to land-use change in some models allowed for species migration or species richness increases (Table S2).

Our analysis suggests that during the 20th century the planet lost almost 0.8% of species from land-use change impacts alone, roughly 70,000 species if one assumes the planet's diversity to be approximately 9 million species (*24*). This rate may vary across taxa, but is consistent with vertebrate extinctions documented by the IUCN (*2*), although some of the documented extinctions have been caused by other drivers which are not included in our models, particularly invasive alien species and direct exploitation. This agreement is even more apparent when one consider the time lags between habitat loss and extinction (*25*), which suggest that some extinctions from historical land-use change are still forthcoming. We also estimate that reductions in local species richness during the last century are around 0.9%. This contrasts with recent studies that have found no trends in local species richness in global meta-analysis of community time series (*26*, *27*). Criticisms to these meta-analysis have emphasized spatial sampling biases, limited duration of time series, and the response metric used (*28*). Our analysis suggests an additional explanation: the signal may be too small to be detectable amongst the noise in available time series.

With the negotiations for a post-2020 strategy and targets underway by the parties to the Convention on Biological Diversity, our scenario analysis delivers a much-needed examination of a range of possible futures and their consequences for biodiversity and ecosystem services. Recently, it has been proposed that society must move from targets about reducing extinction rates to targets for bending upwards the curve of biodiversity loss (*29*). The global sustainability scenario comes close to achieving this for land use only, but even the modest climate change in this scenario leads to an acceleration of biodiversity loss. In addition, we see a much smaller trade-off between provisioning and regulating services in this scenario. These results provide some hope for better protection of biodiversity, particularly because the examined scenarios do not deploy all the policies that could be put in place to protect biodiversity in the coming decades. For instance, in the global sustainability scenario there is still a loss of pasture and grazing land, which are important habitats for many species, further declines in primary vegetation which is a major global driver of species extinctions (*30*), and bioenergy deployment which despite contributing to mitigate climate change can also reduce species habitats (*31*). Introducing further measures such as further regulation of deforestation, increasing effectiveness of protected areas (*32*), stronger changes in consumption patterns (*33*), and sensible natural climate solutions (*34*), could result in even better prospects for biodiversity and ecosystem services. We need to develop a novel generation of global scenarios that aim at achieving positive futures for biodiversity (*35*), to identify better development policies and biodiversity management practices.

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Supplementary Materials:

Materials and Methods
Figures S1-S9
Tables S1-S3
References (*36-80*)

Figures

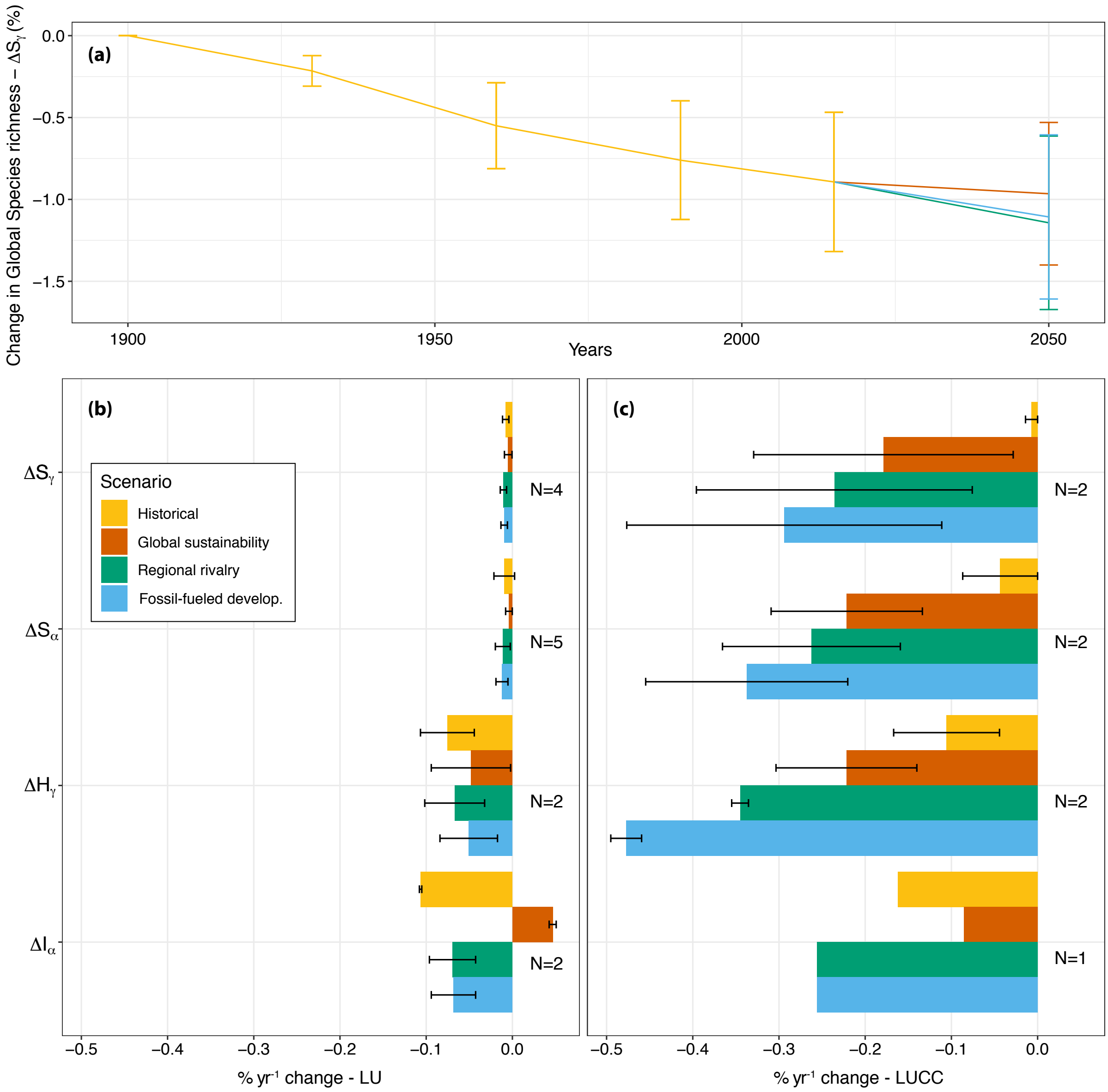

Fig. 1. Historical trends in biodiversity since 1900 and future projections for each scenario to 2050. **(a)** Proportional global species richness change (ΔS_γ) relative to 1900 from land-use change only. Change in different dimensions of biodiversity for the historical period (1900-2015) and for each future scenario (2015-2050): **(c)** from land-use alone; **(d)** from land-use change and climate change combined. Metrics correspond to proportional changes in: global species richness (ΔS_γ), local species richness averaged across space ($\overline{\Delta S_\alpha}$), mean species global habitat extent ($\Delta \dot{H}_\gamma$), and local intactness averaged across space ($\overline{\Delta I_\alpha}$). All values given as means across models with error bars representing standard errors. N is number of models used for metric.

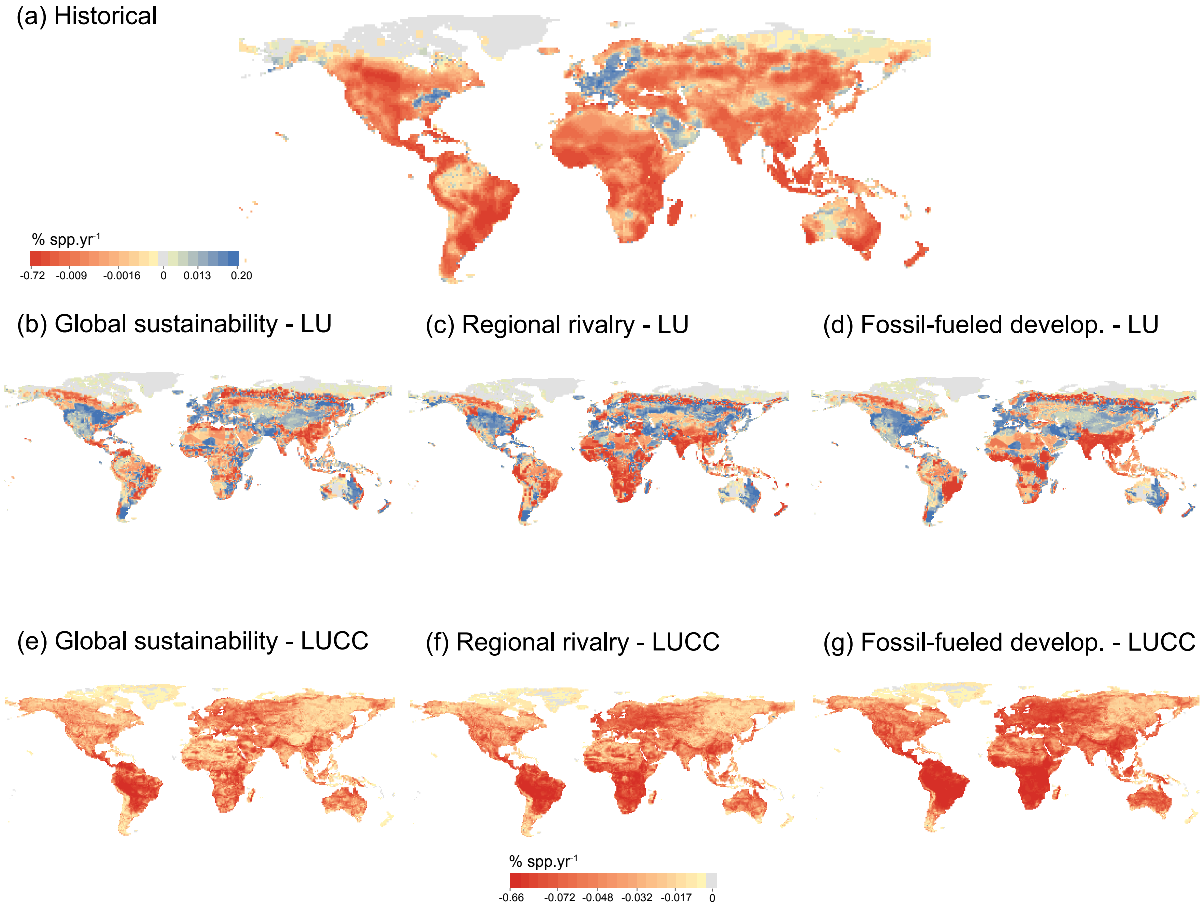

Fig. 2: Spatial distribution of absolute changes in local species richness per year (ΔSS_{α}). **(a)** Historical changes from 1900 to 2015 (number of models, N=5). Future projected changes 2015 to 2050 caused by land-use change alone in each scenario (**b-d**; N=5) and by land-use change and climate change combined (**e-f**, N=2). All values are based on inter-model means and normalized relative to the maximum local species richness in each model (e.g. a value of -50% corresponds to a reduction in species richness equal to half of the maximum species richness across cells). Color scale is based on quantile intervals and differs for **(a-d)** and **(e-g)**.

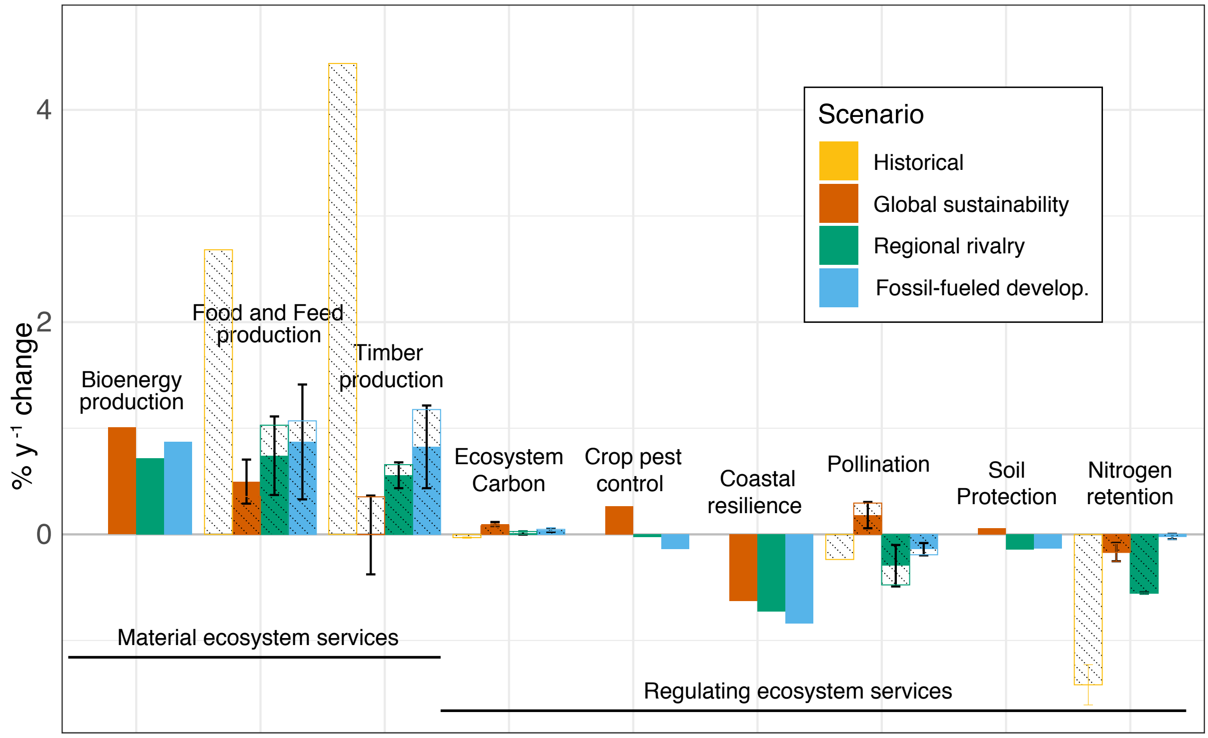

Fig. 3: Historical (1900-2015) rate of changes in material and regulating ecosystem services at the global level and future projections for each scenario (2015-2050). For services assessed with more than one model, reported values are inter-model means and error bars represent standard errors. Dashed bars correspond to the subset of models that project historical changes.

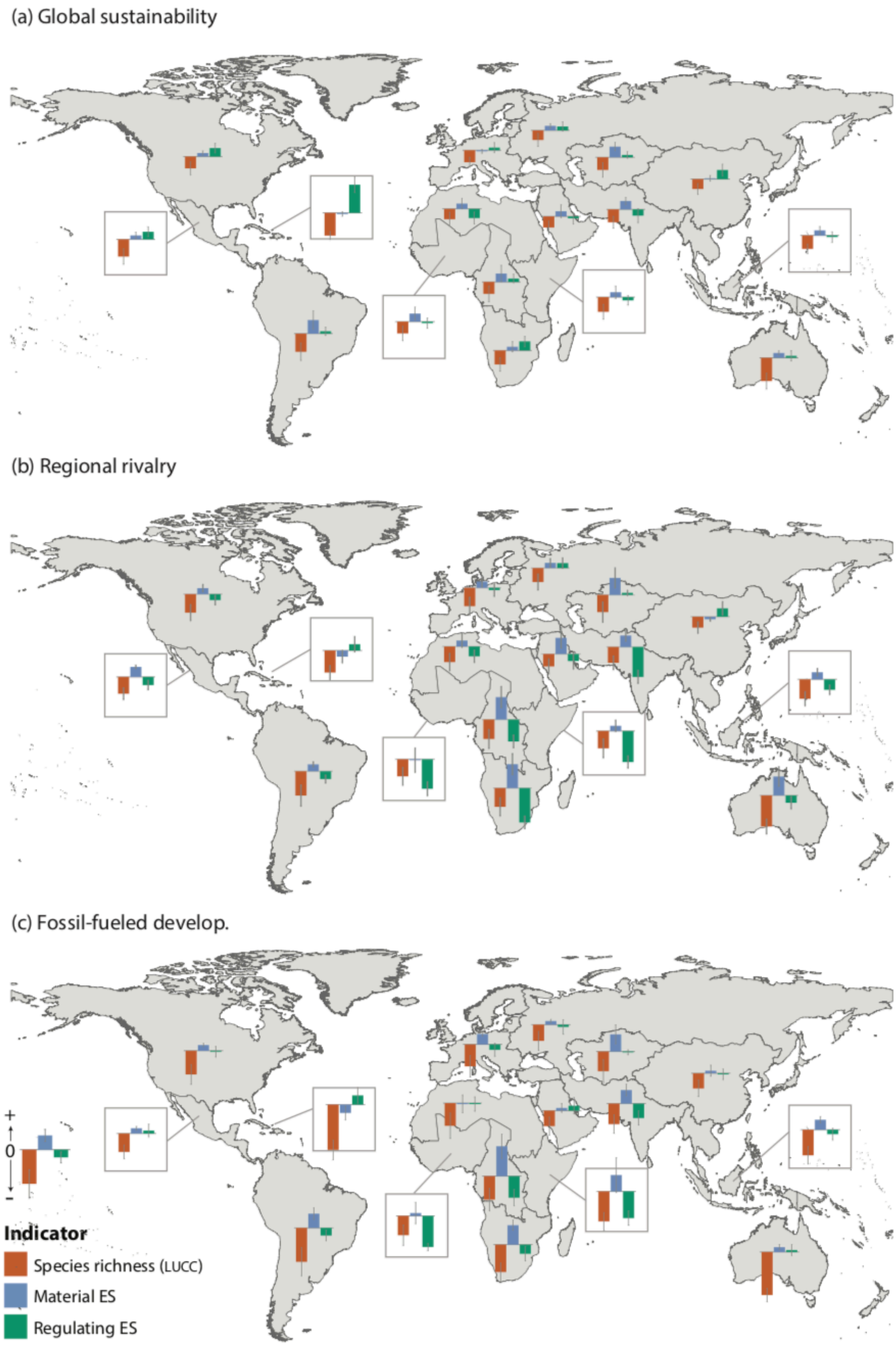

Fig. 4. Projected regional changes in biodiversity and ecosystem services from 2015 to 2050 for (a) Global Sustainability, (b) Fossil-fueled development. Barplots show the average of the normalized values across biodiversity, material ecosystem service, and regulating ecosystem service models. Error bars are standard errors.

Chapter 4

Towards a better future for biodiversity and people: modelling Nature Futures

Towards a better future for biodiversity and people: modelling Nature Futures

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Abstract

The Nature Futures Framework (NFF) is a heuristic tool for co-creating positive futures for nature and people. It seeks to open up a diversity of futures through mainly three value perspectives on nature – Nature for Nature, Nature for Society, Nature as Culture. This paper describes how the NFF can be applied in modelling to support policy. First, it describes key building blocks of the NFF in developing qualitative and quantitative scenarios: i) multiple value perspectives on nature and the frontier representing their improvements, ii) incorporating mutually reinforcing and key feedbacks of social-ecological systems, iii) indicators describing the evolution of social-ecological systems. We then present three approaches to modelling Nature Futures scenarios in review, screening, and design phases of policy processes. This paper seeks to facilitate the integration of relational values of nature in models and strengthen modelled linkages across biodiversity, nature's contributions to people, and quality of life.

Keywords: scenario analysis, biodiversity, conservation, sustainability, values, futures

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1. The need for positive scenarios in transformative change

The Global Assessment of Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) found that existing scenarios developed by the broader climate community (e.g., shared socio-economic pathways [SSPs], representative concentration pathways [RCPs]), even in their most sustainable combinations (i.e., SSP1 and RCP2.6), would fail to halt biodiversity loss and continue to deteriorate regulating ecosystem services into the future in many parts of the world (H. M. Pereira et al., 2020). This comes with potentially large socio-economic consequences (Johnson et al., 2020) and inequitable impacts borne by poorer countries (Chaplin-Kramer et al., 2019).

The drivers of biodiversity loss and other environmental degradation are rooted in population growth and inequality (Hamann et al., 2018), unsustainable production and consumption patterns (Hoekstra and Wiedmann, 2014), provision of environmentally harmful subsidies (Dempsey et al., 2020), poor governance regimes and limited recognition of the importance of biodiversity conservation (Smith et al., 2003), and the firm reliance on fossil fuels (IPCC, 2015) among others. To effectively address these and to increase the willingness to enhance biodiversity conservation policies, we need societal transformations across sectors at all levels concurrently and synergistically (Chan et al., 2020). Furthermore, revitalizing the relationship between people and nature is fundamental in increasing priority for sustainability issues, in particular, but not exclusively, in developed countries (Amel et al., 2017), with a growing share of responsibility on remote biodiversity and habitat loss from natural resource exploitation (Swartz et al., 2010), international trade (Chaudhary and Kastner, 2016) or degraded ecosystem capacity (Marques et al., 2019). We need changes in norms and beliefs that result in behavioural change (Kinzig et al., 2013), aided by effective governance (Amano et al., 2018), financial instruments (Waldron et al., 2017), as well as individual champions who inspire collective action (Amel et al., 2017). Most importantly, optimism and empathy can contribute to responsible actions if actors see that they can make a difference (Blythe et al., 2021; Knowlton, 2019) and when the process engages the imagination of transformative futures (Pereira et al., 2019).

Scenarios that incorporate societal transformation can contribute to reverting negative biodiversity trends and moving towards positive futures (Fischer and Riechers, 2019; Leclère et al., 2020). Here, drawing on a rich plurality of people's values and preferences on nature is key to an improved decision-making (Pascual et al., 2021), ensuring equitable sharing of benefits and responsibilities. Since 2017, a new scenarios and modelling framework is being developed under IPBES to reposition biodiversity and nature at the centre of policy and governance at all levels, recognizing their essential role in supporting human wellbeing and sustainability (Rosa et al., 2017). A series of visioning consultations took place with stakeholders and experts from diverse backgrounds. As a result, the Nature Futures Framework (NFF) emerged to inspire the development of nature and people positive, diverse values-integrated, and multiscale scenarios (L. M. Pereira et al., 2020).

This paper reflects on how the NFF can be applied in modelling Nature Futures scenarios to inform policy. First, we present three key building blocks of the NFF for developing qualitative and quantitative scenarios and models. We then describe three types of applications for integrating Nature Futures scenarios in policy processes. This paper aims to help enhance the utility of scenarios and modelling in the implementation of multiscale policy frameworks such as the Post-2020 Global Biodiversity Framework (GBF) of the Convention on Biological Diversity (CBD) and the United Nations Sustainable Development Goals (SDG) agenda with critical challenges to be overcome.

2. Key building blocks for Nature Futures scenarios

This section presents three key building blocks that are important to incorporate in qualitative and quantitative scenarios of Nature Futures. The order of building blocks does not prescribe the sequences of their application.

2.1 Nature Futures value perspectives and the frontier

Individuals and societies value nature in diverse ways. The NFF attempts to capture these in three main perspectives. The Nature for Nature (NN) perspective appreciates and preserves nature for what it is and does and maps to intrinsic and existence values of biodiversity (e.g., maintaining natural processes and structures such as evolution and migration) (Chan et al., 2016). The Nature for Society (NS) perspective focuses on instrumental values as in benefits nature provides to people (e.g. supporting crop production and climate regulation) (Pascual et al., 2017). Finally, the Nature as Culture (NC) perspective values the relationships that nature and people co-create, not as separate entities but as an indivisible whole (e.g., preserving emblematic species, sacred landscapes, and traditional knowledge) (Himes, 2018). These value perspectives of the Nature Futures Framework are envisaged to broaden and diversify stakeholders' visions for nature and people through exploring, mapping and combing different futures on the gradients such as management intensity, instrumental values and cultural importance of nature (Figure 1).

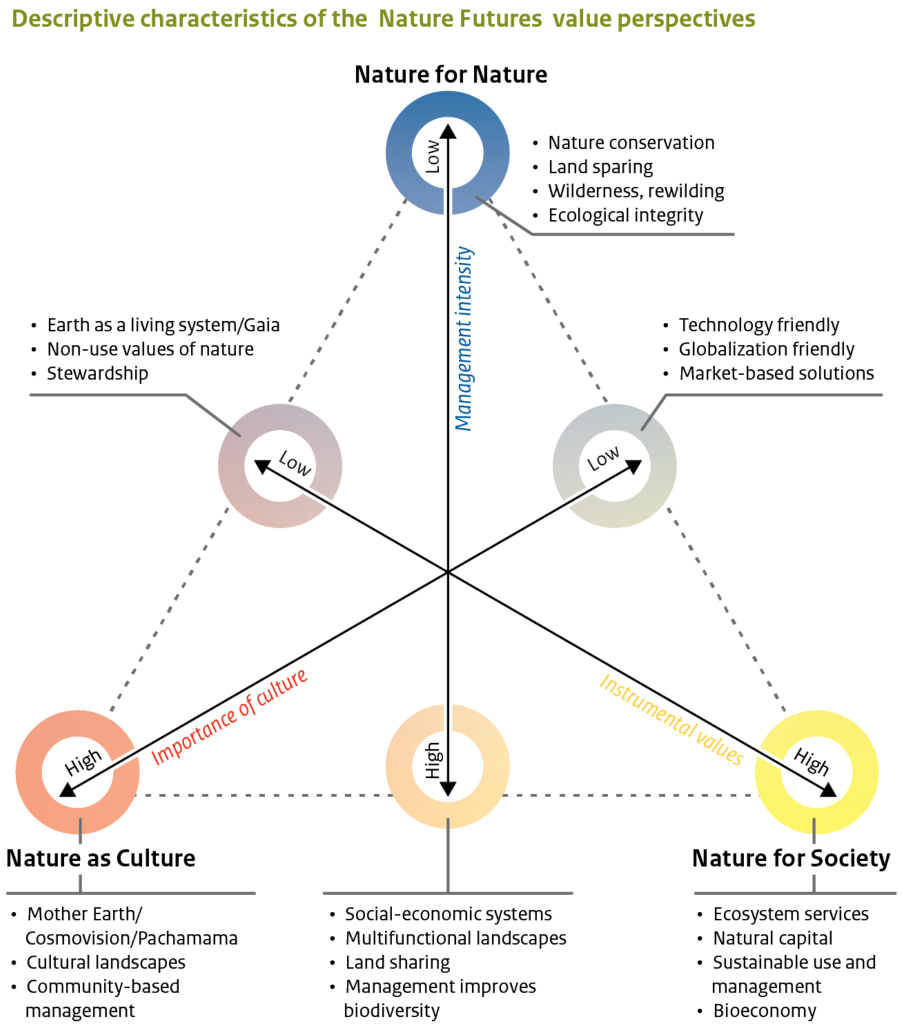

Figure 1. Descriptive characteristics of the Nature Future value perspectives and the space between these perspectives. Most systems and places in the world would have a mix of these values and map somewhere inside the triangle of the Nature Futures Framework.

However, the three value perspectives on nature are not mutually exclusive of each other – in fact, they are intricately connected and can reinforce each other (Martín-López, 2021). Keystone species are such an example with their functional role benefiting both nature and people (e.g., top predators control herbivore populations and reduce damage to crops, animal movements mediate carbon exchange between ecosystems and the atmosphere) (Martin et al., 2020; Schmitz et al., 2018). Thus, although we represent the Nature Futures state space of social-ecological systems with three axes as orthogonal for simplicity (Figure 2a), a more precise representation would have these axes as partially overlapping, as some of the values overlap across the three perspectives (Figure 2b). This means an increase of the values along one axis can per se correspond to an increase along another axis. In some parts of the state space, there may be trade-offs between improvements in the three axes, corresponding effectively to a frontier in the state space (Figure 2a). When the values of a given axis are already very high, further improvements along that axis may only be achievable by decreasing the values along another axis. We do not know the shape of this frontier, but we represent it as a concave surface because the trade-offs in most instances may not be as strong, and for most of the state space, increases are possible across the three value perspectives.

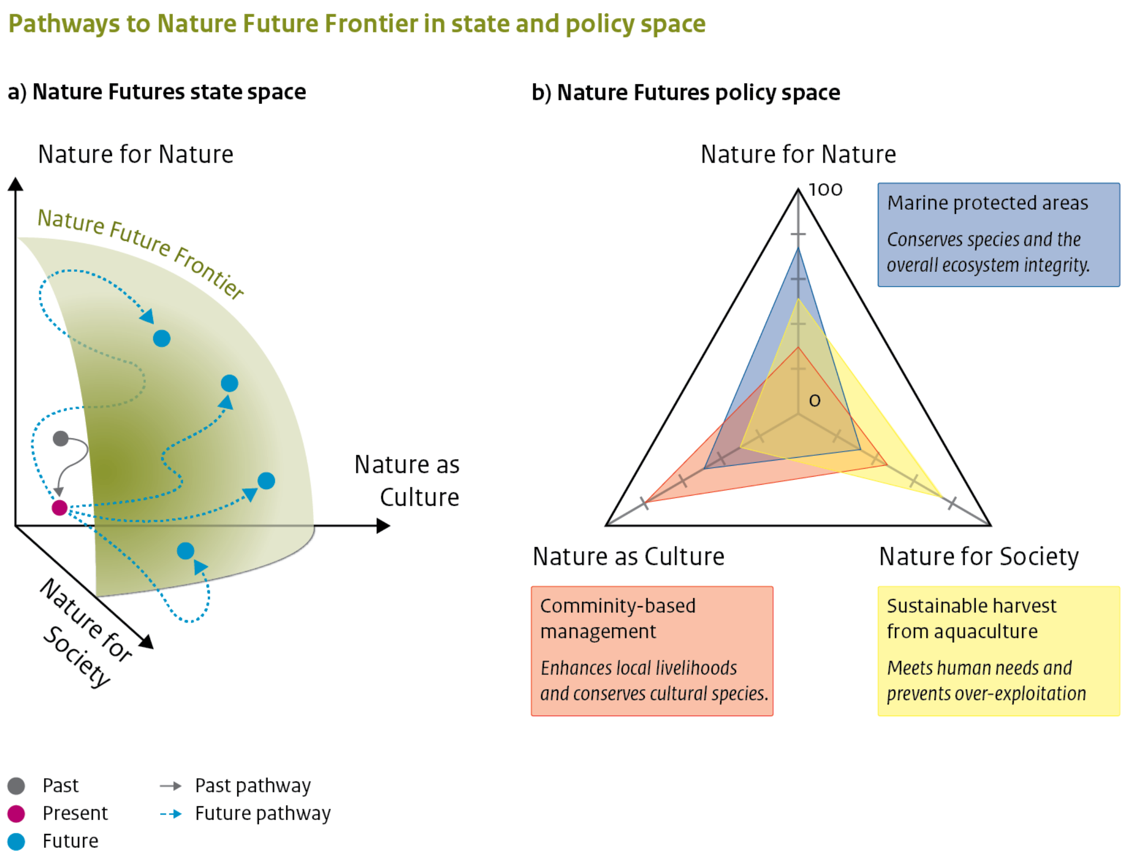

Figure 2. (a) Nature Futures state space and frontier (green concave with blue dots) with multiple pathways to desirable futures where all three value perspectives improve relatively to present. (b) Nature Futures policy space with interventions and indicators scored and mapped across value perspectives for a point in time or as progress over two-time points, illustrated with example policies (blue, yellow and orange triangles).

The state of a social-ecological system can be plotted into a multidimensional state space by evaluating the system on each dimension of the value perspectives (Figure 2a). Conceptually speaking, these perspectives can then be seen as projections representing both the historical pathway of a system from the past to the present and future pathways towards desirable endpoints (so-called 'Nature Futures

Frontier') in this state space (Figure 2a). Typically, desirable Nature Futures correspond to points in the state space where there is an improvement in all three value perspectives into the future relative to the present. We can assess particular actions or policies to see how the system moves towards different points of the state space. To do this, we can score the relative contribution of a given action or policy on the axes representing different value perspectives and map them in a policy space of Nature Futures (Figure 2b). Important to point out that many interventions can be appropriate and are necessary under more than one perspective. In this sense, many systems and future scenarios of Nature Futures would map somewhere inside the NFF triangle with a mixture of interventions with different degrees. As an illustrative example, there are different categories of protection in protected areas – they can strictly limit human access, allow access for active management and recreational use, or be placed in indigenous peoples' land – all with the mixed representation of value perspectives and different short to long term co-benefits and trade-offs.

Furthermore, one can envision a world where different locations are managed exclusively for one of the value perspectives at the more local scale, but at the regional and certainly, at the global scale, all three value perspectives must co-exist given diversity in the scale of geographic coverage. In addition, one can envision futures where all perspectives co-exist in all locations or alternatively a world where there is some spatial segregation of the perspectives, clustering a cloud of points towards the centre or dispersing them across all corners of the frontier.

2.2 Social-ecological systems with feedbacks

Feedbacks between people and nature are central to the IPBES conceptual framework (Díaz, 2015). Understanding these feedbacks is key to understanding what can move the world towards or away from nature and people positive futures. However, only limited social-ecological feedbacks are captured in the existing environmental models (Pereira et al., 2021).

In Nature Futures scenarios, we want to find interventions that lead to improvements in more than one value perspective or even trigger synergies in interventions across the perspectives in social-ecological systems. For instance, securing land ownership and management by indigenous and local communities (predominantly representing NC) can maintain intact habitats to conserve biodiversity (NN), preserving long-standing traditional knowledge and cultural heritage, thereby ensuring societal benefits from sustainable livelihoods (NS) (Dinerstein et al., 2020). Thus, identifying interventions for a specific or combination of nature value perspectives are particularly important for understanding where multiple values are present and can reinforce each other.

Different feedback dynamics are more dominant in each value perspectives of the NFF, but they are not equally well represented in existing models. To date, most modelling approaches have adopted Nature for Nature and Nature for Society perspectives (Robinson et al., 2018), but only partially (e.g., the role of pollination in food provision but not the soil). Furthermore, many models represent agricultural land conversion in which crop production interacts with demand for it to drive land-use change (Lambin and Meyfroidt, 2011) and, in some cases, changes in production feedback to impact human wellbeing (Chaplin-Kramer et al., 2019). But we lack models representing how some interventions such as land-use change result in changes in regulating ecosystem services, and this may, in turn, affect societal decisions so that land-use change processes are altered. The Nature for Nature perspective is represented in ecological models, some of which capture ecological feedback processes such as fire dynamics (McLauchlan et al., 2020), but for instance, the role of keystone species, such as beavers creating wetlands and landscape heterogeneity by felling trees and blocking water flows, is still missing in estimating their eventual contributions to human wellbeing (Willby et al., 2018) (Figure 3).

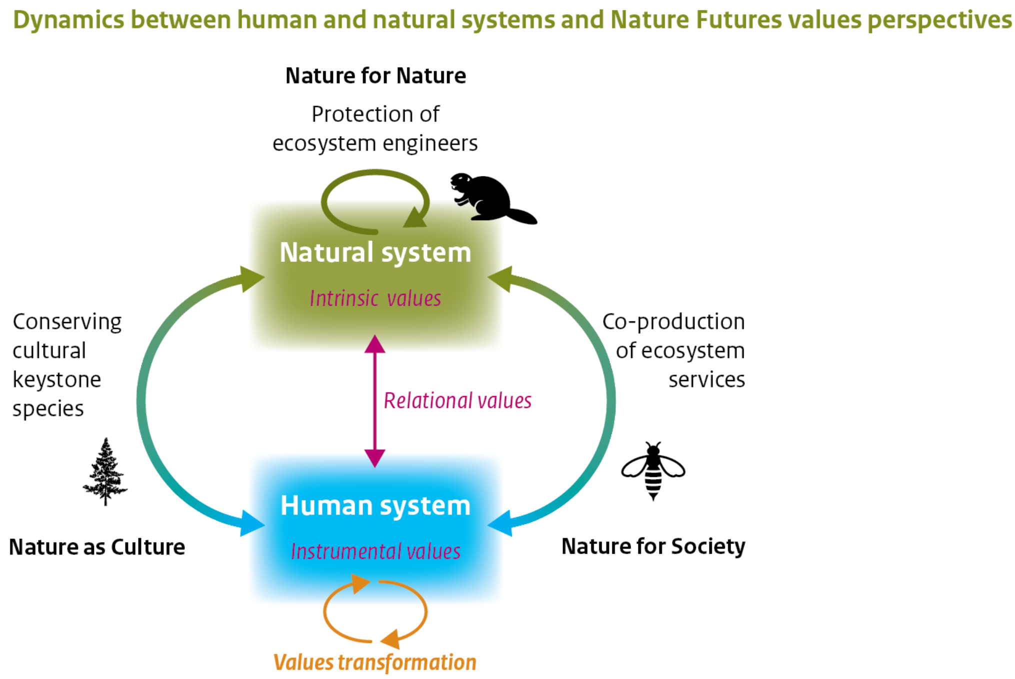

Figure 3. A simple diagram with feedback loops represents the dynamics between human and natural systems within and between the systems that reflect Nature Futures value perspectives.

Feedbacks important for the Nature as Culture perspective are the least understood and modelled. For example, cultural keystone species, such as Western Red Cedar in Coastal British Columbia, connect a web of social-ecological feedbacks in which cultural practices are linked to spiritual traditions and a long-term outlook of the community's livelihood and heritage (Garibaldi and Turner, 2004). However, we do not have models that incorporate social-ecological feedbacks around cultural keystone species. There are initiatives that enhance a structured understanding of the social-ecological feedbacks (Lauerburg et al., 2020; Rocha et al., 2020) with participatory scenarios applied at one system's scale (Sitas et al., 2019). In general, however, coupled social-ecological modelling is still in its infancy and requires further development (Elsawah et al., 2020; Keys et al., 2019).

2.3 Indicators of knowledge and data as multiple evidence bases

Going from the narratives of Nature Futures scenarios to policy support, indicators derived from models, data, and other knowledge systems can build integrative evidence bases for the decision-making (Tengo et al., 2014). Indicators can describe and measure the status, trends, and magnitudes of relationships between components of key social-ecological systems, and help identify models, variables and data required to generate evidence (Guerra, 2019; Gutzler et al., 2015). Methods such as mental mapping, decision tree and multi-criteria analyses can be used to select or derive key indicators to be assessed. To include and to explicit diverse value perspectives on nature, indicators are ideally co-determined and co-developed with stakeholders and users of the information (Miola, 2019; van Oudenhoven et al., 2018).

Using the IPBES conceptual framework and the Nature Futures Framework, interventions can be selected on a range of direct (anthropogenic, natural) and indirect (institution, governance, anthropogenic assets) drivers for exploration and assessment of their potential impacts on goals set on nature, nature's contributions to people and quality of life. As illustrated in Table 3 and Figure 4, interventions and goals can be cross-cutting, for example, supporting community learning facilities that enhance public awareness on conservation and sustainability issues and preventing species extinction and ecosystems degradation for intergenerational equity – or they can have a "home" in one of the value perspectives, as also demonstrated in the policy space of Figure 2b. For life satisfaction as a goal on quality of life, NN can be measured by the enjoyment of experiencing nature and knowing other species are protected, NS from using quality goods from nature and knowing that they are equitably shared or NC from preserving nature-based cultural heritage and thereby maintaining social cohesion (Table 1).

As illustrated, indicators representing diverse roles and benefits of nature can provide rich insights and evidence for assessing changes in social-ecological systems and lead to more integrated and comprehensive analyses, optimization, and prioritization of conservation and sustainability strategies for multiscale policy frameworks such as the CBD GBF and UN SDGs (CBD Secretariat, 2022; Soto-Navarro et al., 2021).

Table 1. Illustrative features of the Nature Future scenarios perspectives with example indicators from existing sources or aspirational ones. The components of the IPBES conceptual framework are used to identify the interventions and goals (rows) across the three Nature Futures value perspectives and those that are cross-cutting (columns).

Framework components	**Cross-cutting**	**Nature for Nature**	**Nature for Society**	**Nature as Culture**
Interventions on indirect drivers - Institutions and governance	Promoting national and international systems and cooperation on biodiversity issues *(e.g., CBD, SDG. Number of countries that have reported legislative, administrative and policy frameworks or measures to implement international environmental treaties)*	Giving legal rights to nature and adequate management capacity to protect nature *(e.g., LIT. number of countries/municipalities that have assigned rights to nature in their constitutions)*	Developing environmentally friendly infrastructure for human settlement *(e.g., SDG 7.b.1. Investments in energy efficiency as a proportion of GDP and the amount of foreign direct investment in financial transfer for infrastructure and technology to sustainable development services)*	Including indigenous and local knowledge on nature in education curriculum *(e.g., LIT. number of countries/municipalities that have education curriculum on indigenous and local knowledge on nature)*
	Implementing agro-environmental measures not perverse to nature conservation and human wellbeing *(e.g., indicator/index measuring the overall impact of agro-environmental measures on nature and people)*	Implementing agro-environmental measures targeting high production on most fertile lands, avoiding biodiverse areas, to spare space for nature *(e.g., % agro-environmental measures allocated to fertile lands and their productivity level)*	Implementing agro-environmental measures targeting maximum co-production of ecosystem services *(e.g., % agro-environmental measures allocated to maximize co-production of ecosystem services)*	Implementing agro-environmental measures targeting environmentally friendly smallholder production in cultural landscapes for local consumption *(e.g., % agro-environmental measures allocated to smallholder production in cultural landscape for local consumption)*
- Anthropogenic assets	Community learning facilities that enhance public awareness and activities on conservation and sustainability issues (*e.g., number of public events on conservation and sustainability topics)*	Creating protection, management and education facilities for wildlife watching *(e.g., number of wildlife watching facilities by protection level, management type, and educational programs)*	Engaging the private sector to deploy nature-based solutions that benefit both nature and people *(e.g., amount of investment of private firms deploying nature-based solutions)*	Establishing community associations for supporting local production and consumption and fair trade *(e.g., INI D2. Trends in consumption of diverse locally-produced food)*
Interventions on direct drivers - Anthropogenic and natural	Designating different types of protected areas *(e.g., CBD AT 11. % of area covered by protected areas by type – marine, coastal, terrestrial, inland water)*	Rewilding of abandoned and degraded land to improve biodiversity, e.g. introduction of large herbivores Reforestation to protect watershed and mangrove areas	Applying nature-based solutions to mitigate climate impact, e.g. afforestation, urban parks, renewable energy like solar and wind power	Community based management (CBM) of natural resources, e.g. other effective area-based conservation measures (OECMs) where wild crop relatives grow

Framework components	Cross-cutting	Nature for Nature	Nature for Society	Nature as Culture
		(e.g., % of total land being rewilded, reforested and restored)	*(e.g., % contribution of NBS to climate change mitigation by type)*	*(e.g., % of total land with wild crop relatives by management type)*
Goals on nature - Biodiversity and ecosystems	Preventing species from extinction *(e.g., CBD AT12 Species Protection Index, number of species prevented from extinction)*	Protecting species important for biodiversity, ecological processes and ecosystem functions *(e.g., protection status of species important for ecosystems)*	Protecting species and ecosystems important for material and regulating services *(e.g., protection status of species important for providing ecosystem services)*	Protecting species and landscape important for local communities and cultural heritage *(e.g., protection status of species important for cultural reasons)*
Goals on nature's contributions to people - Ecosystem services	Preventing degradation of ecosystem functions and services *(e.g. trends in natural ecosystem extent, water regulation)* Equitable sharing of benefits from nature *(e.g., distribution, stocks and flows of ecosystem services by type across regions)*	Advancing remote and longer term benefits from conserving nature *(e.g., % change in carbon capture and sequestration from nature by type – forest, oceans, etc.)*	Provision of immediate material and regulating services from nature *(e.g., % population who benefited from pollination-based crop consumption, % population who benefited from water regulation/nitrogen retention)*	Provision of benefits from nature that communities appreciate for their relational connections *(e.g., # of cultural keystone species, % population that preserved intergenerational cultural heritage from nature)*
Goals on quality of life	Life satisfaction from basic needs met (e.g. food, water, security) *(e.g., SDG 2.5.2 % of undernourished people* *SDG 6.1.1. % of population using safely managed drinking water services, % population that were protected from nature-based coastal risk reduction)*	Life satisfaction from enjoyment of experiencing nature and knowing that other species are being protected *(e.g., % population with life satisfaction from experiencing nature, % population with access to green space within X miles of their residence, % population donating their time or money to environmental causes)*	Life satisfaction from various types of quality goods and services from nature and knowing that they are equitably shared *(e.g., % population with life satisfaction from goods and services from nature, % population that believe nature's benefits should be equally distributed)*	Life satisfaction from preserving nature-based cultural heritage and intergenerational social cohesion *(e.g., INI L1. Possibility to perform traditional occupations (such as pastoralism, hunting/gathering, shifting cultivation, fishing) without restriction as a proxy)*

*Sources: CBD AT: Convention on Biological Diversity Aichi Target, SDG: Sustainable Development Goals, INI: Indigenous Navigator Indicator, LIT: literature

*Note that the assignment of specific interventions to specific value perspectives does not mean that they cannot be used under other value perspectives. It only indicates that they are particularly relevant for that value perspective.

3. Modelling Nature Futures scenarios to inform policy

This section presents three application approaches to modelling Nature Futures scenarios to inform policy processes: policy review, policy screening and policy design and agenda-setting as laid out in the IPBES methodological assessment on scenarios and models (IPBES, 2016) (Table 1).

Table 2. Modelling application of Nature Futures scenarios in policy processes

	Application 1. Policy review *(ex-post)*	**Application 2. Policy screening** *(ex-ante)*	**Application 3. Policy design and agenda setting** *(ex-ante)*
Objectives	Evaluates effects of implemented policies retrospectively in time	Assesses particular policy and management options, often for the short term	Identifies broader goals for policy-making over longer time scales
Policy question (examples)	What were the trends of biodiversity and ecosystem services in the past? What happened in places where particular policies were implemented (e.g., different types of protected areas and their impact)?	What will be the consequences for biodiversity, ecosystem services and quality of life of different policy interventions affecting, particularly, direct drivers (e.g., location and types of protected areas)?	What societal transformations need to occur to achieve long-term visions for people and nature? How do changes in nature's contributions to people affect societal decisions (e.g., how do benefits of protected areas feedback to societal decisions)?
Policy tool (examples)	CBD National Reports	CBD Local and National Biodiversity Strategy and Action Plans	CBD Post-2020 Global Biodiversity Framework
Modelling approaches (examples)	Emphasizes past observations. Counterfactuals can be examined with techniques such as statistical matching or before-after control impact	Models of impacts of direct drivers on biodiversity and ecosystem services models	Integrated assessment models at large scales, dynamic social-ecological models at smaller scales
Key modelling challenges	Integrating time series monitoring in biodiversity and ecosystem services, impact models of diverse drivers	Connecting biodiversity, ecosystem services and quality of life, incorporating a broader set of drivers in impact models	Long term social-ecological feedbacks at large scales, and incorporation of tipping points/regime shift

3.1 Objectives and methods for modelling application

The Nature Futures Framework can be used in exploring a much broader array of interventions, compared to previous environmental scenarios, integrating diverse values, roles and benefits of nature. Thus, it can help identify the interventions and monitor the goals set in policy frameworks at local, national and global scale (e.g., CBD National Biodiversity Strategy and Action Plans, CBD National Reports, CBD Post-2020 Global Biodiversity Framework). The NFF can be applied retrospectively to evaluate the performance of implemented policies and interventions (policy review), assess potential consequences of particular policy and management options (policy screening) or identify broader goals for policy-making (policy design and agenda-setting) (Table 2).

For policy review, evidence synthesis can use methods such as systematic review (Bowler et al., 2010) and meta-analyses (Konno and Pullin, 2020) or impact assessment employing econometric and statistical techniques such as matching (Schleicher et al., 2020) and before-after control impact (Ferraro et al., 2019). Counterfactual analysis of direct drivers on biodiversity and nature's contributions to people can inform where and how biodiversity has been changing due to implemented policies (e.g. protected areas with different priorities on nature, people and culture) compared to those areas where such measures did not take place (Sze et al., 2021). Furthermore, impact models of direct drivers on biodiversity can fill spatial and temporal gaps in historical data that are then key to assess impacts on the ecosystem services (Fernández et al., 2020).

For policy screening, models can predict the consequences for different policy interventions, particularly direct drivers (e.g., location and types of protected areas), reflecting different nature value perspectives on biodiversity, ecosystem services, and quality of life (O'Connor et al., 2021). For these relatively short-term analyses (e.g., one decade), modelling a broader range of direct drivers are more important than incorporating full dynamics of indirect drivers, which may not be necessary or feasible.

For policy design and agenda-setting, a broader set of social-ecological feedbacks should be modelled to identify societal transformation pathways to different Nature Future scenarios in achieving long-term visions, ensuring that the impact of interventions on nature on people inform the future decisions (e.g., how benefits of protected areas inform societal changes). Here, both the modelling of interventions on indirect drivers and the key feedbacks in social-ecological systems are essential in developing robust scenarios (Figure 4).

3.2 Scenario analysis in state space and policy space

For scenarios analyses to support policy using the NFF, a single policy can be scored and mapped in the Nature Futures policy space to assess how the system is likely to evolve along with the three perspectives (Figure 2b). Although most policies will impact the system across the three value perspectives, some policies may particularly favour one perspective over the others. When it is done well in discussion with stakeholders, assigning interventions to different nature value perspectives allows us to evaluate the consequences of different preferences and priorities inherent in decision options.

Furthermore, a combination of policies can be tested through a modelling framework and analyze how the key levers can improve the system along the three axes in the state space and eventually towards the Nature Futures Frontier (Figure 2a). For example, marine protected areas (predominantly representing NN), community-based management (NC) and sustainable harvest from aquaculture (NS) can be assessed individually in the policy space (Figure 2b) or together in an integrated way in the state space (Figure 2a). Furthermore, multiple variables and indicators can be selected to generate Nature Futures scenarios in state space as an output of models (as illustrated in Table 1). A modelling framework can be developed (as shown in Figure 4) to assess the system's state. This means, to represent the evolution of the system quantitatively in a three-dimensional state space, some projections of indicators with a single score per axis are needed into the three Nature Futures axes. For instance, the overall score along the Nature for Nature axis can be calculated by deriving an index across all indicators on the state of nature, nature contributions to people and quality of life associated with Nature for Nature scenarios. To generate indicators that are either common or specific across the three Nature Future value perspectives, an individual to a suite of models can be used to assess the impacts of different drivers on nature, nature's contributions to people and eventually the quality of life, either retrospectively or prospectively (Figure 4).

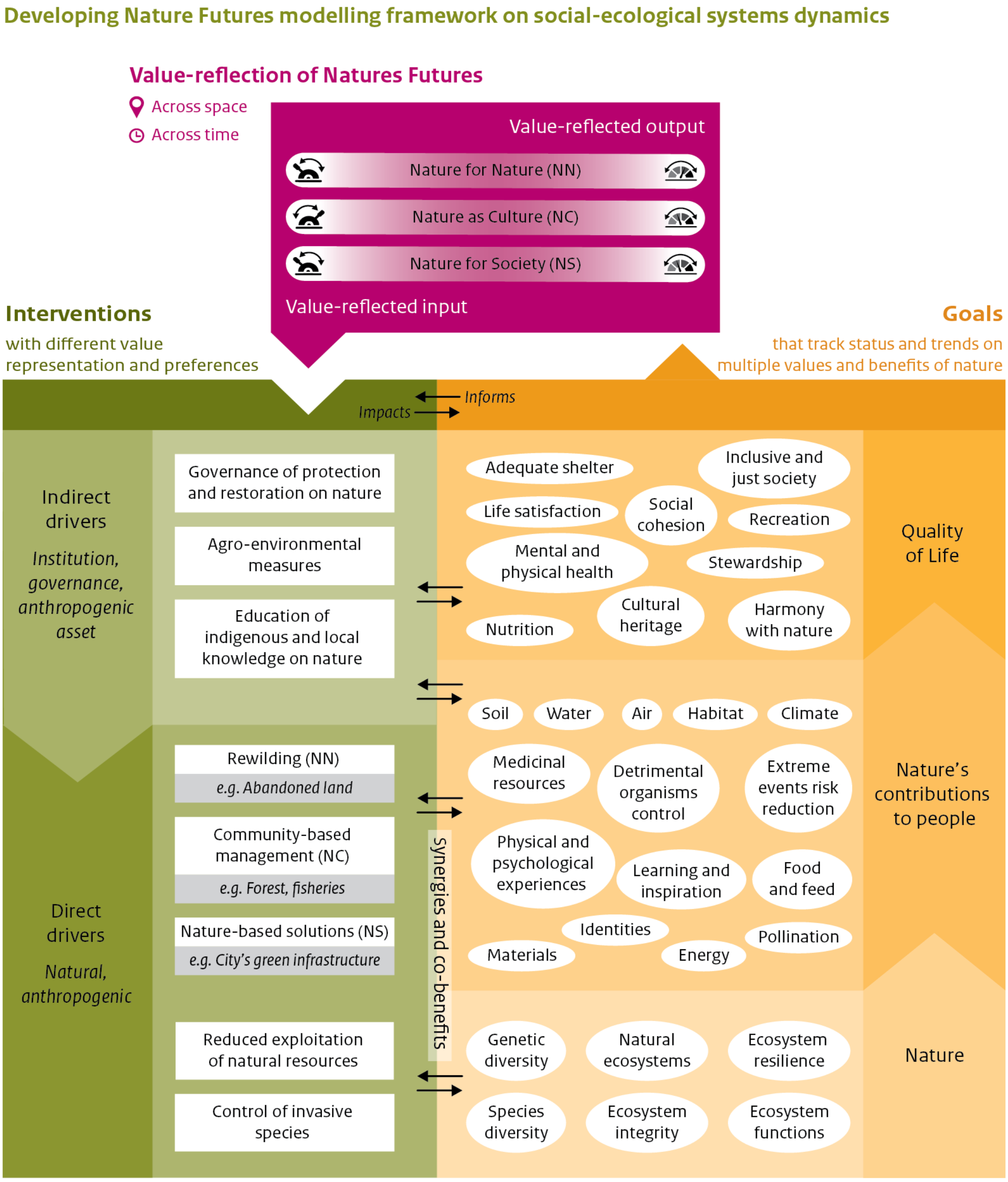

Figure 4. An illustrative modelling framework on the sustainable sea and land use using components of the IPBES conceptual framework with interventions on indirect and direct drivers (left panel) and goals on nature, nature's contributions to people and quality of life (right panel). The Nature Futures scenarios can combine different degrees of nature values to assess the consequences of value reflected interventions (input) on nature and people (output). A few illustrative interventions on direct drivers are rewilding (e.g., abandoned land) primarily, however not exclusively, for Nature for Nature, community-based management (e.g., forest and fisheries) for Nature as Culture and nature-based solution (e.g., green infrastructure) for Nature for Society as value reflected input into modelling, further supported by indirect drivers such as governance, subsidies and education. The state of nature, nature's contributions to people, and quality of life can be measured using multiple indicators to represent diverse values and benefits. The Nature Futures scenarios emphasize identifying synergistic interventions with co-benefits that can reinforce each other onto pathways to the Nature Futures Frontier.

3.3 Key remaining challenges to modelling Nature Futures scenarios

Most modelling approaches have not yet incorporated multiple values of nature or only do so in a limited fashion (Brown et al., 2019). This is particularly true for the relational values of nature. As illustrated, integrating diverse value perspectives in modelling the NFF is essential for a more comprehensive assessment of the consequences of value-reflected decisions on nature and people. (Table 1, Figure 4).

Time-series monitoring data in models of the impacts of direct drivers on biodiversity and ecosystem services remains a key challenge (Rosa et al., 2020). Most existing biodiversity models use space for time replacement in the calibration of models (Walters and Scholes, 2017). This is relevant for retrospective policy evaluation where time-series data are prerequisites for impact evaluation or evidence synthesis. Furthermore, historical observation data and empirical evidence are fundamental for building more rigorous models that predict the future.

An increasing suite of models, variables and indicators are being made available for assessments on biodiversity and nature's contributions to people (Chaplin-Kramer et al., 2020; Kim et al., 2018; Tittensor et al., 2017; Willcock et al., 2020). However, a broader set of drivers needs to be represented in impact models for screening and identifying positive policy interventions that are critically called for in the Nature Futures scenarios (IPBES, 2019; PBL, 2019a).

New models are in development that incorporates feedbacks reflecting the effect of biodiversity and ecosystem services provision factors on economy and vice versa (Banerjee et al., 2020; Johnson et al., 2020). However, long term social-ecological feedbacks at large scales and incorporation of tipping points/regime shift need to be fully considered in Nature Futures scenarios to efficiently inform the policy (PBL, 2019b; Rosa et al., 2017).

Furthermore, uncertainties need to be explored in Nature Futures scenarios, including the models and their structures, methodologies, assumptions, parameters, data and indicators, and from epistemological and ontological differences across sectors, disciplines and cultures (Dunford et al., 2015; Regan et al., 2002; Rounsevell et al., 2021). Common definitions, modelling protocols, standard data format, and further guidance on the application of the NFF will support more consistent scenarios and modelling practices. Importantly, uncertainties associated with Nature Futures scenarios and modelling should be communicated clearly and transparently to the end-users (IPBES, 2016).

4. Moving towards Nature Futures

To date, scenarios and models in environmental assessments have tended to focus on representing human impacts on ecosystems and lacked positive futures for nature and the people (IPBES, 2016; Pereira et al., 2021). Scenarios and models can integrate a broad set of the world's dynamics that can transform people and the nature (L. M. Pereira et al., 2020). To achieve this, the existing models on biodiversity, ecosystem services and social-ecological systems need to be mapped and coupled to form comprehensive frameworks that integrate potential feedbacks across them, improving the representation of globally connected social-ecological systems that exhibit cross-scale interactions (Keys et al., 2019). Furthermore, relational values of nature need to be reflected better in the models and indicators, notably improved capacity in modelling how environmental changes alter human behaviour, institutions, or culture and vice versa (Elsawah et al., 2020; O'Neill et al., 2020).

Model algorithms developed based on observed data are crucial to predicting changes into the future rigorously (Mouquet et al., 2015; Urban et al., 2016), enhancing the credibility of models. We can use a wide range of observation data and correlation based on observed trends in drivers to forecast responses of biodiversity and ecosystems under different policy interventions (Petchey et al., 2015). High-resolution remote-sensing and other observational evidence ("big data"), jointly with advanced machine learning technologies and cloud-based computing, can contribute significantly to increasing the predictive power of changes in biodiversity and nature's contributions to people (Urban et al., 2022; Willcock et al., 2018). Making Nature Futures scenarios truly biodiversity-centric thus presents a critical challenge in biodiversity science to shift the conventional impact modelling of negative anthropogenic drivers on the environment to positive anthropogenic drivers and impacts of biodiversity on nature, and in turn, on people and society, in a full circle.

As elaborated in this paper, the NFF aims to support transformative change towards sustainable futures by placing human-nature relationships at the centre. It bridges across knowledge systems and communities of practices through continuous dialogue, creating a culture of stakeholder-driven scenarios development and their co-implementation while maintaining a minimum consistency and comparability (Lundquist et al., 2017). In the coming years, we expect that the Nature Futures approach will enable scientific and broader stakeholder communities to identify policy and management interventions that reflect diverse ways people can value nature more than we have until now. To achieve this, a participatory approach is being followed to engage stakeholders in developing narratives, engineering models and building evidence bases for solutions to conservation and sustainability issues (PBL, 2019a, 2019b; L. M. Pereira et al., 2020). This inclusive approach is meant to ensure that the information generated from Nature Future scenarios is relevant for and is used by the stakeholders to initiate and amplify necessary societal transformations. Addressing interlinkages, co-benefits and trade-offs between sectors, such as food, biodiversity, water and energy with so-called nexus approaches, will be vital to finding pathways towards achieving multiple societal goals (Liu et al., 2018; Singh et al., 2018). This work is also expected to contribute to the future assessments of IPBES on "transformative change" and "nexus", which were initiated at the eighth IPBES Plenary session in June 2021.

The ambition of Nature Futures is to help expand the integration of nature in policy-making across sectors and better link the efforts of scientists and knowledge holders to values and associated decisions for nature and people positive futures. In an era where combined global environmental changes are at play, marine, terrestrial and freshwater biodiversity is imperilled. The spread of COVID-19 has transformed social-ecological systems, pressing new norms on all societies and bringing a sense of extreme urgency to build back better and greener. The Nature Future Framework presented in this paper is expected to stimulate that development through scenarios and models that can inform the realization of multiscale policy frameworks such as the CBD Post-2020 Global Biodiversity Framework and the UN Sustainable Development Agenda, thereby bringing the world onto pathways towards more ecological, livable and just futures.

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Contributions

HMP coordinated this work as co-chair of the IPBES Expert Group. HJK, HMP, WWLC, SF and GP developed the idea for the manuscript and led discussions and post-workshop synthesis. All authors participated in workshops and contributed to co-developing concepts and approaches presented. HJK led writing and revision with the guidance of HMP. All authors improved the manuscript with comments and corrections. HJK developed figures based on input from all authors and graphical support from Sandy van Tol at PBL. All authors gave final approval for publication.

Chapter 5

Performance of terrestrial protected areas under the Nature Futures prism

Performance of terrestrial protected areas under the Nature Futures prism

[1]HyeJin Kim, Henrique M. Pereira

ABSTRACT

This paper provides a spatio-temporal analysis of essential variables on biodiversity and ecosystems between 2000 and 2018 and ecosystem services between 2000 and 2015 across different categories of protected areas, indigenous land, and the rest of the land as status quo. The analysis uses the new scenarios approach of IPBES – the Nature Futures Framework – and maps protected areas onto the three nature value perspectives of the framework. We assign strictly protected areas without active human management (IUCN I-III) to Nature for Nature (appreciating intrinsic values of nature), protected areas with human interventions for conservation or sustainable use (IUCN IV and VI) to Nature for Society (utilitarian values), and protected areas on the cultural landscape (IUCN V) and the indigenous land to Nature as Culture (relational values). We assess how the state of biodiversity, ecosystems, and ecological supply of nature's contributions to people were in 2000 and how it changed by 2015 or 2018 in these areas compared to the areas without protection (Status Quo). We compare the performance of Nature Future protection regimes across the four IPBES region based on the mean of pixel-level values at the national scale. We find that nature and its ecological supplies to ecosystem services were at its best state and conserved the most in the Nature for Nature protection regime, then Nature for Society and Nature as Culture, then the worst in the Status Quo. There are however heterogeneous patterns at finer scales across the regions. The study highlights the importance of regular evaluation of protected areas on its effectiveness and impact using a broader range of indicators beyond the area measure. It recommends an integrative assessment on diverse roles, values and benefits of nature for an effective implementation of the CBD Post-2020 Global Biodiversity Framework with broader stakeholders.

INTRODUCTION

The global community is developing new strategies for conserving biodiversity for the next decade with the Convention on Biological Diversity (CBD). There is hopeful anticipation that the new strategies and goals endorsed by the member states in the Post-2020 Global Biodiversity Framework (GBF) will be better implemented by the nations and subnational governments in the coming years (Perino *et al.* 2021). The Post-2020 GBF currently proposes twenty-one action targets on a range of direct and indirect drivers relevant for biodiversity change and four goals on biodiversity, ecosystems, and ecological supply of nature's contributions to people with equity and enabling conditions (UN CBD 2021). For an effective delivery of the CBD Post-2020 GBF, a regular monitoring of interventions set in achieving targets and assessing their impacts on the performance against the goals set on nature will be critical (Kim *et al.* 2021). For instance, the questions should be raised to answer if interventions such as protected areas (Target 3 of Post-2020 GBF) contribute effectively to conserving biodiversity and ecosystems (Goal A) and to benefiting people's wellbeing and livelihood (Goal B), and if this information further informs future decisions for a continuous improvement of interventions in the implementation phase of the GBF.

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Protected areas have long been a cornerstone intervention for biodiversity conservation. Today, 16.64% of terrestrial land is protected, and it is one of the few Aichi targets achieved in the 2010-2020 CBD global biodiversity strategies (CBD Secretariat 2020). There have been different successes, challenges, and implications of protected areas in conserving biodiversity (Watson *et al.* 2014; Pimm *et al.* 2018; Visconti *et al.* 2019; Maxwell *et al.* 2020; Rodrigues & Cazalis 2020). Numerous studies have evaluated whether protected areas are placed in most biodiverse areas or if they cover habitats for critically endangered or vulnerable species from extinction (Rodrigues *et al.* 2014; Venter *et al.* 2014; Jenkins *et al.* 2015). Increasing number of impact evaluation are being conducted on the effectiveness of protected areas using counterfactual analysis (Joppa & Pfaff 2011; Ferraro *et al.* 2019; Geldmann *et al.* 2019).

Recent global analyses found that forest loss was reduced, local biodiversity was measured higher and threatened or endangered forest species were conserved better in protected areas than in unprotected areas (Gray *et al.* 2016; Leberger *et al.* 2019; Cazalis *et al.* 2020). Furthermore at the national level, protected areas were found effective in reducing deforestation in Coasta Rica (Andam *et al.* 2008) while decentralized forest management was found to reduce deforestation and alleviate poverty in Nepal (Oldekop *et al.* 2019). Over the years, conservation scientists suggested integrating multidimensional indicators for measuring the effectiveness of protected areas (Chape *et al.* 2005), considering the growing impact of urbanization in protected areas (Mcdonald *et al.* 2008), and adopting a coordinated network approach in determining local and national targets within and across the region in achieving global goals more effectively (Le Saout *et al.* 2013; Rodrigues & Cazalis 2020).

Today, increasingly more data are being made available to assess non-material values of nature to society, and there is a growing consensus on the critical role that indigenous and local communities play in the nature stewardship (Dinerstein *et al.* 2020; Sze *et al.* 2021). Engaging local communities in regional conservation planning and assessing social impacts of protected areas on local livelihoods are, therefore, key to its success (Naughton-Treves *et al.* 2005; West *et al.* 2006). Furthermore, exploring diverse values and benefits of nature, reflecting them in the assessments of conservation interventions, and explicating them in decision contexts can help examine the consequences of protecting biodiversity more comprehensively and fairly for all stakeholders.

In this study, we ask two main questions: 1) what was the state of biodiversity, ecosystems, and the ecological supply of nature's contributions to people across different terrestrial protected areas, indigenous land and the rest of the land in 2000, and 2) how did they change to 2015 (or 2018) across the IPBES regions and the globe on national average? We respond to these questions through the lens of the Nature Future Framework, a new scenarios and modelling framework under development by the IPBES community – using the essential variables from biodiversity and ecosystem services model (Pereira *et al.* 2013; Rosa *et al.* 2017; Pereira *et al.* 2020b; Balvanera et al. In review; Fernandez In review). We mapped different categories of protected areas designated before 2000 to the three Nature Futures value perspectives – Nature for Nature, Nature for Society, Nature as Culture – as an intervention layer for a retrospective evaluation (Dudley 2013; Garnett *et al.* 2018; UNEP-WCMC 2019) (see Table 1 for description). In this study, we chose the strictness of protection and the intensity and types of human management as criteria for mapping protected areas to different Nature Future protection regimes. Important to note is that the three nature value perspectives in the framework can overlap with synergistic effects in terms of short to long term benefits (Kim *et al.* 2021). Therefore, these mapping of interventions to nature value perspectives can be different depending on the objectives and the context of the study. This analysis aims to demonstrate how diverse roles, values and benefits of nature can be integrated into a retrospective policy evaluation to regularly inform decisions in conserving biodiversity.

Table 1. Descriptions and primary objectives of protected areas by category mapped to Nature Futures Framework (Source: (Dudley 2013)

NATURE FUTURES	IUCN CATEGORY	DESCRIPTION	PRIMARY OBJECTIVES
NATURE FOR NATURE	**Ia** Strict nature reserve	Category Ia are strictly protected areas set aside to protect biodiversity and also possibly geological/geomorphological features, where human visitation, use and impacts are strictly controlled and limited to ensure protection of the conservation values. Such protected areas can serve as indispensable reference areas for scientific research and monitoring.	To conserve regionally, nationally or globally outstanding ecosystems, species (occurrences or aggregations) and/or geodiversity features: these attributes will have been formed mostly or entirely by non-human forces and will be degraded or destroyed when subjected to all but very light human impact.
	Ib Wilderness area	Category Ib protected areas are usually large unmodified or slightly modified areas, retaining their natural character and influence, without permanent or significant human habitation, which are protected and managed so as to preserve their natural condition.	To protect the long-term ecological integrity of natural areas that are undisturbed by significant human activity, free of modern infrastructure and where natural forces and processes predominate, so that current and future generations have the opportunity to experience such areas.
	II National park	Category II protected areas are large natural or near natural areas set aside to protect large-scale ecological processes, along with the complement of species and ecosystems characteristic of the area, which also provide a foundation for environmentally and culturally compatible spiritual, scientific, educational, recreational and visitor opportunities.	To protect natural biodiversity along with its underlying ecological structure and supporting environmental processes, and to promote education and recreation.
	III Natural monument or feature	Category III protected areas are set aside to protect a specific natural monument, which can be a landform, sea mount, submarine cavern, geological feature such as a cave or even a living feature such as an ancient grove. They are generally quite small protected areas and often have high visitor value.	To protect specific outstanding natural features and their associated biodiversity and habitats.
NATURE FOR SOCIETY	**IV** Habitat/ species management area	Category IV protected areas aim to protect particular species or habitats and management reflects this priority. Many category IV protected areas will need regular, active interventions to address the requirements of particular species or to maintain habitats, but this is not a requirement of the category.	To maintain, conserve and restore species and habitats.
	VI Protected area with sustainable use of natural resources	Category VI protected areas conserve ecosystems and habitats, together with associated cultural values and traditional natural resource management systems. They are generally large, with most of the area in a natural condition, where a proportion is under sustainable natural resource management and where low-level non-industrial use of natural resources compatible with nature conservation is seen as one of the main aims of the area.	To protect natural ecosystems and use natural resources sustainably, when conservation and sustainable use can be mutually beneficial.
NATURE AS CULTURE	**V** Protected landscape/ seascape	A protected area where the interaction of people and nature over time has produced an area of distinct character with significant ecological, biological, cultural and scenic value: and where safeguarding the integrity of this interaction is vital to protecting and sustaining the area and its associated nature conservation and other values.	To protect and sustain important landscapes/seascapes and the associated nature conservation and other values created by interactions with humans through traditional management practices.

METHODS

We first looked at how different countries have designated protected areas before 2000 through the Nature Futures lens, mapping protected areas to different nature value perspectives. We then assessed the status of biodiversity and ecological supply of nature's contributions to people in the baseline 2000 and how it changed to year 2015 (or 2018) across the Nature Futures protection regimes and in unprotected land. We used five essential biodiversity and ecosystem services variables as response variables. The area of habitat based species richness for the mammals was used as a proxy indicator for biodiversity (Lumbierres *et al.* 2021) and natural and semi-natural ecosystem extent was used as a proxy indicator on ecosystems (Remelgado & Meyer 2020). For nature's contributions to people, the ecological supply proxies of pollination, nitrogen retention and coastal risk were used (Chaplin-Kramer *et al.* 2020). The geospatial maps on these five variables were available for 2000 and 2018 for biodiversity and ecosystems (BES) and for 2000 and 2015 for ecological supply of nature's contributions to people (NCPs) at either 300m or 1km resolution (see SM Table 1). We derived the mean of pixel-level values at the national level for each of the three Nature Future protection regimes (NN, NS, NC) and for the rest of the land as status quo (SQ) and compared these national values in four IPBES regions and globally. We looked at the state of BES and NCPs in the baseline year 2000 and their relative change values to 2015 or 2018 from the baseline. We conducted statistical analyses to assess if the state and trends in BES and NCPs were significantly different between the Nature Future protection regimes and the rest of the land, keeping protected areas constant at pre-2000 to roughly account for the time lag in their impact on nature.

Data

Nature Futures intervention map with protected areas and indigenous land: The intervention layer of Nature Future protection regimes used two data sources - World Database on Protected Areas (WDPA) downloaded in June 2020 and indigenous people's land published by Garnett and colleagues in 2018 (Garnett *et al.* 2018; UNEP & IUCN 2020). The IUCN categories of protected areas were grouped into three Nature Futures value categories based on protected area's primary objectives and management styles (Dudley 2013). IUCN categories I to III with comparatively strict protection and limited human management were assigned to Nature for Nature (NN). IUCN categories IV and VI with active human management for conservation or sustainable use of nature were assigned to Nature for Society (NS). IUCN category V of landscape with conservation and other values created through traditional management were assigned to Nature as Culture (NC). Only the protected areas with polygons were used as point data did not have the spatial information required for this analysis. We only used protected areas designated before year 2000, excluded the ones with status as 'not reported' or 'proposed', and also removed those with more than 90% as marine areas (MARINE=2). To remove the overlapping protected areas within and across IUCN categories, polygons were rasterized for each IUCN category in a hierarchical order of Ia, Ib, II, III, IV, V, and VI. The IUCN categories 'Not Assigned', 'Not Reported', 'Not Applicable' were grouped into NAs to account for their protection but were treated separately from the main Nature Futures categories and not included in the Status Quo (SQ). We used Indigenous Land polygons published in Garnett et al 2018 and assigned it to Nature as Culture (NC) together with the IUCN category V. This additional map was included between the IUCN category V and VI when removing the overlap. All rasterization was done at 300m resolution to match the highest resolution of datasets on response variables. For the analysis, we excluded those countries and overseas territories smaller than 1000km^2 because in several cases, the entire country or island was covered as protected areas potentially due to large marine protected areas with some terrestrial areas. A total of 169 countries were included in this study with their mean values on Nature Future protection regimes

(NN, NS, NC, SQ). We used the geographic coordination system WGS84 on all geospatial maps. The intervention map and statistics by country is in SM Figure S2 and Table S2.

Area of habitat-based species richness: Area of Habitat (AOH) is the 'habitat available to a species, that is, habitat within its range' produced by subtracting areas of unsuitable land cover and elevation from the range (Brooks *et al.* 2019). AOH uses IUCN Habitats Classification Scheme and unvalidated expert opinion to associate species habitat to land cover classes. Lumbierres and colleagues developed a data-driven and model-based method to classify IUCN habitat classes to land-cover based on point locality data using logistic regression models (Lumbierres *et al.* 2021). We used species-specific AOH maps provided by Lumbierres et al. and stacked them across the 5,519 mammal species for the global species richness map based on the total number of species inhabiting in each pixel at 300m resolution with binary data (presence or absence). Additional metadata are provided in SM Table S1 with maps in SM Figure S3 and summary statistics in SM Table S3.

Natural and semi-natural ecosystem extent: The GlobES data cube includes an annual extent of ecosystems following the IUCN Red List habitat classification scheme used in the assessment of over 100,000 species. This data cube is composed by 59 ecosystem types from 1992 to 2018 and each layer depicts per-pixel areas of a given ecosystem within a given year. To develop the individual ecosystem maps, Remelgado and Meyer interpreted the interaction of 59 environmental variables that define ecosystem types, which was derived from 24 global state-of-the-art datasets, including remotely sensed and in-situ measurements of vegetation and abiotic land-surface cover, climate, soil, coastal and stream topography, and other environmental dimensions (Remelgado & Meyer 2020). We used the total occupancy of natural and semi-natural (non-artificial) ecosystems with a maximum value of 85.99 hectare in each pixel at 1km resolution provided by Remelgado and Meyer. The natural and semi-natural (non-artificial) ecosystems include forest, savanna, shrubland, grassland, freshwater, rocky, desertic, and coastal ecosystems and exclude dry and inundated (artificial) ecosystems. Additional metadata are provided in SM Table S1 with maps in SM Figure S4 and summary statistics in SM Table S3.

Ecological supply of pollination (around farmland): The InVEST pollination module models the potential contribution of wild pollinators to nutrition production (Chaplin-Kramer *et al.* 2019, 2020). We used the pollination sufficiency dataset from the model as the ecological supply proxy of pollination around farmland, which is based on the area of pollinators' habitat around farmland. The pollination sufficiency maps are agricultural pixels with more than 30% of natural habitat in the 2 km area surrounding the farm. These agricultural pixels are designated as receiving sufficient pollination for pollinator-dependent yields and the pixel values were rescaled from 0 (0% of natural habitat) to 1 (30% of natural habitat) (Kremen *et al.* 2004). We used these pollination sufficiency values at the pixel level in 300m resolution provided by Chaplin-Kramer et al. Additional metadata are provided in SM Table S1 with maps in SM Figure S5 and summary statistics in SM Table S3.

Ecological supply of nitrogen retention: The InVEST Nutrient Delivery Ratio module models nitrogen load, export, and retention (the difference between load and export) by mapping nutrient sources from watersheds and their transport to the stream (Chaplin-Kramer *et al.* 2019, 2020; Natural Capital Project 2022b). The nutrient load across landscape is determined based on land use land cover map and associated loading rate of nutrient sources. The delivery factors are computed for each pixel belonging to the same flow path based on slope and retention efficiency of the land use. The model represents the long-term, steady-state flow of nutrients through empirical relationships but does not include nutrient cycle. We use the ecological supply proxy of the nitrogen retention which is the nitrogen export subtracted from the modified load of nitrogen in kilogram at the pixel level in 300m resolution provided by Chaplin-Kramer et al. Additional metadata are provided in SM Table S1 with maps in SM Figure S6 and summary statistics in SM Table S3.

Ecological supply of coastal risk reduction: The InVEST Coastal Vulnerability Module models the potential contribution of coastal habitat to coastal risk reduction through attenuation of storm waves and shoreline stabilization which reduces impacts from flooding and erosion (Chaplin-Kramer *et al.* 2019, 2020; Natural Capital Project 2022a). This model produces a qualitative index of coastal exposure to erosion and inundation in a range of 1 (lowest risk) to 5 (highest risk), derived from six bio-geophysical variables: natural habitats, sea level change, wind exposure, wave exposure, relief, and surge potential depth contour. Exposure to coastal risk is assessed through a ranked index on a variety of physical factors determining the exposure of coastline to coastal hazards. The contribution of coastal habitats (e.g. coral reefs, mangroves, seagrass) to mitigating that risk is used as an ecological supply proxy of coastal risk reduction (i.e. coastal risk with mitigating natural habitat – coastal risk without mitigating natural habitat), which is calculated at shore-points where the exposure to coastal risk occurs, and is then mapped back to habitat based on the protective distance of the habitat from the shore. This index values were provided at a pixel level in 300m resolution by Chaplin-Kramer et al. Additional metadata are provided in SM Table S1 with maps in SM Figure S7 and summary statistics in SM Table S3.

IPBES region shapefile: We used the IPBES shapefile published and accessible on Zenodo for national administrative and IPBES regional boundaries (IPBES TSU Knowledge and Data 2020).

Analysis

Country averages for 2000 and 2015/2018: We used individually rasterized Nature Future protection regime layers – NN, NS, NC, SQ – and multiplied them to raster datasets of response variables on BES and NCPs (i.e., essential variables) using ArcGIS version 10.7.1. We then calculated the mean of pixel-level values for each of Nature Future regime categories for the two-time steps at the national level using the administrative boundaries in the IPBES shapefile. We kept the original unit of all five response variable datasets at the pixel level and used the raster calculator and zonal statistics functions in ArcGIS. These country means were tabulated as datasets for statistical analyses in R. The analytical framework of this study is provided in SM Figure S1.

Statistical model for state analyses: To respond to the first research question if the state of BES and NCPs was different across the Nature Future protection regimes and across the four IPBES regions, we used a generalized linear regression model with two categorical variables using the equation [$EBVt_0 \sim NFF + Region$] and the R package 'stats'. The first categorical variable was the Nature Futures regimes (variable: NFF) with unprotected land (SQ) as the reference group to test if there was a significant difference between Nature Futures categories and the Status Quo. The second categorical variable was the IPBES regions (variable: Region) with Europe and Central Asia as the reference group as this region had an overall lowest performance on BES and NCPs in the baseline year 2000. Different Link function was used based on the characteristics of each response variable. Of the five response variables, area of habitat-based species richness (dataset: AOHSR) used the Link function 'log' under the gaussian family as data was continuous and positive with a slightly right tailed distribution. The natural and semi-natural ecosystem (dataset: NATECO) variable used the "identity" Link function under the gaussian family as the data is continuous and positive with a relatively normal distribution. We applied the "logit" Link function under the quasibinomial family for the ecological supply of pollination variable (dataset: POLLECO) since this data is proportional between 0 to 1 with a severe left-tailed distribution. Then Link function "log" under the Gamma family was used for the ecological supply of nitrogen retention (dataset: NITREECO) as this data is continuous with a right-tailed distribution. The ecological supply of coastal risk reduction (dataset: COASTECO) used the Link function “log” under the gaussian family as data is positive and continuous with a slightly right tailed distribution. The ANOVA Chi and F tests were conducted on each response variable’s model to test the overall significance of the model. We ran Tukey contrasts to test the significance in the difference of means between all categories of the two categorical variables. The R codes and results of the statistical models are in SM Models S1.

Statistical model for trend analyses. To respond to the second research question if there were changes in BES and NCPs between 2000 and 2015 (or 2018) across the Nature Futures protection regime and the four IPBES regions, we calculated the relative percent change in 2015 (or 2018) from the baseline year 2000. We ran linear regression models with two categorical variables using the equation [(EBVt_1-t_0 /EBV t_0)*100 ~ NFF + Region] and the R package ‘stats’. The categorical variables and their reference groups were the same as the generalized linear regression model for the state analyses. All five response variables’ relative percent change values were normally distributed, so we did not transform data. The ANOVA Chi and F and Tukey contrasts were conducted similarly to the state analysis to test the significance of the model and the differences between each category of the categorical variables. The R codes and results of the statistical models are in SM Models S2.

RESULTS

Pre-2000 Nature Futures land protection regimes

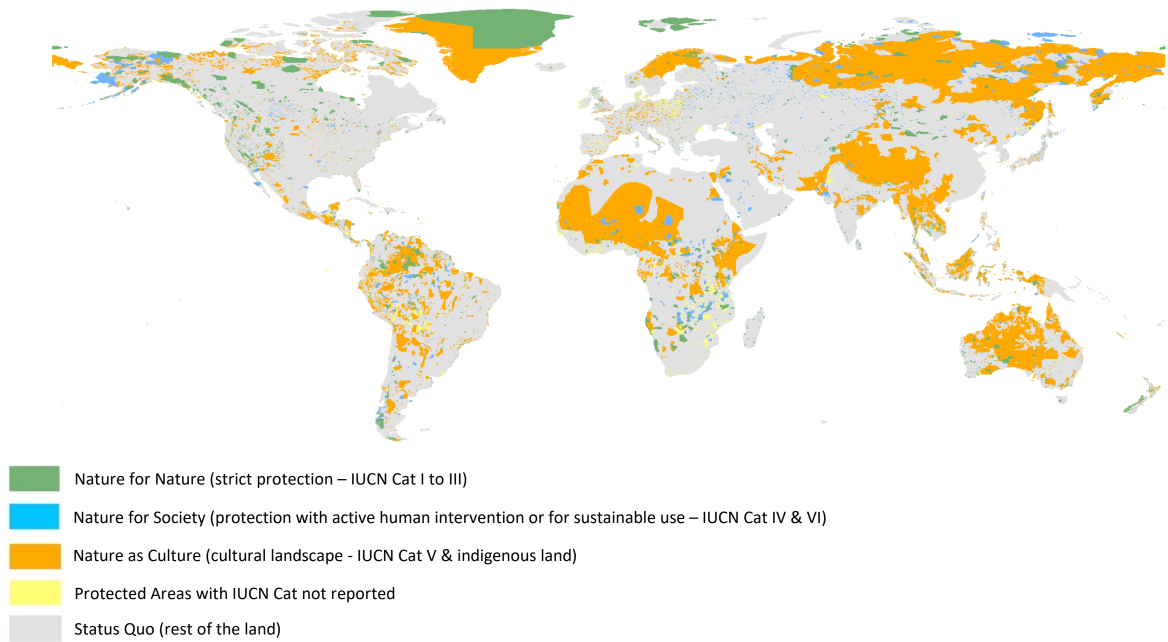


Figure 1. The intervention map of protected areas designated before 2000 and indigenous land mapped to the Nature Future protection regimes with the rest of the land as Status Quo.

As shown in Figure 1, about two-thirds of the earth’s land (62%) were neither protected nor in indigenous territories before 2000. Of those protected, we could not assign about 2.6% of the land to any of the Nature Future protection regimes because they did not have an IUCN category and, therefore, they were omitted from the analysis. Globally, 6% of terrestrial land was for Nature for Nature, 2% for Nature for Society, and 29% for Nature as Culture (also see SM Figure S2, Table S2). In Africa, 3% of land was for Nature for Nature and Nature for Society, with 32% for Nature as Culture. In the Americas, 11% was for Nature for Nature, 2% for Nature for Society, and 17% for Nature as Culture. In Asia and the Pacific, 3% was for Nature for Nature, 1% for Nature for Society, and 33% for Nature as Culture. Finally, in Europe and Central Asia, 3% was for Nature for Nature, 4% for Nature for Society, and 39% for Nature as Culture. The proportion of protected areas mappable to Nature for Nature and Nature for Society were small under 4% in all regions except for the Americas' Nature for Nature (11%). Within each Nature Futures regime, the Americas had the most portion of land for Nature for Nature (68%) and Europe and C. Asia had the largest for Nature for Society (42%) before 2000.

State of nature across the Nature Future protection regimes and IPBES regions in 2000

Our data show that the global means of national mean values were the highest in Nature for Nature, then similarly in Nature for Society and Nature as Culture next and the lowest in the Status Quo on all five BES and NCP response variables in 2000 (Figure 2). Our generalized linear model results show that Nature for Nature had a significantly higher global mean in species richness (0.12±0.06), natural and seminatural ecosystems (12.86±1.91), and ecological supply of pollination (1.21±0.12), nitrogen retention (-0.27±0.08), and coastal risk reduction (0.13±0.06) compared to the Status Quo (Table 2, SM Models S1). Nature for Society and Nature as Culture also had significantly higher global means for natural and semi-natural ecosystem extent (9.36±1.94, 4.80±1.92) and pollination (0.76±0.11, 0.59±0.11) compared to the Status Quo. At the regional level, the Americas had significantly higher means than the reference group Europe and Central Asia on all BES and NCP response variables (Table 2). In Africa, we see similar trends except for pollination with no significant difference. In Asia and the Pacific, natural and semi-natural ecosystem extent and the coastal risk reduction had significantly higher means (9.72±1.90, -0.12±0.05), and the pollination had a lower mean (-0.25±0.11) than Europe and Central Asia.

Table 2. Generalized linear model results (mean, s.d. and p-value) on five response variables *[EBVt0 ~ NFF + Region] (Ref. group: NFF - SQ, Region - Europe and Central Asia)*

	AOHSR	NATECO	POLLECO	NITREECO	COASTECO
NFF NN	0.122* (0.059) 0.041	12.858*** (1.909) 3.91e-11	1.210*** (0.120) < 2e-16	-0.271*** (0.078) 0.00043	0.128* (0.057) 0.025
NFF NS	0.088 (0.062) 0.156	9.357*** (1.935) 1.69e-06	0.755*** (0.110) 1.43e-11	-0.100 (0.078) 0.202	0.010 (0.060) 0.866
NFF NC	0.036 (0.062) 0.559	4.799* (1.919) 0.013	0.592*** (0.106) 2.77e-07	-0.086 (0.078) 0.270	0.090 (0.058) 0.119
REGION AFRICA	0.581*** (0.063) < 2e-16	23.471*** (1.797) < 2e-16	0.181 (0.105) 0.086	-0.371*** (0.072) 3.85e-07	-0.218*** (0.065) 0.001
REGION AMERICAS	0.566*** (0.068) 8.1e-16	26.874*** (2.063) < 2e-16	0.686*** (0.137) 7.24e-07	-0.336*** (0.083) 5.82e-05	-0.113* (0.056) 0.044
REGION ASIA PACIFIC	-0.004 (0.083) 0.962	9.721*** (1.900) 4.24e-07	-0.249* (0.105) 0.018	0.119 (0.079) 0.125	-0.117* (0.054) 0.033
CONSTANT	3.650*** (0.067) < 2e-16	33.039*** (1.679) < 2e-16	0.448*** (0.091) 1.04e-06	4.419*** (0.068) < 2e-16	0.129** (0.048) 0.008
OBSERVATIONS	598	595	577	568	348

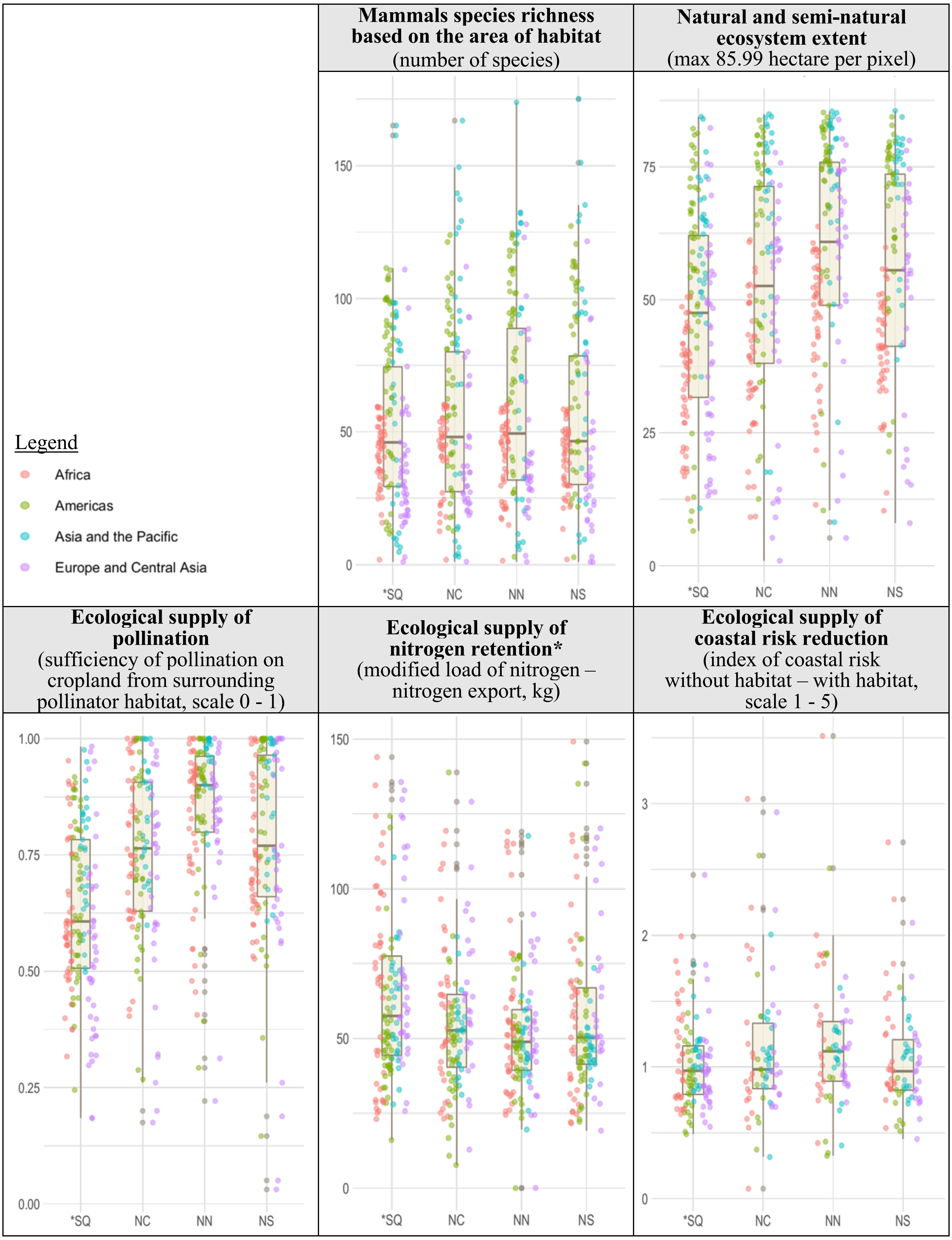


Figure 2. State of biodiversity, ecosystems and ecological supply of nature's contributions to people in 2000

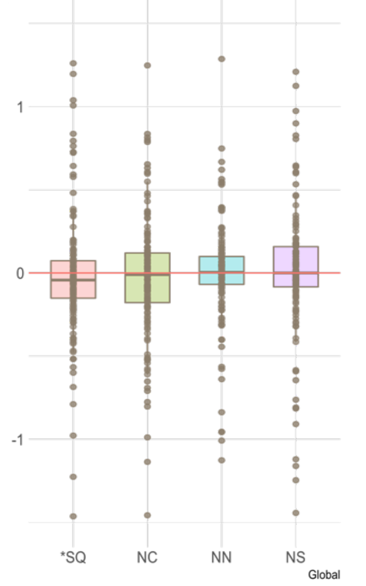
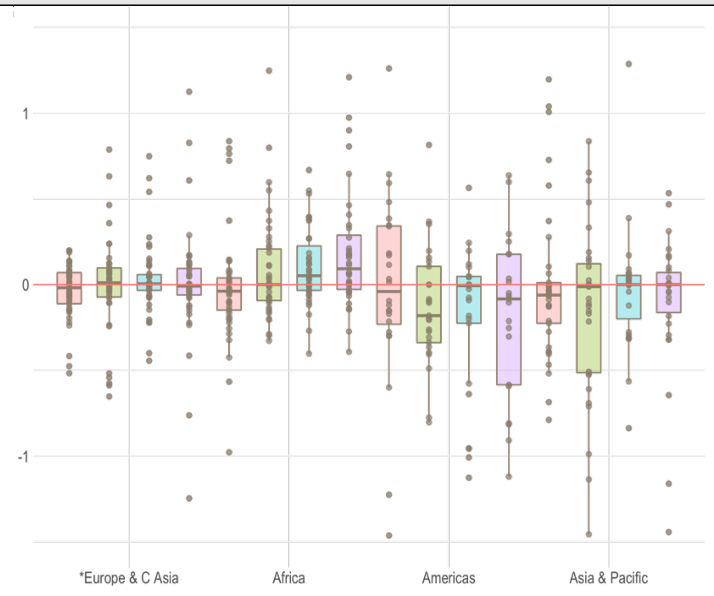
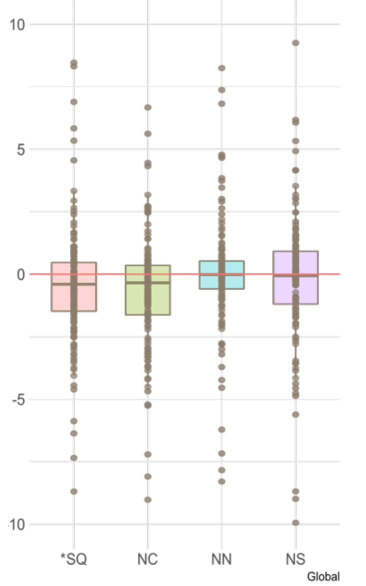
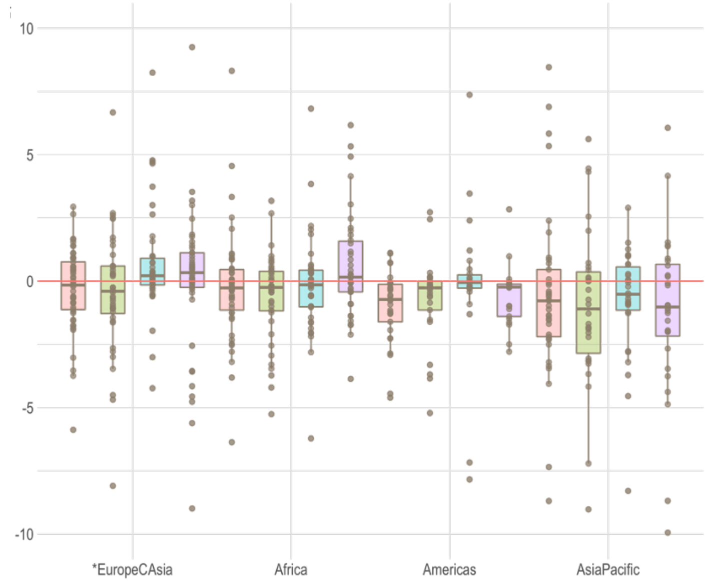
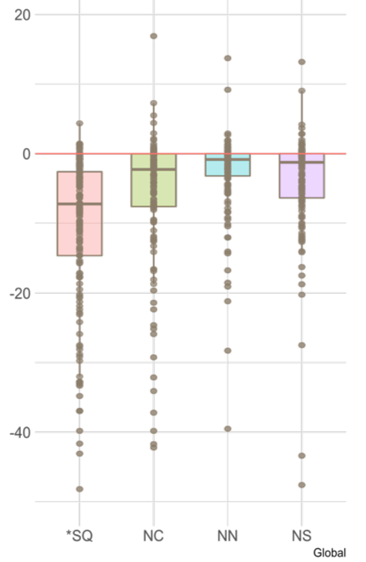
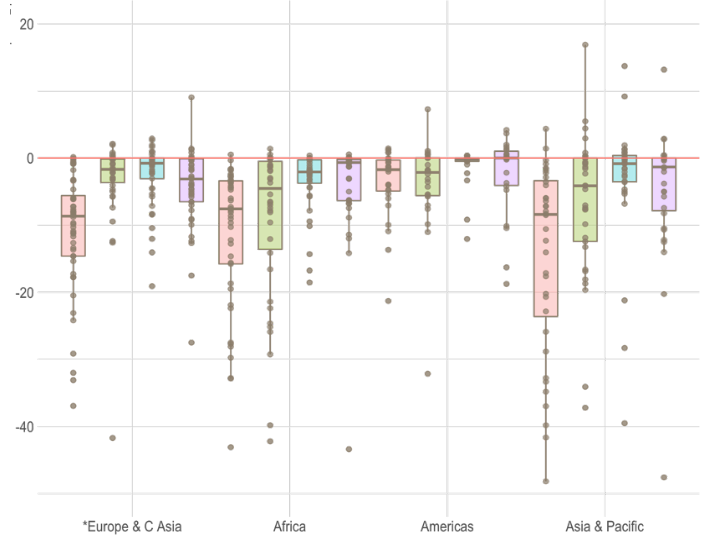
Trends in nature across the Nature Future protection regime and IPBES regions to 2015/18

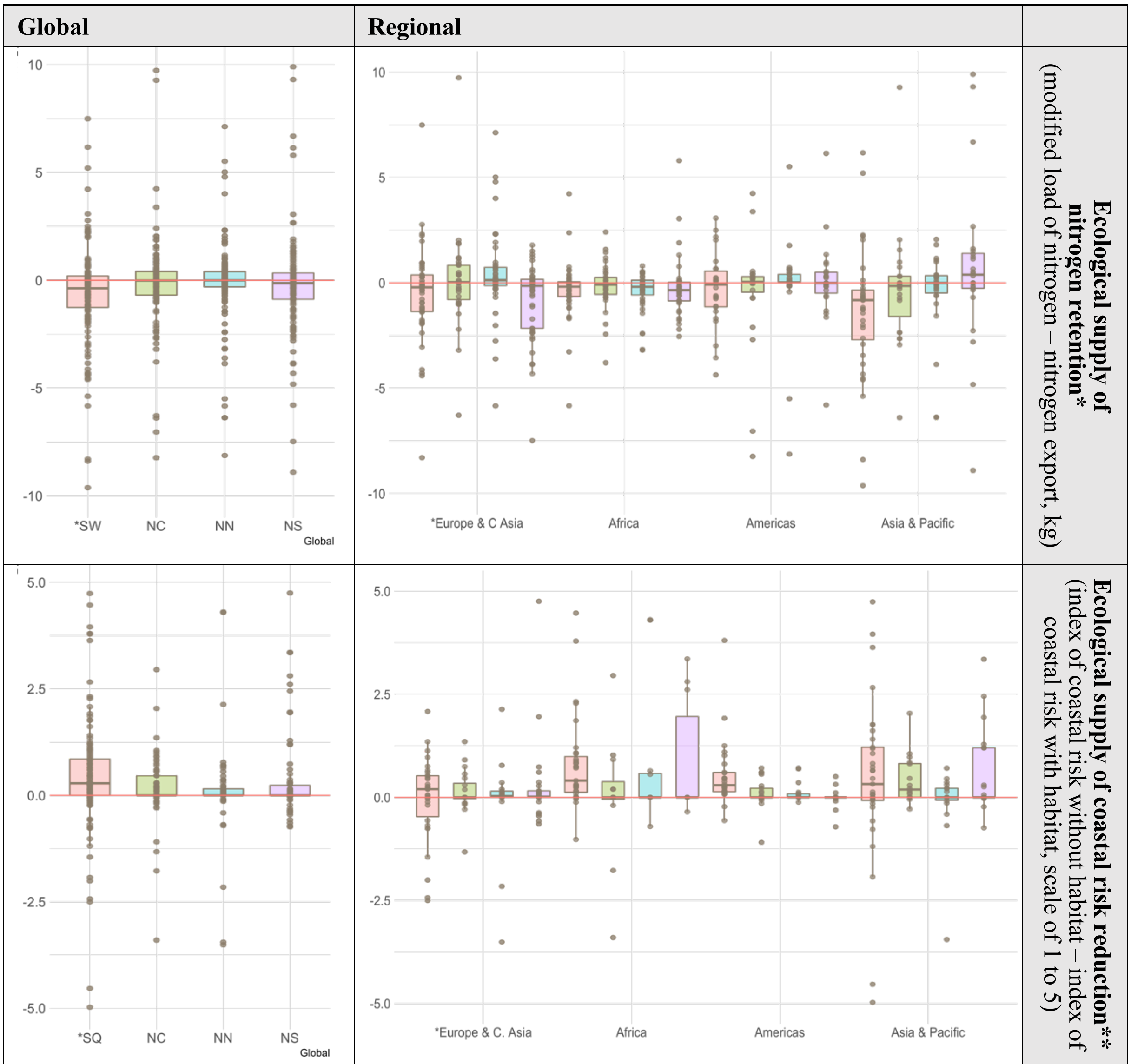
Globally, the percent change in 2015 (or 2018) relative to the baseline 2000 [($EBVt_1$-t_0)/EBV t_0*100] were negative and the largest in the Status Quo across five BES and NCP response variables (note that positive means greater risk for the coastal risk reduction variable) (Figure 3). The changes were relatively small on all variables and nearly insignificant for Nature for Nature. However, the regional mean of national mean values on the mammal species richness was higher in Africa than in Europe and Central Asia. Similarly, natural and semi-natural ecosystem extent increased slightly in Europe and Central Asia and decreased the most in Asia and the Pacific. The pollination decreased across all Nature Future protection regimes for most countries across all regions. Nitrogen retention improved slightly in Asia and the Pacific's Nature for Society and Europe and Central Asia's Nature for Nature. The coastal risk increased in many countries across all regions, with the Status Quo having the highest increase in the risk.

Our linear regression model results show that for natural and seminatural ecosystem extent, there is a significant difference in the global mean values of Nature for Nature (0.37±0.48) and of Nature for Society (0.22±0.49) to the Status Quo (Table 3, SM Models S2). The pollination also had significant difference in global means for Nature for Nature (9.32±1.35), Nature for Society (8.28±1.35) and Nature as Culture (6.26±1.35) compared to the Status Quo. At the regional level, compared to Europe and Central Asia, the relative change in the species richness was significantly lower in the Americas (-0.33±0.13), while for natural and semi-natural ecosystem extent, it was significantly lower in the Americas (-1.20±0.52) and Asia and the Pacific (-1.75±0.48). The pollination had significantly lower decline in Africa (-3.49±1.26) and Asia and the Pacific (-4.93±1.32) than Europe and Central Asia.

Table 3. Linear model results (mean, s.d. and p-value) on five response variables
[$EBVt_1$-t_0 ~ NFF + Region] (Ref. group: NFF - SQ, Region - Europe and Central Asia)

	AOHSR	NATECO	POLLECO	NITREECO	COASTECO
NFF NN	-0.074	0.373**	9.421***	0.652	0.269
	(0.118)	(0.479)	(1.346)	(1.178)	(0.370)
	0.530	0.437	7.13e-12	0.580	0.467
NFF NS	-0.094	0.215*	8.278***	0.367	0.130
	(0.119)	(0.486)	(1.351)	(1.199)	(0.368)
	0.430	0.658	1.65e-09	0.760	0.725
NFF NC	-0.185	0.929	6.258***	1.508	0.194
	(0.119)	(0.482)	(1.350)	(1.194)	(0.369)
	0.121	0.054	4.43e-06	0.207	0.599
AFRICA	0.057	-0.155	-3.486**	0.106	0.730
	(0.111)	(0.451)	(1.261)	(1.111)	(0.398)
	0.606	0.732	0.006	0.924	0.0673
AMERICAS	-0.333**	-1.195*	2.378	-0.665	0.060
	(0.128)	(0.518)	(1.478)	(1.277)	(0.370)
	0.009	0.021	0.108	0.603	0.871
ASIA PACIFIC	-0.087	-1.747***	-4.931***	1.234	0.499
	(0.117)	0.477	(1.324)	(1.194)	(0.361)
	0.455	0.0003	0.0002	0.302	0.167
CONSTANT	0.074	-0.764	-10.916***	-0.641	0.060
	(0.104)	(0.444)	(1.176)	(1.045)	(0.318)
	0.478	0.694	< 2e-16	0.540	0.850
OBSERVATIONS	598	595	577	568	348

Global	Regional	
		**Mammals species richness based on the area of habitat** (number of species)
		**Natural and semi-natural ecosystem extent** (max 85.99 hectare per pixel)
		**Ecological supply of pollination** (sufficiency of pollination on cropland from surrounding pollinator habitat, scale of 0 to 1)



**The lower values of nitrogen retention mean lower volumes of nitrogen in water.*
***The lower value of coastal risk reduction means lower risks with mitigation from natural habitats*

Figure 2. Global and regional trends in biodiversity, ecosystems, and ecological supply of nature's contributions to people between 2000 and 2015/2018

DISCUSSION

Using the global protected areas and indigenous land maps, our analyses reveal that terrestrial protected areas were placed where values of biodiversity and ecological supply of nature's contributions to people were higher than in unprotected land in 2000. The species richness were higher and the nitrogen retention were lower in strictly protected areas (NN) on national average at the global level (Table 2). Albeit with relatively small differences across the Nature Future protection regimes, this pattern was consistent across the five essential biodiversity and ecosystem services variables used in the analyses. Furthermore, biodiversity and ecological supply of nature's contributions to people were in better states in Africa and the Americas than in Europe and Central Asia likely due to the larger occupancy of natural and pristine land (Table 2). This finding is in agreement with previous studies that found higher values of biodiversity in protected areas than in unprotected areas (Coetzee *et al.* 2014; Gray *et al.* 2016; Pimm *et al.* 2018; Cazalis *et al.* 2020). A critical question still remains if these protected areas are placed where a large fraction of biodiversity are conserved (Rodrigues *et al.* 2014; Venter *et al.* 2014; Jenkins *et al.* 2015; Grantham *et al.* 2020) and if the management of different protected areas matches the condition of biodiversity and its conservation outcome (Boitani *et al.* 2008; Leroux *et al.* 2010)

Our analysis further reveals that, on national average at the global level, the trends in biodiversity and ecological supply of nature's contributions to people improved in protected areas and indigenous land compared to unprotected land from 2000 to 2015 (or 2018), in particular, in natural and semi-natural ecosystem extent and pollination supply with significant differences. Albeit with small variances, their relative change from the baseline was the greatest where nature was strictly protected (NN), then with human management (NS), then where people and nature co-inhabit (NC) (Table 3), similarly to the findings on their state in baseline year. This finding is in agreement with previous studies that found positive effects of protected areas on biodiversity conservation and reduction in deforestation (Andam *et al.* 2008; Leberger *et al.* 2019; Sze *et al.* 2021).

Compared to Europe and Central Asia, species richness in the Americas, and natural and semi-natural ecosystems in the Americas and Asia and the Pacific declined to 2018 (Table 3). When interpreted with positive trends in the Nature Future protection regimes, this may reveal that protected areas are not sufficient enough to conserve the overall state of biodiversity and ecological supply of nature's contributions to people in these regions. This may be supported by recent studies on the mismatch between biodiverse or intact areas and protected areas in the U.S. and the Americas (Jenkins *et al.* 2015; Cazalis *et al.* 2021). It may also be attributable to the greater extent of deforestation in biodiverse areas in South America and Southeast Asia in recent decades (Leberger *et al.* 2019; Wolf *et al.* 2021), whereas in Europe, farmland abandonment and afforestation may have slightly improved or sustained the state of nature relative to the baseline (Pereira *et al.* 2020a). Furthermore, compared to Europe and Central Asia, pollination supply has reduced in Africa and Asia and the Pacific, and for the latter region, it was in the worst state amongst the four regions in the baseline (Table 3). This may be explained by the intensified agricultural productivity with demand for food and feed and increased monoculture reducing natural habitats and pollinator-dependent crop productions in these regions (Aizen *et al.* 2019).

This analysis used a novel approach of assessing the state and trends in biodiversity and ecological supply of nature's contributions to people in protected areas through the lens of nature value perspectives (intrinsic, instrumental, and relational) and utilized simple indicators derivable from the model-based essential variables on biodiversity, ecosystems and ecosystem services. We found that only a small portion of protected areas are assignable to Nature for Nature (6% of the total land) and Nature for Society (2%) compared to Nature as Culture (29%) globally based on the criteria we used to map the framework (i.e., strictness of protection and intensity and types of human management). However, different protected areas can map to more than one nature value perspectives given their multi-purpose and benefits (Ostrom & Nagendra 2006; Tallis *et al.* 2008). For instance, nature reserves like Natura 2000 can be assigned to Nature for Nature based on its primary objective but they can be managed more closely to Nature for Society or Nature as Culture. Similarly, it is difficult to ascertain the actual condition of protected areas (Leroux *et al.* 2010; Starnes *et al.* 2021) or the agreement between national and the IUCN definitions of protection categories (Leroux *et al.* 2010; Shafer 2015) or any standard practice in ensuring their management effectiveness (Andam *et al.* 2008; Geldmann *et al.* 2019). Furthermore, some nature reserves such as Natura 2000, UNESCO Map of Biosphere and World Heritage Sites do not have a category assigned in the World Database of Protected Area (WDPA), which makes retrospective evaluations such as this incomplete.

In this study, we analyzed the average performance of the nations for regional and global comparison across Nature Futures protection regimes and the rest of the land. Future analyses can look at the heterogenous patterns at finer scales for richer insights to what aspects of nature and its contributions to people are improving or worsening where, and identify positive drivers of change. The essential variables used and the indicators derived to assess the state and trends of biodiversity and nature's contributions to people can expand (e.g., beta diversity, functional diversity, carbon sequestration, pest control) for more comprehensive analyses (Chape *et al.* 2005; Brauman *et al.* 2020; Chaplin-Kramer *et al.* 2020). Furthermore, the counterfactual analysis using methods such as statistical matching or before-after impact control (BACI) would allow a causal inference on the effect of different protection regimes to unprotected land, controlling for various environmental variances (Schleicher *et al.* 2020; Ribas *et al.* 2021; Wauchope *et al.* 2021). Finally, this analysis lacked response variables that measure cultural or relational benefits of protected areas for human livelihood and wellbeing, which will be essential for a more inclusive impact evaluation in informing future decisions (Pullin *et al.* 2013; Oldekop *et al.* 2019; Schröter *et al.* 2019, 2020).

Biodiversity and conservation scientists have been sending clear messages over the years on the importance of placing protected areas where biodiversity values are high (Venter *et al.* 2014; Watson *et al.* 2014; Pimm *et al.* 2018; Visconti *et al.* 2019) and ensuring their effectiveness through continuous monitoring of biodiversity change and human pressures (Geldmann *et al.* 2019; Visconti *et al.* 2019). This study demonstrated how essential biodiversity and ecosystem services variables produced from predictive models can be used in evaluating implemented interventions retrospectively and reveal how their results agree with similar studies that use in-situ monitoring data from different observation sites. In the future, causal inference studies can potentially provide magnitude of effects of different protection regimes on biodiversity, ecosystem, and nature's contributions to people across scale and regions. To date, many models assume no effects of protected areas on biodiversity in predicting biodiversity change from land use data (Visconti *et al.* 2011; Schipper *et al.* 2019). Using the models and variables such as those in this analysis, different effect sizes of land protection and management regimes can be integrated in forecasting biodiversity change under different conservation scenarios to inform the future spatial planning more accurately.

This study highlights the importance of retrospective evaluation of protected areas in regularly monitoring and informing the progress towards goals and targets set in the CBD Post-2020 Global Biodiversity Framework. Furthermore, as voiced by countries and observers in the discussion up to the current CBD Post-2020 GBF, the role of indigenous and local communities needs to be better recognized and supported and diverse values of nature and people need to be better incorporated in its monitoring framework. It is therefore essential that we consider a complementary set of indicators to track the conditions, performance, and contributions of protected areas comprehensively and meaningfully in collectively implementing the new global biodiversity goals with broader stakeholders.

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Chapter 6

Synthesis

This dissertation contributes to developing and interweaving the recent global initiatives that aim to improve science-based policy design and implementation and enhance the usability of scenarios-based biodiversity information in conservation policies and practice by broad stakeholders. I first explored the scenarios in the environmental assessments and studied biodiversity and ecosystem services models through the BES-SIM model intercomparison. I then engaged in developing the new biodiversity centric scenarios and modelling framework with IPBES – the Nature Futures Framework. I synthesized stakeholder and expert consultation results on developing Nature Futures scenarios and modelling them in generating integrative evidence bases for conservation and sustainability policy. Finally, together with scientists in the GEO BON network, I conducted a retrospective evaluation of protected areas between 2000 and 2015/2018 through the Nature Futures lens using the essential variables to inform the implementation of the CBD Post-2020 Global Biodiversity Framework.

6.1 State of the art projections on biodiversity and ecosystem services using the RCP and SSP scenarios

The BES-SIM model intercomparison found a steep decline in global species richness from 1900 to 2015 at 0.8% per century, suggesting that roughly 70,000 species on the planet went extinct from land-use change impacts alone if there are approximately 9 million species on the planet (Mora *et al.* 2011). This trend is projected to continue at a similar rate across all scenarios assessed, with a slower rate in the global sustainability scenario, but at a much faster rate when combined with climate change (**Chapter 3**). Considerable reduction in net local species richness occurred over the last century globally, and some regions are expected to continue losing biodiversity from the land-use change, particularly in the tropics, Northern boreal regions, and central Africa from deforestation and conversion to pastureland. On the contrary, some areas in Western Europe and Northeast Americas have gained in net local species richness in the past, possibly due to farmland abandonment and afforestation, and this trend is expected to expand to other temperate areas in the future. Across the three combinations of scenarios, moderate to restricted losses from land use is expected in the areas already degraded in the past century in the global sustainability scenario. In contrast, a more regionalized socio-economic development exacerbates biodiversity losses globally in the regional rivalry scenario and more concentrated biodiversity losses in South America, Central and East Africa, and South Asia in the globalized fossil-fueled development scenario.

For ecosystem services, we found that there have been increases in material services such as food and timber, but likely at the cost of declines in regulating services such as pollination and nutrient retention in the last century (**Chapter 3**). In the coming decades, similar trends are expected across all combinations of scenarios studied but at a reduced rate in the global sustainability scenario with limited growth in population and agricultural productivity. The increases in food and feed and timber demand are expected to continue in the regional rivalry and fossil-fueled development scenarios but at a lower rate than in the past century due to decelerating population growth. There are heterogeneous patterns in ecosystem services across the regions. In the global sustainability scenario, the trade-offs between material and regulating services are smaller, with American regions, Eastern Europe, Southern Africa, and Central Africa increasing both services. Oceania, Mesoamerica and North Africa will have much higher declines in regulating services in the regional rivalry scenario than the fossil-fueled development scenario (Pereira *et al.* 2020b).

Our results alert us to the growing impact of climate change on biodiversity loss than the impact of land-use change. However, this may be due to the insignificant land-use change assumed in these scenarios compared to the past century and the time lags between habitat loss and species extinction still forthcoming (Dullinger *et al.* 2016). Furthermore, climate and biodiversity impact models need to be understood in interpreting these results. Whereas projections of large scale land-use change impacts on biodiversity are typically based on their empirical relationships at the local scale, projections for climate change use statistical models relating current climate with distribution patterns of species at large scales (Bellard *et al.* 2012; Pereira and Borda-de-Água 2013). This study also raises important considerations for more coherence between biodiversity and climate scenarios. Bioenergy production in the global sustainability scenario is a favorable policy for climate mitigation, but it can lead to land-use conversion that negatively impacts biodiversity. This is evident in insignificant differences in projected total ecosystem carbon across scenarios, possibly due to its fertilization effects in higher climate change scenarios compensated with a reduction in total forest area (regional rivalry, fossil-fueled development).

The BES-SIM model intercomparison highlighted a few challenges in making policy-relevant biodiversity and ecosystem services scenarios. The SSP scenarios and the BES-SIM results pointed to the need to recognize the role of nature better in socio-economic development scenarios (Rosa *et al.* 2020). Furthermore, multiple dimensions of biodiversity and ecosystem services can be reflected better in indicators used to inform policy (Perino *et al.* 2021). Biodiversity and ecosystem services models have relied heavily on climate and land-use scenarios and their datasets. Still, a broader range of drivers should be integrated into impact models for more comprehensive assessments and predictions on biodiversity and nature's contributions to people (IPBES 2019). Reconstruction and projection data on land use and climate change can improve with a higher resolution and quality, potentially sourced and validated by finer-scale national data. Furthermore, integrated assessment models and ecosystem services models could represent and link to biodiversity models more (Schipper *et al.* 2016; Sharp *et al.* 2016). Going forward, it will be critical that biodiversity and climate research communities come together in developing scenarios that respond to environmental and climate issues more synergistically and advise across sectors to prevent undesirable consequences (O'Neill *et al.* 2020; Pörtner *et al.* 2021).

6.2 Novel framework for biodiversity scenarios and the role of EBV- and EESV-based indicators for policy support

To develop a biodiversity-centric scenario and modelling framework, the IPBES Expert Group on Scenarios and Models started its scenarios co-development process in 2017. Stakeholders and experts from diverse disciplines and backgrounds got engaged through the IPBES, CBD, Natural Capital

Project, and other venues to collectively vision positive futures for nature and people, reflecting on their relationship with nature (**Appendix B. Pereira *et al.* 2020**). We explored good seeds of Anthropocene (opportunities) and lock-ins (challenges) from different stakeholders' positions across regions in different thematic areas. We placed them on three horizon pathways towards the visions, how the seeds can be amplified, and lock-ins can be resolved (Sharpe *et al.* 2016; Bennett *et al.* 2016; Geels *et al.* 2017). We mapped our visions on the axis of state of biodiversity, values of nature, management of nature, governance systems, production and consumption of ecosystem services, socio-economic development, technology use, and lifestyle in developing an open framework (Lundquist *et al.* 2017). The Nature Futures Framework (NFF) emerged as a result, which is a heuristic tool for co-creating positive futures for nature and people. It seeks to open up a diversity of futures through three main value perspectives on nature – Nature for Nature respecting intrinsic values of nature, Nature for Society appreciating instrumental values nature provides to people, and Nature as Culture recognizing relational values nature and people co-create (PBL 2018; Pereira *et al.* 2020a; Lundquist *et al.* In preparation).

Additional consultations took place with broader scientific and stakeholder communities, including the GEO BON network, integrated assessment models and marine and freshwater modelling experts, and others to develop methodologies in going from the Nature Futures Framework to developing scenarios and modelling them (PBL 2019a, b). As a result, a few key building blocks emerged, and further discussion took place to see how the framework can be used in policy processes (**Chapter 4**). Nature Futures opens up the worldviews, considers diverse values of nature and explores multiple pathways to positive future visions. First, the concept of Frontier is to be considered in developing Nature Futures scenarios to integrate positive levers in Nature Future value reflected interventions, which can help systems transition towards the Frontier (Cheung and Sumaila 2008; Polasky *et al.* 2008). Second, Nature Futures scenarios look at the social-ecological systems to identify mutually reinforcing and positive feedbacks across the Nature Future value perspectives that are key to transformation (Miller *et al.* 2013; Lafuite and Loreau 2017). Third, Nature Futures scenarios can be modelled or otherwise evidenced on how these key social-ecological systems can evolve towards positive pathways by using indicators produced from the models or other quantitative and qualitative sources to incorporate multiple systems of knowledge (Tengo *et al.* 2014; Cebrián-Piqueras *et al.* 2020). We applied these key concepts in urban systems through a working group that led to a publication, "Nature futures for the urban century: Integrating multiple values into urban management" (Mansur *et al.* 2022).

Further integrating the IPBES methodological assessment on scenarios and models and IPBES conceptual framework (Díaz *et al.* 2015; IPBES 2016), we conceptualized three approaches to modelling Nature Futures scenarios in the review, screening and design phases of policy processes (**Chapter 4**). In policy review, the NFF can retrospectively evaluate the effects of implemented policies using observation-based models and data and techniques such as statistical matching or before-after control impact through the Nature Futures lens (Schleicher *et al.* 2020; Wauchope *et al.* 2021). In this phase, key challenges are integrating time-series monitoring data on biodiversity and ecosystem services and broadening the range of drivers in impact models beyond climate and land use (Akçakaya *et al.* 2016). In policy screening, the NFF can be applied to assess the consequences of different policy and management options that reflect diverse nature value perspectives, often for the short-term using impact modelling of direct drivers on biodiversity and ecosystem services (Sala *et al.* 2021; O'Connor *et al.* 2021). Here, connecting biodiversity, ecosystem functions and services and quality of life is one of the key challenges (Brauman *et al.* 2020; Ceaușu *et al.* 2021). In policy design and agenda-setting, the NFF can be used to identify broader goals for policy-making, which consider and incorporate diverse values of nature, over longer time scales, using models such as integrated assessment models at larger scales or dynamic social-ecological models at smaller scales (Schlüter *et al.* 2019; Leclère *et al.*

2020). In this phase, reflecting long term social-ecological feedbacks at large scales and incorporating tipping points and regime shifts are key challenges (Rocha *et al.* 2018; Otto *et al.* 2020).

We applied one of the modelling approaches proposed in Chapter 4 to retrospectively evaluate protected areas' performance through the Nature Futures lens using the essential variables on biodiversity and ecosystem services (**Chapter 5**). We found that on a national average, biodiversity, ecosystems and nature's contributions to people were in a better state in 2000 and were generally conserved better to 2015/2018 in protected areas and indigenous land compared to the rest of the land. The state of nature was the best in Nature for Nature (strict protection), then Nature for Society (protection with human management) and Nature as Culture (cultural landscape and indigenous land) with heterogeneous patterns across regions and at finer spatial scales. The study highlights the importance of regular retrospective evaluation of conservation interventions such as protected areas in monitoring biodiversity and reporting on progress towards the goals and targets in the CBD Post-2020 Global Biodiversity Framework. Furthermore, this analysis provides a proof of concept that Nature Futures Framework and essential variables can be used together with other scientific and policy frameworks (e.g., IPBES NCPs, CBD GBF) in representing diverse roles, values and benefits of nature in informing future decisions more comprehensively (Sala *et al.* 2021; O'Connor *et al.* 2021; Soto-Navarro *et al.* 2021). Ultimately, the Nature Futures scenarios and modelling present novel challenges in biodiversity science to integrate relational values of nature in models and transform the conventional impact modelling of negative anthropogenic drivers to positive anthropogenic drivers on nature and people to inform our pathways towards sustainable futures (Schröter *et al.* 2020; Chan *et al.* 2020).

6.3 Interweaving multiscale science and policy frameworks for more effective conservation and sustainability implementation

The negotiations for the post-2020 Global Biodiversity Framework are informed, to some extent, by our failures and the growing need to enhance the accountability and monitoring of targets at both national and global scales, which require biodiversity observations and scalable indicators (Xu *et al.* 2021). An analysis of the indicators used in the 5th National Reports to the UN CBD shows that only one-fifth of indicators used by nations matched those recommended by the CBD (Bhatt *et al.* 2020). This disconnect between global and national targets and the lack of coordination for scalable indicators limit our ability to measure progress and impact with inefficiencies in monitoring systems within nations (Jones *et al.* 2011). While the global frameworks are critical for coordinating national efforts globally with a standard framework, conservation measures are ultimately implemented at the national and subnational levels, so national target tracking and scalable indicators are key (GEO BON 2021).

As illustrated in this dissertation, the indicators derived from the essential variables can help detect changes in biodiversity (e.g. species diversity, natural ecosystem extent) (Kissling *et al.* 2018; Jetz *et al.* 2019; Remelgado and Meyer 2020). They are scalable and interoperable for multiscale analyses and policy support (Turak *et al.* 2017; Seebens *et al.* 2020). In addition, a wide range of ecosystem services (e.g. climate regulation, water purification, crop production, coastal risk reduction, nature-based recreation) are being mapped across time and space to value material and non-material values of nature to society (Brauman *et al.* 2020; Wang *et al.* 2021). When combined with socio-economic information (e.g. distribution and density of population), the indicators derived from the EESV can inform the quality of life and distributional equity across regions and scales (Chaplin-Kramer *et al.* 2019). Using complementary metrics of EBVs and EESVs that stakeholders find relevant, credible and accessible, it is possible to assess, for instance, which land is essential in conserving the functional, provisional regulating and relational role of nature spatially (Sala *et al.* 2021; O'Connor *et al.* 2021). This can further inform where to place protected areas to conserve biodiversity, place cities for human settlement, or maintain the cultural landscape while preventing unintended harm on nature and people.

Nature Future scenarios can support policy screening and design by analyzing combinations of interventions on direct and indirect drivers that achieve a set of policy goals towards nature and people positive futures. It can be a heuristic to explore a much broader array of conservation and sustainability interventions, assessing their co-benefits and synergies that emerge from different prioritizations on societal goals from diverse value perspectives (Mansur *et al.* 2022). Therefore, modelling multiple interventions on indirect drivers (institutions, governance, anthropogenic assets) and direct drivers (both natural and anthropogenic) in Nature Futures scenarios requires bridging existing social, ecological, and economic models across the scale. Nature Futures scenarios could explore, for instance, the interventions on international trade that minimize species extinction and restore biodiversity (Nature for Nature), the potential impacts of changes in human consumption (e.g. plant-based diet, protein alternatives) on regional economy, ecosystems, land use, and ecosystem services (Nature for Society), pathways towards a locally-sourced consumption with traditional agricultural and fishery management and their impact on biodiversity, ecosystem integrity and human health (Nature as Culture) (PBL 2019a).

With advances in Earth observations, an extensive suite of models can now generate globally standardized variables on biodiversity and ecosystem service, which can be used to derive a wide range of indicators for quantifying diverse values and benefits of nature (Pettorelli *et al.* 2016; Cord *et al.* 2017; Ramirez-Reyes *et al.* 2019). Complementary models overcome the limitations of previous approaches on using single or selective models for estimating biodiversity change or prioritizing actions for conservation and restoration, all of which have different degrees of uncertainties associated with data, modelling methods, and indicators used (Rowland *et al.* 2021; Rounsevell *et al.* 2021). Furthermore, social-ecological systems can be evaluated by overlaying the essential variables with social-ecological data (e.g. population, consumption patterns) and science or policy frameworks (e.g. IPBES conceptual framework, SDGs) in fostering data-driven dialogue with stakeholders (Reyers and Selig 2020). Therefore, a unique opportunity arises in connecting biodiversity and ecosystem services models to modelling Nature Futures scenarios, potentially informing future social, ecological and economic milestones for policy goals that can be transformative and are evidence-based.

The effectiveness of global policy frameworks such as the CBD Post-2020 Global Biodiversity Framework requires cross-sectoral and cross-scale collaboration. Clarifying the complementary roles of the institutions at each regional scale with shared governance and coordination can improve their efficacy (Shrivastava *et al.* 2020). At the global level, CBD GBF sets an overarching policy framework with strategies and goals to be achieved on biodiversity and nature's contributions to people with indicators that measure the progress and effectiveness of diverse indirect and direct drivers (**Appendix A. Bonn *et al.* 2020**). The GEO BON network develops essential variables on biodiversity, ecosystem, ecosystem services, based on ecological research and modelling, harmonizing diverse primary observation data, to inform indicators that are scalable for detecting changes in biodiversity and ecosystem services (Navarro *et al.* 2017). The IPBES scientific community synthesizes multiple knowledge systems and develops sustainability scenarios centred on nature conservation and human wellbeing (Díaz *et al.* 2015), which can be interwoven with frameworks of the IPCC reports and scenarios (**Appendix C. Matias *et al.* 2021)**. Suppose science and policy frameworks are integrated effectively through institutional collaboration in assessments and policy processes (Tengö *et al.* 2017), scenarios and modelling can play its intended role to identify optimal pathways for biodiversity, climate and people and help set ambitious targets that are achievable through evidence-based decision making.

6.4 Concluding remarks

This dissertation aspires to contribute to developing and interweaving the recent global initiatives that aim to improve science-based policy design and implementation and enhance the usability of scenarios-based biodiversity information in conservation policies and practice. It highlights the urgent need to bring climate and biodiversity research communities together in developing scenarios that work for both nature and people. It presents the importance of reflecting diverse values and worldviews in developing new scenarios that can engage and inform all societal actors in achieving sustainable futures. It recommends more concerted efforts be given in interweaving science and policy frameworks at each scale and across scales in implementing conservation and sustainability interventions going forward. The Nature Futures scenarios and modelling framework and model-based essential variables on biodiversity and ecosystem services bring a unique opportunity to support these ambitions in creating more ecological, livable and just futures with broader stakeholder communities.

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Halle (Saale), den 04.02.2022

HyeJin Kim

Appendix I

A. Bonn *et al.* 2020. "Conservation goals in international policies".

CHAPTER FIFTEEN

Conservation goals in international policies

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15.1 Introduction

Biodiversity and its importance has long been recognised and enshrined in national and international policies. While the earliest conservation policies were framed around 150 years ago and mainly consisted of national policies to protect biodiversity, over the last century conservation policies have undergone a significant shift in emphasis towards integration of, and alignment with, societal goals (Mace, 2014). Moving from a sole focus on species and habitat protection in the early twentieth century, or 'Nature for itself' as framed by Mace (2014), policies have gradually aligned with other societal aims. This started with a recognition of ecosystem services (Daily, 1997), as the benefits people derive from nature ('Nature for People'), which was brought into the mainstream by the Millennium Ecosystem Assessment (MA, 2005). There has since been a move away from utilitarian values to consider 'Nature and People' (Mace, 2014; Díaz et al., 2018) as a more inclusive concept to better support synergies and negotiate trade-offs of conservation and societal goals. In this chapter, we aim to demonstrate and discuss how this increasingly integrative view is reflected in the development of international conservation policies and related institutions. After briefly sketching the historical origins of current international conservation policies, we focus on the Convention on Biological Diversity (CBD), which couples its core objective of nature conservation with human well-being. Next, we show how an integrative view on nature conservation has shaped the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES). Finally, we explore the

Sustainable Development Goals (SDGs) as a third global enterprise that closely links the conservation of nature to other societal aspirations. Using these three examples, we address the following questions.

1. How do these three agreements function and how are decisions made?
2. What is the role of science and evidence in the CBD, IPBES and the SDGs?
3. What are the achievements so far, and how can scientists engage to foster progress?

15.2 A short history of conservation policies

To understand current conservation policies, it is useful to reflect briefly on their development. Historically, conservation policies were created in response to a realisation of loss of natural habitat, and led to national conservation designations, notably the first big national parks. In the USA, Yellowstone was established as the first National Park worldwide by the Yellowstone National Park Act in 1872, withdrawing almost one million hectares from further land use development to be 'dedicated and set apart as a public park . . . for the benefit and enjoyment of the people'. In Europe, the UK was the first country to establish national parks under the 1949 National Parks and Access to the Countryside Act, also born out of a strong demand for open public access to private land. The Peak District National Park, designated in 1951, remains one of the most-visited national parks worldwide. Many more national parks followed in the 1970s and 1980s in Africa, Europe and across all continents. Often, however, these designations showed little consideration of local communities and their livelihoods ('Nature despite people'; Mace, 2014), leading at times to violations of rights of indigenous people and severe conflicts (Colchester, 2004). Protected areas continue to provide crucial cornerstones of local, regional and international strategies for biodiversity conservation. They have significantly contributed to halting losses of species and habitats, although their performance is at times mixed and often not known (Gaston et al., 2008; Mora & Sale, 2011).

International conservation policy development started with a series of global conventions in the 1970s and 1980s focusing on species and habitat protection (Table 15.1). Once countries ratified these multi-lateral environmental agreements, they proved to be drivers for national law development. For example, the US Endangered Species Act of 1973 was developed as a response to the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) that had entered into force the same year. As another example, the European Union met its obligations for bird species under the Bern Convention (1979) and Bonn Convention (1979) through the *Council Directive 79/409/EEC on the conservation of wild birds* (*Birds Directive*) adopted in 1979. This has since been substantially amended several times to the Directive 2009/147/EC adopted in

Table 15.1 *Important multi-lateral environmental agreements in the nature conservation context. Information retrieved from the treaty's websites or from www.informea.org (accessed 9 December 2018)*

Treaty name	Abbreviation	Adoption	Entry into force	Parties*	Main target
Convention on Wetlands of International Importance	Ramsar Convention	1971	1975	170	Conservation and sustainable use of wetlands
Convention Concerning the Protection of the World Cultural and Natural Heritage	WHC/World Heritage Convention	1972	175	193	Protection of the world cultural and natural heritage
Convention on International Trade in Endangered Species of Wild Fauna and Flora	CITES	1973	1975	183	Regulation of trade of wild plants and animals
Convention on the Conservation of European Wildlife and Natural Habitats	Bern Convention	1979	1982	51	Conservation of wild flora and fauna and their natural habitats, and promotion of European cooperation
Convention on the Conservation of Migratory Species of Wild Animals	CMS/Bonn Convention	1979	1983	126	Conservation and sustainable use of migratory animals and their habitats
United Nations Framework Convention on Climate Change	UNFCCC	1992	1994	197	Prevention of dangerous anthropogenic interference with the climate system, slowing global warming and mitigating its impact

Table 15.1 (*cont.*)

Treaty name	Abbreviation	Adoption	Entry into force	Parties*	Main target
Convention on Biological Diversity	CBD	1992	1993	196	Conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of benefits arising from the use of genetic resources
United Nations Convention to Combat Desertification	UNCCD	1994	1996	197	Prevention of desertification and land degradation

* Number of member states as of December 2018.

2009 and sits alongside the *Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora* (Habitats Directive) adopted in 1992. Legal mechanisms for the achievement of international conventions at national scales are at the discretion of each member state.

During the 1980s, environmental pollution, the over-use of resources and the resulting loss of species and natural habitats gained increasing attention from the public and political representatives. This led to the 'Rio World Summit' in 1992 (United Nations Conference on Environment and Development, UNCED), at which three new conventions were opened for signature: the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Convention to Combat Desertification (UNCCD) and the Convention on Biological Diversity (CBD). Further details of the set up, operation and achievements of these three conventions are described in the sections below.

15.3 General set up and mode of operation

15.3.1 The Convention on Biological Diversity (CBD)

The CBD is, with regards to goals addressed, the most comprehensive global treaty dealing with nature conservation. Its three overarching objectives are (Article 1 of the Convention):

(a) the conservation of biological diversity,
(b) the sustainable use of its components and
(c) the fair and equitable sharing of the benefits arising out of the utilisation of genetic resources.

Thus, the CBD's objectives refer to both intrinsic and instrumental values of biodiversity. It does so by including an unconditional call for the conservation of biodiversity in combination with the acknowledgement that people depend on nature and need to make use of it, as well as a call for dividing the benefits that are derived from nature equitably.

In total, the Convention's text contains 42 Articles that further define aims and assign duties to the bodies of the Convention. The CBD's clear recognition of the interaction between nature-related and societal goals is also codified in its principles. For example, the first CBD principle states that the 'objectives of management of land, water and living resources are a matter of societal choices', while the twelfth acknowledges that 'the ecosystem approach should involve all relevant sectors of society and scientific disciplines'. The CBD is a legally binding treaty. Thus, a state that has signed and ratified the Convention is obliged to implement the Convention on its territory through national policies and practical management. Every two years, representatives of the member states meet at the Conference of the Parties (COP). The COP is the highest decision-making body of the CBD and it operates according to the consensus principle. This means that the text of a decision is negotiated until a compromise is reached among all parties present. If no consensus is reached, parties do not vote. Instead, only text to which no party objects is agreed upon and a decision on unresolved questions is postponed. A CBD COP decision therefore almost always represents a compromise between states with differing views. This 'consensus principle' has been criticised for preventing progress and watering down any suggestion to the lowest common denominator, often resulting in general, vague or ambiguous text (Kanie, 2014; Kemp, 2016). However, a shift from the consensus principle to a voting system faces many obstacles, e.g. the fear that parties could perceive this as a loss of sovereignty and could therefore drop out of the Convention, or that such a reform would open a 'Pandora's box' and encourage open disputes on, and possibly change in, other principles or rules of procedure (Kemp, 2016).

To facilitate negotiations under the consensus principle, the CBD parties are divided into groups of states that discuss and align their positions; one of their members is then responsible for representing them in the plenary of the COP. Important associations of states are the European Union and the official United Nations Regional Groups (African Group, Asia–Pacific Group, Eastern European Group, Latin America and Caribbean Group, Western European and Others Group), alongside some informal groups, such as an alliance of

industrialised non-EU countries called JUSCANNZ (i.e. Japan, United States, Switzerland, Canada, Australia, Norway, New Zealand).

Meetings of the CBD COP and of many other CBD bodies (e.g. of the Subsidiary Body of Technical and Technological Advice – SBSTTA, see 15.5.1) are open to so-called 'observers'. The observer status can be obtained by, for example, non-governmental organisations, business associations or scientific institutions and it gives the right to speak in plenary but not to veto a decision.

One way in which the CBD fosters progress towards its objectives is by setting up particular Programmes of Work, each with a vision and suggested actions that CBD parties are encouraged to support. These are concerned with topics related to Agricultural Biodiversity, Dry and Sub-humid Lands Biodiversity, Forest Biodiversity, Inland Waters Biodiversity, Island Biodiversity, Marine and Coastal Biodiversity and Mountain Biodiversity. The CBD also dedicates work to cross-cutting issues, such as Climate Change and Biodiversity; Communication, Education and Public Awareness, Economics, Trade and Incentives Measures or Identification, Monitoring, Indicators and Assessments. It aims to link work on these themes closely with other UN Conventions by collaborating with, for example, UNFCCC and UNCCD secretariats (www.unccd.int/convention/about-convention/unccd-cbd-and-unfccc-joint-liaison-group).

Approximately every five years, parties must report the steps taken to implement the CBD provisions and their effectiveness to the CBD Secretariat. These 'National Reports' are used by the CBD Secretariat to gain an overview of global trends in the implementation process. However, as the parties are sovereign entities, they decide individually about their national implementation approaches, and are free to set own priorities (with the exception of EU member states who coordinate their efforts and are committed to EU regulations). There are no established CBD non-compliance procedures. The degree of compliance therefore varies widely and, overall, has proven to be generally insufficient, as the CBD's goals and targets, formulated in the Convention's Strategic Plans, have been repeatedly missed. For the period 2002–2010, the core element of the CBD's Strategic Plan was the '2010 Target': a 'significant reduction of the current rate of biodiversity loss at the global, regional and national level as a contribution to poverty alleviation and to the benefit of all life on Earth' (COP-Decision VI/26). However, this 2010 Target was widely missed (Butchart et al., 2010; Dirzo et al., 2014).

For the following decade, the level of ambition was raised further: 'to halt the loss of biodiversity' by 2020. To better address the underlying causes of biodiversity loss and be more explicit about what needed to be done to make progress towards the CBD objectives, the Strategic Plan for 2011–2020 was underpinned with five strategic goals and 20 'Aichi Biodiversity Targets' that formed the backbone of the Plan (see Figure 15.1). Setting up such a comprehensive framework that addressed the direct and indirect drivers of

Figure 15.1 The 20 Aichi Biodiversity Targets. Image: Copyright BIP/SCBD. (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

the ongoing biodiversity crises was seen as a major achievement. Furthermore, the Strategic Plan 2011–2020 has been highly relevant, beyond the global biodiversity agenda; it was endorsed by the UN General Assembly and other multi-lateral environmental agreements and therefore formed the principle global roadmap for the conservation of nature. The 20 Aichi Biodiversity Targets that formed the core of the Strategic Plan 2011–2020 were also incorporated into the global development agendas and fed into the Millennium Goals (until 2015) and subsequently the Sustainable Development Goals (until 2030).

However, despite this high political recognition, the Aichi Targets were not on track in 2018 and most will be widely missed by 2020, as indicated by the fourth Global Biodiversity Outlook report (Leadley et al., 2014) and the IPBES Global Assessment (IPBES/7/10/Add.1). Despite progress towards some Targets, the overall picture leaves no doubt: efforts need to be increased dramatically to halt and reverse the current situation, in which the drivers of biodiversity loss worldwide strongly override conservation efforts. There have been accelerated policy and management responses to the biodiversity crisis, but these are unlikely to significantly reverse trends in the state of biodiversity by 2020 (Tittensor et al., 2014).

For the post-2020 period, it is therefore crucial to focus on the implementation of the new CBD strategic framework that will then be in place. This needs to be achieved, in the first place, by the parties at the national level. Therefore, besides increased globally concerted efforts, place-based and context-specific approaches are essential for monitoring, conserving and sustainably using biodiversity.

15.3.2 Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES)

As a response to knowledge needs that became evident in the context of the CBD and other multi-lateral environmental agreements, the Millennium

Ecosystem Assessment (MA, 2005) was conducted in 2005, followed by several national ecosystem assessments (Schröter et al., 2016). Building on this experience (Carpenter et al., 2009) and modelled on the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES) was established in 2012 to generate an integrative knowledge foundation on biodiversity, ecosystems, ecosystem services and their impact on human and societal well-being (UNEP, 2012). IPBES is not a convention but a science–policy interface that supports governments and stakeholders in decision-making at multiple scales by providing policy-relevant and scientifically credible information on the status and trends of nature and its contributions to people (Brooks et al., 2014). IPBES does not enforce decisions on conventions or countries, but aspires to develop an expert-based platform that provides an accessible, useful and scientifically rigorous evidence base to support biodiversity-related decision-making by national governments and international conventions (e.g. CBD, RAMSAR, CITES, UNCCD).

To achieve this, IPBES operates via four main functions – assessment, knowledge generation, policy support and capacity-building – that are implemented through voluntary participation of experts chosen by governments and organisations globally, with balanced representation across regions, gender and disciplines (IPBES, 2014). Over the coming years, IPBES aims to continue bringing together the best knowledge-holders and institutions on biodiversity around the globe, synthesising the complex dynamics of nature and their impact on human societies and the planet, providing the most credible information available through research and practice, and catalysing the generation of new knowledge to fill critical gaps in order to better conserve nature and ensure human and societal well-being (Figure 15.2).

The IPBES Plenary, where 130 member states form a governing body, meets annually to track the progress of the work programme and to make decisions on the way forward. A Multidisciplinary Expert Panel (MEP) advises on scientific and technical aspects of the programme. The expert groups, taskforces and assessment authors are the scientists and knowledge-holders. Stakeholders and observers also play significant roles in IPBES by providing diverse perspectives and forms of knowledge and acting as catalysts for conservation in their respective communities of practice. In particular, IPBES is developing a mechanism to better integrate holders of indigenous and local knowledge into the process for a more comprehensive understanding and outlook on nature's values and futures (IPBES, 2014).

The decision-making process of IPBES is lengthy but transparent, due to the nature of the intergovernmental plenary system (Figure 15.3 shows the participants).

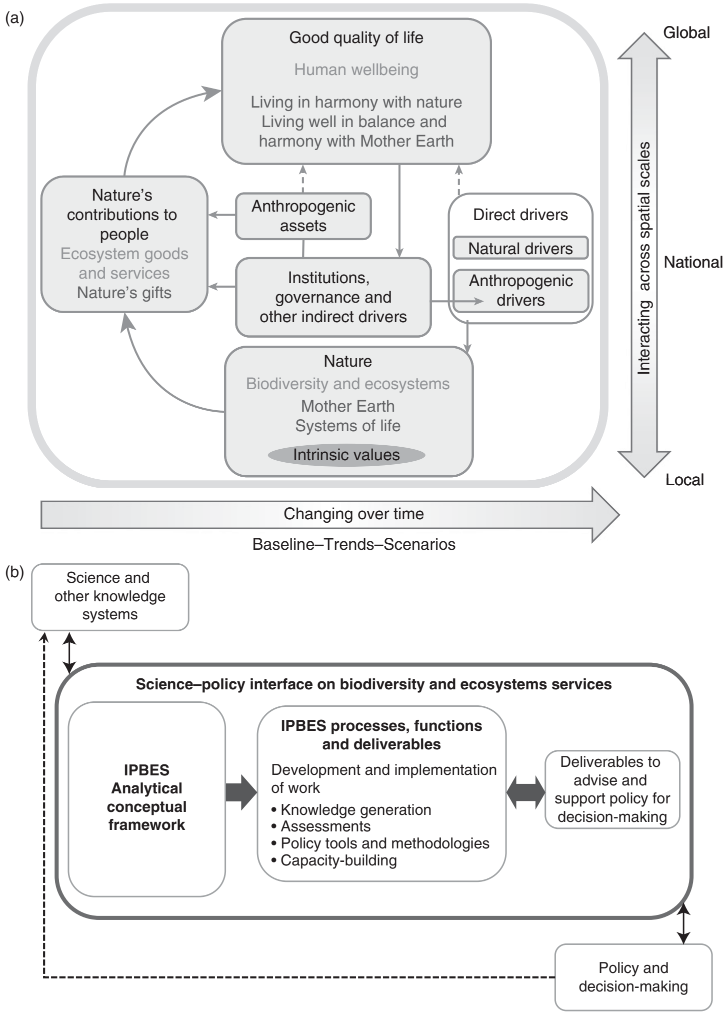

Figure 15.2 (a) IPBES operational model of the Platform (adapted from IPBES, 2014), (b) analytical conceptual framework of assessments (adapted from Díaz et al., 2015). (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

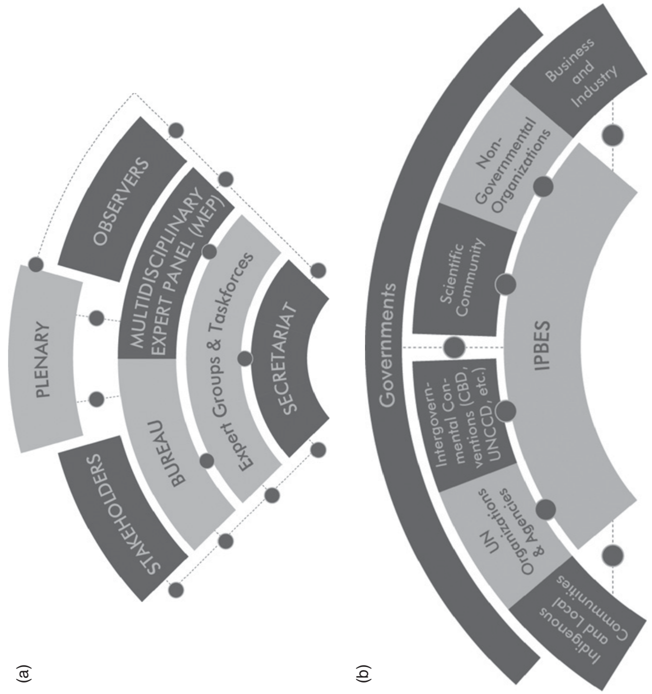

Figure 15.3 Structures of IPBES (a) science–policy platform, (b) intergovernmental plenary (IPBES, 2018b). (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

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IPBES is an independent intergovernmental platform that works in partnership with the large United Nations Programmes such as the UN Environment Programme (UNEP), the UN Educational, Scientific and Cultural Organization (UNESCO), the Food and Agriculture Organization of the UN (FAO) and the UN Development Programme (UNDP). Its work is aligned to the CBD and other international Conventions (e.g. Ramsar, CITES, as well as the UNCCD). Its unique role is to mobilise scientific communities from multiple disciplines to harmonise research agendas on biodiversity and its impact on societies among key organisations, such as the International Union for the Conservation of Nature (IUCN), Future Earth and the Group On Earth Observations Biodiversity Observation Network (GEO BON) (IPBES, 2018a). While the social sciences and humanities are still underrepresented in the process (Vadrot et al., 2018), IPBES aims to attract more social scientists.

15.3.3 The Sustainable Development Goals

The establishment of IPBES was well timed to coincide with the inception of United Nation's new global agenda, the Sustainable Development Goals (SDGs) (UN, 2015). Historically, the concept of sustainability builds on more than 30 years of intense political discourse, following the Brundtland Commission (1987), the Rio Declaration on Environment and Development (UN, 1992) and the eight Millennium Development Goals (MDGs) (McArthur, 2014). These included a goal to 'ensure environmental sustainability', but did not relate to biodiversity specifically. Based on the MDGs, the SDGs were developed as a more holistic and integrated approach to development following the United Nations Conference on Sustainable Development in 2012. In January 2016, the *2030 Agenda for Sustainable Development*, comprising 17 SDGs with 169 targets and a declaration, were officially approved during a UN Summit attended by 193 member states (UN, 2015). The 2030 Agenda aimed to stimulate action in areas of critical importance for humanity and the planet with a set of approved goals (Figure 15.4). It provides a holistic strategy that combines economic development, social inclusion and environmental sustainability and applies to all countries – poor, rich and middle-income alike – and to all segments of society (ICSU, 2017); this is the major novelty and strength of this framework, in which biodiversity conservation is no longer isolated.

Its main decision body, the High-level Political Forum, provides a central platform for all member states to review progress towards the 2030 Agenda for Sustainable Development and the SDGs. To foster the implementation of the SDGs, the United Nations partnered with several governmental and non-governmental organisations worldwide to ensure commitment to this cause and also enhance synergies across global conventions. Several international coalitions, including the G20 and G8, have incorporated the 2030 Agenda

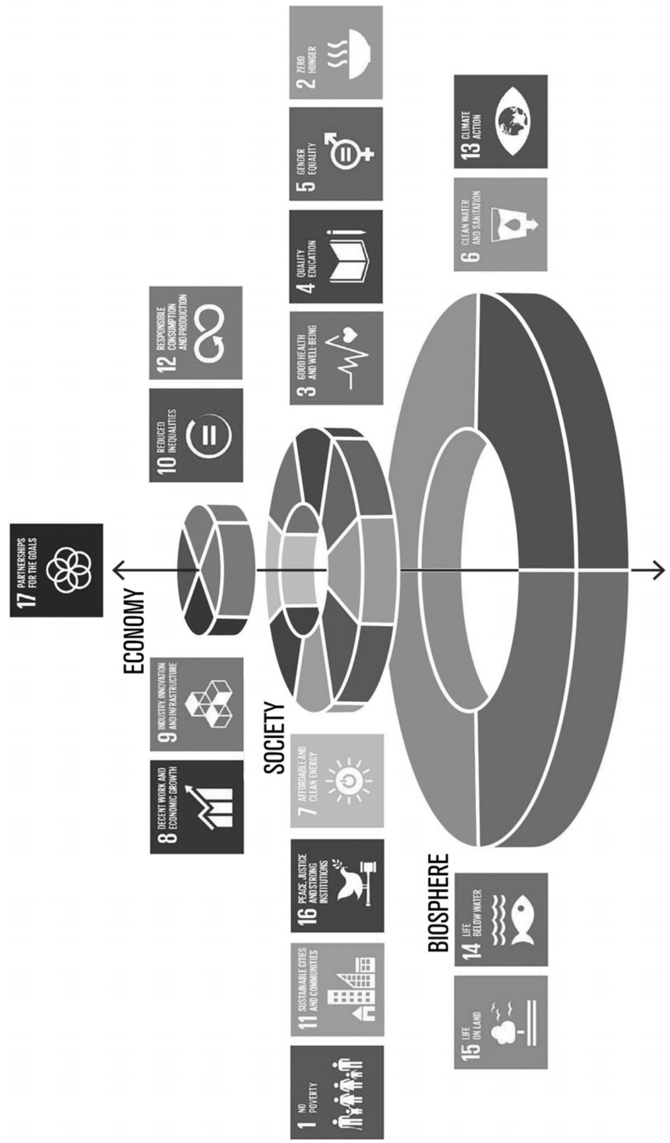

Figure 15.4 The Sustainable Development Goals 'wedding cake' (source/credit: Azote Images for Stockholm Resilience Centre, Stockholm University). (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

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into their policy frameworks, although reviews have indicated that the implementation of SDGs in general and the biodiversity goals in particular (SDG 14 life below water and SDG 15 life on land) are not yet sufficiently incorporated into national policies of either OECD or non-OECD countries (O'Connor et al., 2016; Schmidt-Traub et al., 2017). Achieving the SDGs requires a willingness to cooperate at the international level and sustainable development to be anchored as a guiding principle in all policy fields at national, European and international levels (Schmidt-Traub et al., 2017). However, the achievement of many SDGs depends largely on action taken in member states and above all requires the development and implementation of strong operative concepts at national and regional levels (Schmidt-Traub et al., 2017). Governments and other stakeholders are expected to mobilise efforts to establish national and regional plans towards implementation of the SDGs (ICSU, 2017). This requires a balance between addressing the scope and systemic nature of the 2030 Agenda with budgetary, political and resource constraints that inevitably mean countries prioritise certain targets (ICSU, 2017) and the associated risk of negative effects for 'non-prioritised' ones, particularly if they are in a conflicting, even mutually exclusive, relationship (Schmalzbauer & Visbeck, 2016). Furthermore, the goals are rarely independent and consequently failures in one area can quickly undermine progress in other areas (Schmalzbauer & Visbeck, 2016). National policy-makers thus face the challenge of understanding the inter-dependencies across the SDGs and achieving coherent implementation to ensure that progress in some areas is not made at the expense of progress in others. In addition, national policies often have implications on neighbouring countries or across globalised value chains, i.e. we need to avoid pursuing objectives in one region that negatively affect other countries' pursuit of their objectives (ICSU, 2017).

15.4 Joint working of the CBD and SDG 2030 Agenda

According to the CBD, the Strategic Plan for Biodiversity and the 2030 Agenda are consistent with each other and mutually supportive (CBD et al., 2017). The central role of the biosphere is explicitly acknowledged in the new illustration of the SDGs, as layers in a 'wedding cake' that build on one another, developed by the Stockholm Resilience Centre (see Figure 15.4). It implies a transition away from sectoral approaches embedding economy and society as parts of the biosphere and recognises that the related goals of promoting human dignity and prosperity can only be achieved sustainably if the Earth's vital biophysical processes and ecosystem services are safeguarded (ICSU, 2017). However, working towards the implementation of the SDGs in UN member states requires a process of prioritisation. This poses a fundamental challenge and possibly a genuine risk to

biodiversity conservation, as biodiversity concerns may not always be adequately anchored in other non-environmental policy sectors and thus may be overridden by other interests, especially when trade-offs arise between short-term development achievements and long-term sustainability (Schmalzbauer & Visbeck, 2016). These trade-offs will often be at the expense of biodiversity (SDGs 14 and 15), with likely negative consequences for several other SDGs, such as those related to food security, water supply and climate change mitigation. There have been some attempts to analyse these links further (Scharlemann et al., 2016; SRC 2016; CBD et al., 2017), but the critical question of how to resolve potential trade-offs in practice remains to be negotiated at the local, national and regional scales.

15.5 Role of science and evidence

15.5.1 CBD

To conserve biodiversity, it is important to devise action on reliable, sound knowledge about its components. The CBD has incorporated this principle by obliging all contracting parties to identify and monitor particularly diverse ecosystems and habitats, threatened species and other biodiversity components of ecological, social, economic, cultural or scientific importance (Article 7 and Annex 1 of the Convention). To effectively conserve biodiversity, it is furthermore crucial to build action on sound evidence about the factors that lead to its loss and measures to reduce their impact, e.g. possible policy and management responses and their effectiveness.

The CBD collates, utilises and synthesises such knowledge in various ways. The CBD secretariat, for example, regularly publishes notifications that call for input with regard to particular questions. Approximately every five years, it publishes the 'Global Biodiversity Outlook', an assessment of global biodiversity states and trends and of the progress toward the CBD objectives (Leadley et al., 2014).

The CBD's Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) is responsible for processing knowledge-related tasks and providing advice and guidance to the COP with respect to scientific (and technical and technological) questions. The SBSTTA plays a crucial role because it presents recommendations that are often later followed by the COP (sometimes with modifications). Therefore, its meetings are highly politicised and cannot provide a comprehensive and balanced evidence base with regard to upcoming COP negotiations. This has long been a major criticism of the SBSTTA and was one of the major motivations for creating the Intergovernmental Platform on Biodiversity and Ecosystem Services.

15.5.2 IPBES

As a platform of scientific communities and knowledge-holding networks, IPBES is expected to play a critical role in providing the best available, rigorous and comprehensive scientific evidence to various biodiversity-related conventions and international initiatives. Since its establishment in 2012, IPBES has brought together more than a thousand scientists and knowledge-holders from around the globe to integrate knowledge systems from multiple disciplines. The main IPBES products and deliverables are assessments, which synthesise scientific findings and evidence on biodiversity change and its impact on human well-being to inform policy decisions.

One of the first IPBES assessments, the IPBES pollination assessment (IPBES, 2016) has made a significant global impact on policy development. For instance at the 13th Conference of the Parties to the Convention on Biological Diversity in Mexico in 2016 (CBD COP13), a COP decision recognised its relevance for the planned fifth edition of the Global Biodiversity Outlook and listed it among the best available scientific information. The COP also encouraged parties, other governments, relevant organisations, the scientific community and stakeholders, as well as indigenous peoples and local communities, to develop and use these tools and contribute to their further development (CBD, 2016a). The pollination assessment provides a best-practice 'toolkit' of the approaches that can be used to decide policies and actions by governments, the private sector and civil society. Different valuation methodologies are evaluated according to different visions, approaches and knowledge systems, as well as their policy relevance, based on the diverse conceptualisation of values of biodiversity and nature's benefits to people, including provisioning, regulating and cultural services. As such, this assessment has generated a wide range of follow-up products, actions and policy initiatives, including the following.

- A formal endorsement of the key messages of the assessment by the parties to the CBD at the 13th Conference of the Parties (COP13) in Mexico (CBD, 2016b).
- The formation of a 'Coalition of the Willing' by a growing number of governments around the world, inspired by the assessment to act nationally to protect pollinators and promote pollination (Promote pollinators, 2018).
- Publications in high-ranking scientific journals building on and reviewing the assessments (Potts et al., 2016; Díaz et al., 2018).
- An expanding list of national strategies and action plans on pollination in countries including, among others, Brazil, France, Germany, the Netherlands, the Republic of Korea and South Africa.

The IPBES scientific community also made significant contributions to the controversial discourse on the appropriateness of the ecosystem service concept and paved the way to reconciling differing views on conceptualisation of the human–nature relationship (Díaz et al., 2018; Stenseke & Larigauderie, 2018). It should be recognised, however, that the community will continue to

use many different terms for ecosystem services or the contributions people receive from nature, depending on context, and this plurality should be welcomed (Peterson et al., 2018). Both the open-ended stakeholder network and the new concept of nature's contributions to people reflect the co-design and co-development aspects of IPBES as a learning organisation.

The challenges posed in IPBES are many, including a more balanced integration of scientists and experts from both natural and social sciences for a holistic understanding of biodiversity and its interactions with society and humanity (Jetzkowitz et al., 2018; Stenseke & Larigauderie, 2018). A more thorough consideration of, and improvement in, achieving the balance and quality of geographic, gender and disciplinary representations will be critical in filling the knowledge gaps and adding interdisciplinary value to the IPBES assessments (Obermeister, 2017; Heubach & Lambini, 2018). Moving forward, it will be important for IPBES to liaise with the private sector for greater impact on socially responsible and sustainable development, and with the public in disseminating scientific knowledge to promote changes in individual behaviour and decisions conscious of biodiversity conservation.

15.5.3 SDGs

It is crucial that progress in the implementation of the SDGs in national policy processes is adequately monitored (Hák et al., 2016; Reyers et al., 2017). To track the SDGs, the UN Statistics Commission has recommended over 230 official indicators, and countries are invited to submit voluntary national reviews of their progress to the High-Level Political Forum (Sachs et al., 2017). However, not all of the indicators have well-established definitions or data for all UN member states. A review of reports submitted so far (Bizikova & Pinter, 2017) found they were particularly weak on the environmental SDGs 12–15 (Sachs et al., 2017) and the assessment of interlinkages, synergies and trade-offs between targets (Allen et al., 2018). The evaluation of SDGs and tracking the progress to their achievement requires holistic scientific approaches to better understand the linkages between the SDGs and their underlying challenges, to understand thresholds, rebound effects and tipping points, and to explain the benefits and trade-offs of a range of development pathways that could lead to a more sustainable global society (Schmalzbauer & Visbeck, 2016).

The IPBES community of scientists can also provide best expert knowledge and scientific evidence for the sustainable development of the planet to inform the SDGs. For example, the recent IPBES assessment of land degradation and restoration (IPBES, 2018c) mapped the relevance of land degradation against the SDG goals. This may help to mainstream biodiversity across sectors and societies and bring forth synergies between global initiatives. A well-functioning knowledge generation mechanism connecting scientific and policy bodies of the platform will be particularly important if IPBES is to become an effective catalyst and orchestrator of harmonised science, policy and practice for better conservation.

15.6 Achievements of the CBD, IPBES and SGDs

There are several developments at the national level that can directly be traced to the CBD, such as the adoption of National Biodiversity Strategies and Action Plans in 185 countries of the world (as of December 2018, according to the CBD website). Other examples of direct influence of the CBD on its member states are the national regulations that parties have adopted to comply with the provisions of the two Protocols that have arisen from the CBD: the Cartagena Protocol on biosafety and the Nagoya Protocol on Access and Benefit Sharing. However, the CBD's influence on biodiversity governance at the national scale still appears limited. This is partly due to the power imbalances that exist among global institutions, and strong global forces that prioritise economic considerations over nature conservation, as well as power relations and societal preferences at the national scale. Furthermore, the fact that the CBD lacks a non-compliance mechanism may further weaken its influence.

Nonetheless, the CBD has provided inspiration to a great variety of state and non-state actors to initiate conservation actions. For example, the Aichi Biodiversity Targets (included in the Strategic Plan of the CBD for the period 2011–2020) have sparked debates and research on biodiversity-related questions and serve as important reference points in calls for greater efforts in nature conservation (e.g. they are often referred to by non-governmental organisations). These Targets, along with the UN Decade on Biodiversity with the same timeframe (2011–2020), have also inspired numerous actions on the ground, as documented on the CBD website (www.cbd.int/2011–2020/). Furthermore, the CBD mobilises resources and may provide finances to developing countries for the purpose of implementing the Convention (e.g. via the Global Environment Facility).

An important area where the CBD and SDGs exert influence is through fostering collaborations, between different biodiversity-related conventions and among relevant organisations and stakeholder groups at all subglobal scales. Alongside IPBES, they have also raised awareness of the values of biodiversity and their integration in other societal goals.

15.7 What next – how to engage?

As demonstrated, the past decades have seen an alignment of biodiversity-related agendas with different sectoral policies. Now the Aichi Biodiversity Targets and the SDGs need an increased implementation effort to deliver tangible results. In the national policy context this hinges on ensuring consistency within and between these two agendas and other political processes, effective governance systems, institutions and partnerships, and intellectual and financial resources

(ICSU, 2017). Scientists can – jointly with societal and policy actors – help to provide supporting evidence (see also Schmalzbauer & Visbeck, 2016):

- to build new partnerships across disciplines, to engage different knowledge domains and thereby foster innovation;
- to develop problem- and solution-oriented metrics, tools and indicators to aid the process of continuous learning and adaptive management;
- to provide open-source and open-access data and infrastructure to share knowledge and good practice;
- to conduct economic, social and health cost–benefit analyses to assess joint action versus silo approaches;
- to assist forecasting and informed decision-making through scenarios and models.

In order to maximise the impact of science in society through international conventions, national policies and local implementations, scientists can:

- address conservation questions in their own research and proactively enhance the transferability of research results as evidence for real-world application;
- actively engage with government agencies, NGOs and the public to learn about their knowledge needs, the ongoing political processes and the mode of operation, to enhance the societal relevance of their own research and better frame and communicate own research findings in a policy context (see Chapters 10 and 13);
- attend meetings of CBD, SDG, IPBES and other relevant conventions and initiatives as experts, observers, stakeholders or delegations through the channels of organisations and countries;
- proactively engage as authors or reviewers in IPBES assessments or other science–policy reports and contribute scientific evidence throughout the process, even if not a formal contributing author. IPBES has open calls and is open for engagement on many levels;
- develop transdisciplinary research collaborations and networks with experts from agencies, NGOs and other civic organisations.

This engagement at the science–policy interface requires time, openness and willingness for true collaboration between scientists, policy advisors and practitioners. While not always easy in short-term research funding circles, this can be very rewarding for everyone involved. Overall, conservation can only move forward when aligned with other policy goals and through integral support of all disciplines and all sectors to work for 'People and Nature'.

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RESEARCH ARTICLE

PEOPLE AND NATURE | BRITISH ECOLOGICAL SOCIETY

Developing multiscale and integrative nature–people scenarios using the Nature Futures Framework

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Abstract

1. Scientists have repeatedly argued that transformative, multiscale global scenarios are needed as tools in the quest to halt the decline of biodiversity and achieve sustainability goals.
2. As a first step towards achieving this, the researchers who participated in the scenarios and models expert group of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) entered into an iterative, participatory process that led to the development of the Nature Futures Framework (NFF).
3. The NFF is a heuristic tool that captures diverse, positive relationships of humans with nature in the form of a triangle. It can be used both as a boundary object for continuously opening up more plural perspectives in the creation of desirable nature scenarios and as an actionable framework for developing consistent nature scenarios across multiple scales.
4. Here we describe the methods employed to develop the NFF and how it fits into a longer term process to create transformative, multiscale scenarios for nature. We argue that the contribution of the NFF is twofold: (a) its ability to hold a **plurality** of perspectives on what is **desirable**, which enables the development of joint goals and visions and recognizes the possible convergence and synergies of measures to achieve these visions and (b), its **multiscale** functionality for elaborating scenarios and models that can inform decision-making at relevant levels, making it applicable across specific places and perspectives on nature.
5. If humanity is to achieve its goal of a more sustainable and prosperous future rooted in a flourishing nature, it is critical to open up a space for more plural perspectives of human–nature relationships. As the global community sets out to develop new goals for biodiversity, the NFF can be used as a navigation tool helping to make diverse, desirable futures possible.

KEYWORDS
biodiversity, futures, IPBES, models, nature, scenarios, values

1 | INTRODUCTION

The rapid decline in the state of nature and its clear links to the prosperity of human societies has led scientists to argue that transformative change is required in how societies relate to nature. The first Global Assessment by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the recent special report on Global Warming of 1.5°C of the Intergovernmental Panel on Climate Change (IPCC) both argue that a sustainable world cannot be achieved without transformative systemic change of our societies (IPBES, 2019; IPCC, 2018). Achieving such a change requires identifying visions, pathways and plans that can help people navigate away from undesirable futures and towards desirable ones (Balvanera et al., 2017; Bennett et al., 2016; Peterson et al., 2018). The urgency to reframe the future of human societies' relationships with nature has become even clearer since the outbreak of the Covid-19 pandemic, which is sure to enter the global negotiation agendas for the next biodiversity and climate change targets that will take place in 2021. Decisions on how to catalyse transformative change can be supported by the co-production of visions, scenarios and pathways that are collectively and transparently developed and are made accessible to all interested stakeholders (Pereira, Asrar, et al., 2019). New types of globally relevant scenarios and futures are urgently needed that not only provide an orientation of what diverse possibilities might be achievable, but also to catalyse the movement towards these more desirable futures for people and the planet, in all their plurality (Luederitz, Abson, Audet, & Lang, 2017).

In this paper, we address the question of how a new set of scenarios that respond to these needs can be developed. We outline the systematic steps to develop such scenarios that have been made by a group of experts who participated in the IPBES scenarios and models expert group, and we explain the methodology of each element of the process in detail to illustrate how the process differs from the development of previous global environmental scenarios. A key outcome of the process thus far has been the creation of the Nature Futures Framework (NFF), a heuristic tool based on the diverse, positive relationships that humans have with nature, whilst at the same time offering a structure for consistency in the scenarios and models that use it. The NFF enables the co-production of novel scenarios that incorporate diverse interventions towards positive future trajectories for nature and nature's contributions to people. In our discussion, we analyse the contribution of the NFF both as a boundary object to open up more plural perspectives in the creation of nature scenarios and as an actionable framework for developing consistent nature scenarios across multiple scales and levels, whilst enabling this plurality to flourish.

We conclude with a call to arms for the research community to mobilize and help in moving this agenda forward. We see a broad sweep of the research community interested in the future of nature and its contributions to people as the main audience for this paper. By describing here the background, methodological process and rationale underpinning the NFF, we hope that it will inspire other researchers—ranging from those interested in participatory co-production processes with local communities through to global integrated assessment modellers—to integrate the NFF into their own activities. We set out specifics for how we envision this joint venture could be undertaken in the discussion.

1.1 | New scenarios for nature

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services was established in 2012 by 94 member states of the United Nations to become the leading intergovernmental body for assessing the state of nature and nature's contributions to people (NCP), as well as options for action. The IPBES conceptual framework illustrates that the ways that nature, biodiversity and ecosystem services are conceived and valued vary across cultures and societies (Díaz et al., 2015). People ascribe different types of values to nature, and its contributions to a good quality of life are often perceived and conceptualized by people in different and sometimes conflicting ways (e.g. as the environment, Mother Earth, natural resources, natural capital from which people derive ecosystem services, our biological community etc.; IPBES, 2015). Furthermore, people ascribe multiple values to the same natural entity (e.g. a landscape can simultaneously be seen as a provider of food and medicine, a good site for mineral exploitation, important for water supply, a habitat for wildlife, a beautiful place or a sacred space; IPBES, 2015). Being able to recognize this plurality and address it in assessments, policies, models and scenarios is a key goal of IPBES.

Scenarios are recognized as powerful tools to examine how different pathways of future human development and policy choices could affect nature and nature's contributions to people (NCP; Ferrier et al., 2016; Harrison et al., 2018; Rosa et al., 2017). However, to date, most scenarios for global environmental assessments have explored impacts of society on nature, such as biodiversity loss, but have not explored the role of nature and related policies in driving development (Ferrier et al., 2016; Millennium Ecosystem Assessment, 2005; Pereira et al., 2010; Saito et al., 2019). Indeed, the variety of connections between people and nature, and how these vary across the world, have mostly been ignored in scenario processes, and the linkages between nature and nature's contributions to people have been underexplored (Cumming et al., 2005; Johnson et al., 2020; Rosa et al., 2017). Furthermore, most existing global assessment scenarios have only been conducted at aggregated global scales, in which local and regional variation, tele-connections and cross-scale dynamics have not been well captured (IPBES, 2016; Obermeister, 2019; Rosa et al., 2017). Addressing issues of power and rationality in how scenarios are framed, and ensuring an equitable inclusion of voices, especially those of the most marginalized to frame matters of concern is another core challenge (Cairns & Wright, 2019). In relation to nature conservation, IPBES have highlighted the particular importance of including indigenous and local knowledge (ILK), which has long been marginalized or invisible in global scenarios and models. It is therefore increasingly clear that there is a need for new global scenarios for nature (Kok et al., 2016; Rosa et al., 2017; Wyborn et al., 2020).

The scenarios that are currently widely used in global environmental assessments are the Shared Socio-Economic pathways (SSPs). The SSPs were developed by the climate change community to help outline potential socio-economic trends that would influence how climate change manifests in the future (O'Neill et al., 2014, 2017). Whilst they have been successful in both the science and policy domain and in unifying different areas of research, the SSPs have limitations in their applicability to biodiversity and nature research. Firstly, they say little about desirable outcomes for nature and its contributions to people, making it difficult to incorporate biodiversity-specific interventions into models (IPBES, 2016; Rosa et al., 2017). This limits their ability to inspire change (Bennett et al., 2016; IPBES, 2016; Pereira, Sitas, Ravera, Jimenez-Aceituno, & Merrie, 2019). Second, these scenarios are expert-led and have not been legitimized through a co-production process in which a plurality of perspectives are included (Duncan et al., 2018; Kok et al., 2016; Tengö et al., 2017). Finally, the SSPs focus on their use only as inputs to a scientific process (O'Neill et al., 2017). However, in global assessments scenarios also act as boundary objects that are used to mobilize action, and as tools for building future literacy amongst stakeholders (Kok et al., 2016; Tengö et al., 2017). These concerns highlight the need for new, participatory nature scenarios that can inform decision-making and inspire action.

Following from the IPBES methodological assessment of scenarios and models of biodiversity and ecosystem services (IPBES, 2016), the former IPBES scenarios and models expert group set out a research strategy to address some of the above concerns and initiated the development of multiscale scenarios for nature based on pluralistic desirable visions for human relationships with nature (Rosa et al., 2017). These scenarios should be produced at and applicable across **multiple scales** through a process that includes a **diversity of stakeholder voices and values**, and explicitly include pathways that enable humanity to meet the **desired** 2050 vision under the Convention on Biological Diversity (CBD) of 'Living in harmony with nature' where 'biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people' (UNEP, 2010: para 11). Central to this process was the research question of how to develop these new scenarios in a way that addresses the gaps identified in other scenarios in order to support the work programme of IPBES. In this paper, we answer this question by documenting the iterative process that was undertaken by the IPBES scenarios and models expert group from 2016 to 2019. Presenting methodological approaches in scenario development is important to ensure scientific credibility as well as legitimacy (Sarkki et al., 2014), but it also ensures replicability where others are able to build on and further contribute to the approach, and critique it. In the following section, we present the outputs of the process to date, including a description of the visions, stakeholder feedback and framework development, and also outline the plan for the development of scenarios that can be used by modellers and practitioners.

2 | METHODOLOGICAL APPROACH

There is an emerging agreement that sustainability challenges require new ways of knowledge production and decision-making, including the involvement of actors from outside academia into the research process in order to integrate the best available knowledge, reconcile values and preferences, as well as create ownership for problems and solution options (Laing & Wallis, 2016; Obermeister, 2017). As the development of the new nature scenarios is taking place under the auspices of an intergovernmental science–policy platform, such a transdisciplinary approach was required. However, doing transdisciplinary research is not straightforward and requires a deep level of reflection and learning as well as an openness to change direction in response to the needs of diverse participants (Norström et al., 2020; Pereira, Frantzeskaki, et al., 2019). As such, the methodological approach of the scenario development process needed to navigate this complex reality whilst resulting in a usable outcome.

There is currently a debate as to whether ensuring credibility, relevance and legitimacy are of the utmost importance to policy in assessment processes (Sarkki et al., 2015) or whether applicability, comprehensiveness, timing and accessibility are of more relevance (Dunn & Laing, 2017). At the same time, there are trade-offs and constraints to any science–policy process (Sarkki et al., 2014). Whilst being able to leverage the inclusion, representivity and legitimacy offered by intergovernmental platforms, this can also come with certain constraints, including limited time and funding to undertake specific tasks (see Sarkki et al., 2014), and sometimes a lack of interdisciplinary expertise and other forms of knowledge (Harrison et al., 2018; Obermeister, 2017; Vadrot, Jetzkowitz, & Stringer, 2016; Vadrot, Rankovic, Lapeyre, Aubert, & Laurans, 2018). For the expert group, designing a process that could overcome these constraints, whilst producing diverse multiscale positive scenarios for nature was a key challenge. A first step was to ensure a common language of terms within the research group (Box 1). A second step was the development of core principles. Despite these considerations, the overall approach, especially in terms of including stakeholder voices in the process, was a combination of systematic outreach to a broad diversity of stakeholders across all continents and levels of governance, and using additional opportunities as they occurred in order to reach more voices. This process was still constrained by the limited human and budget resources that were available.

We employed three core principles for the approach: co-production, interactive iteration and pluralism. **Co-production** is increasingly seen as an important process in sustainability science as it enables the harnessing of multiple viewpoints and creates buy-in to a process (Norström et al., 2020). A core aspect of the science–policy interface is the dynamic **interaction** between stakeholders and scientists that **iterates** over time, allowing for learning and readjustments (Priess & Hauck, 2014; Sarkki et al., 2015). Finally, according to the IPBES conceptual framework, a **plurality** of perspectives is core to the platform (Díaz et al., 2015). The subsequent approach was largely informed by the multiple evidence base approach where an enriched picture of understanding serves a starting point for further knowledge generation, triangulation and assessment (Tengö, Brondizio, Elmqvist, Malmer, & Spierenburg, 2014; Tengö et al., 2017).

Next, we outline the iterative process (in the form of phases) and outcomes that resulted at each step, and lay out what is planned to continue to build on the process in the future. This iterative approach is how we went about answering the research question of how to create a new set of scenarios that are diverse, desirable, and multiscale. It has taken time and learning along the way has been a key part of this process, which is also why we seek to document it in this paper. In the discussion section, we situate the findings from this process within the existing literature and critically examine the contribution that the NFF could make in its aim for improved nature scenarios for decision-making in the post 2020 agenda.

2.1 | Iterative phases

The scenario development process consisted of five distinct methodological phases (Figure 1): Phase (i) visioning and storyline development through a participatory workshop (Section 3.1); Phase (ii) elaboration through stakeholder engagement to address gaps in the visions (Section 3.2); Phase (iii) formulation of the NFF based on analysis of the elaborated visions by the expert group (Section 3.3); Phase (iv) further refinement of the NFF through stakeholder engagement (Section 3.4); and finally, Phase (v) consolidation of scenario narratives that can be used by diverse research communities, including modellers (Section 3.5). In the results section, we present the methods that were used as well as the outputs that arose from each of the steps. We discuss the implications of the method and the future development of the NFF scenarios in Section 4.

2.2 | Analysis

At each step in the co-production process, information was documented and recorded. For the analysis of the information captured from the stakeholder engagement exercises (Phases i, ii and iv), an approach similar to the Nominal Group Technique (NGT) was

BOX 1 Glossary of terms

Drivers—The external factors that cause change in nature, anthropogenic assets, nature's contributions to people and a good quality of life. They include institutions and governance systems and other indirect drivers, and direct drivers (both natural and anthropogenic; IPBES, 2016).

Future wheels—A graphic method similar to a collectively brainstormed mind-map that identifies direct and indirect future consequences or impacts of a particular change or development (Glenn, 2009).

Nature Futures Framework (NFF)—A heuristic that captures diverse, positive values for human–nature relationships in a triangular space (the NFF triangle; see Figure 5). We consider three main ways of valuing nature at each of the vertices (nature for nature, nature for society and nature as culture). The NFF builds on the three values of nature (intrinsic, instrumental and relational values, respectively) identified by the IPBES and repurposes it to make it actionable for the modelling and scenarios community. The NFF triangle illustrates how it is possible to emphasize a complex mixture of values for appreciating nature depending where in the triangle you are situated and thus allows for a plurality of perspectives to be held in different times, contexts and spaces. As such, the NFF approach and the triangle can be used both as a boundary object for continuously opening up more plural perspectives in the creation of nature scenarios (when referring just to the NFF triangle) and as an actionable framework for developing consistent scenarios and models across multiple scales and levels when referring to the overall process captured in Figure 1.

Pathways—Different strategies for moving from the current situation towards a desired future vision or set of specified targets. They are purposive courses of actions that build on each other, from short-term to long-term actions into broader transformation (Ferguson, Frantzeskaki, & Brown, 2013; Frantzeskaki, Loorbach, & Meadowcroft, 2012; Wise et al., 2014). The Three Horizons approach is often used to define such pathways in future visioning processes (Sharpe, Hodgson, Leicester, Lyon, & Fazey, 2016).

Scenarios—Plausible and often simplified descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions about key driving forces and relationships (Millennium Ecosystem Assessment, 2005). A scenario skeleton is a simplified outline of a scenario.

Seeds—Current positive and inspiring initiatives that hold potential to shape a more just, prosperous and sustainable future. They can be initiatives (social, technological, economic, or social–ecological ways of thinking or doing) that exist, at least in prototype form, and that represent a diversity of worldviews, values, and regions, but are not currently dominant or prominent in the world (Bennett et al., 2016).

Three Horizons approach—A simple, graphical and collaborative approach to build pathways for desirable futures based on a structured and guided dialogue considered along a temporal axis (now, near future, and far future): the first horizon is a business as usual scenario, the second horizon represents the necessary actions to move from the present to the desired future and the third horizon represents emerging paradigms, ideas and innovations for a desirable future (Sharpe, 2013; Sharpe et al., 2016; Figure 6).

Values—A principle or core belief underpinning rules and moral judgements. Values as principles vary from one culture to another and also between individuals and groups (IPBES/4/INF/13).

Visions—A desirable state in the future and therefore, a component of scenarios (the possible future states), demarcated from predictions (likely future states) and pathways (that lead up to the vision). Visions are usually seen as a desirable image of the future and can be defined as a compelling, inspiring statement of the preferred future that the authors and those who subscribe to the vision want to create (Wiek & Iwaniec, 2014).

Visioning—'The process of creating a vision, that is, a representation of a desirable future state, as opposed to scenario building (possible future states), forecasting (likely future states), and backcasting (pathways to desirable future states)' (Wiek & Iwaniec, 2014, p. 497).

chosen to organize the discussion process whereby participants are asked to individually reflect and generate ideas based on predetermined questions (Duncan, 2004). Subsequently, they collectively prioritize the ideas and suggestions issued by the group members (Clemen & Winkler, 1999; Harvey & Holmes, 2012). The process allowed us to combine individual and collective reflection, to explore novel concepts, and eventually generate a list of priorities (Coker et al., 2014; Rankin et al., 2016). There is some criticism of NGT in that it is a version of the Delphi method where the feedback step takes place during a face-to-face meeting of experts instead of filling in anonymized questionnaires. For such group settings, Ayyub (2001) highlights the following as potential limitations: socially reinforced conformity within the group, dominance of strong-minded or strident individuals, group motive of

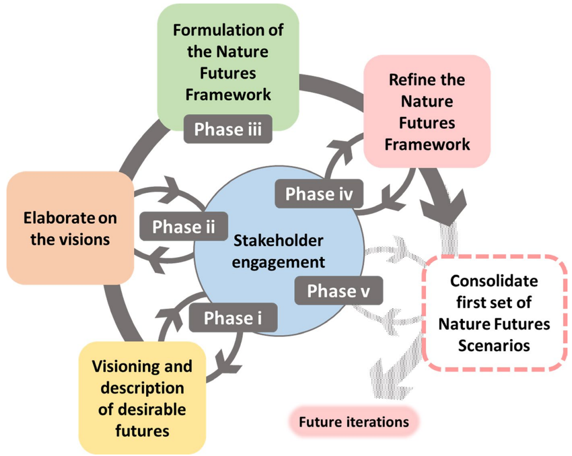


FIGURE 1 The five main methodological phases used for the development of Nature Future Scenarios, which are described in-depth in Section 3. This overall process illustrates how the Nature Futures Framework evolved. (Source: Authors' own)

quickly reaching agreement and group-reinforced bias due to common background of group members. To mitigate these potential limitations, the reflection process was guided by facilitators to ensure that individual personalities and other characteristics did not exert a disproportionate effect on outcomes. Multiple iterations of individual reflections followed by group discussion and synthesis is a valuable technique to avoid confrontation while allowing for a wider range of perspectives to be aired (Dalkey & Helmer, 1963). Multiple rounds of iterative feedback between multiple groups also allows for the attenuation of institutional and psychological biases (e.g. Hannagan & Larimer, 2010).

The description of the visions from Phase i were written in conjunction with all group members to ensure all aspects were covered and the mapping of the visions across a variety of characteristics was inductively undertaken as part of the workshop process. All the participants brainstormed and prioritized a set of characteristics that they thought were most relevant for describing the core aspects of the visions and these were then tested across all of the visions to see whether they were feasible. The final characteristics were chosen based on those that were most relevant to all the visions, and the visions were mapped according to group consensus, as a result of this inductive group process (see Table S1). More information on the specific analysis, including figures of the visions mapped across different characteristics, can be found in Lundquist et al. (2017).

During each stakeholder workshop (Phases ii and iv), notes were taken and these data were then recorded in a spreadsheet under thematic codes and analysed to see where there were overlaps and where gaps could be identified (see Table S3). Finally, expert opinion was used to analyse how the visions and stakeholder inputs could be optimally used to derive model-relevant scenarios that remained true to the co-produced, plural and multiscale nature of the undertaking. Through an inductive process that involved group analysis of the data in the visions and clustering into thematic components, the three dimensions of the triangle were derived (see PBL, 2018 for a full documentation of the expert workshop process undertaken in Phase iii). In Section 3 below, we present the results of how this iterative process was undertaken (Figure 1) as well as the outcomes at each of the phases that fed into subsequent phases.

2.3 | Ethical considerations

As this research was not undertaken through a university, there is no ethical clearance number. However, we endeavoured to follow all ethical guidelines in the involvement of human participants during the course of this research. The work presented was performed in accordance with the declaration of Helsinki and is in conformity with ethical standards of research. The authors have ensured that the information presented in this paper is either sourced from materials available in the public domain as a result of consent from participants or based on anonymous opt-ins to the research process by participants. Chatham House rules are applied in all workshops and nothing is attributed to any specific individual. All participants are authors of the publicly available workshop reports from which information was extracted for Phases i and iii (Lundquist et al., 2017; PBL, 2018). For the stakeholder engagement in Phases ii and iv, all participants were invited to opt in with an explicit explanation that their responses would be used as direct input to the future visions, but that all information would be anonymized. At the beginning of each stakeholder engagement process, we obtained verbal consent from all participants present that the outputs from the session may be used in research publications, but that no personal data would be used. The only personal details recorded were of the participants' nationality for regional representation purposes. More information on the source of data for each workshop is available in Supporting Information S2.

3 | METHODS AND RESULTS: DEVELOPING NATURE FUTURES

We use Figure 1 to structure this section and discuss the different methods and their results by each phase. A more in-depth description of the specific methods used in Phases i, ii, iii and iv is provided in Supporting Information S2.

3.1 | Phase i: Visioning and storyline development

The process began with a global participatory visioning workshop in Auckland, New Zealand, in September 2017 with 73 participants from 31 countries and representing all UN regions (Africa, Asia and the Pacific, Latin America and the Caribbean, Eastern Europe, Western Europe and others). The selection of stakeholders was a rigorous and iterative process that aimed to ensure as wide a range of geographies and perspectives as possible, drawing from a wide set of IPBES stakeholders (see Lundquist et al., 2017, Appendix A1 for the full selection criteria and description of the process). The final group included representatives from intergovernmental organizations, indigenous peoples from New Zealand, Europe, North America and Latin America, national government, non-governmental organizations, academia and the private sector and with a range of expertise on biodiversity topics, from urban development to agriculture to fisheries. The main objective of the workshop was the

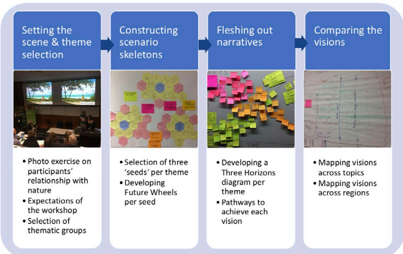


FIGURE 2 Four steps of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Nature Futures Visioning workshop in Auckland (Source: Adapted from Lundquist et al., 2017)

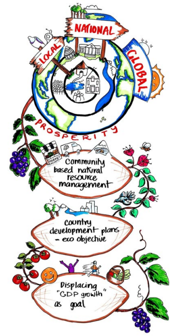
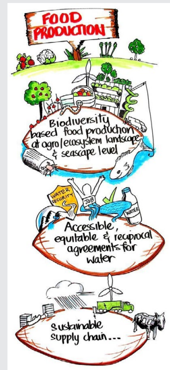
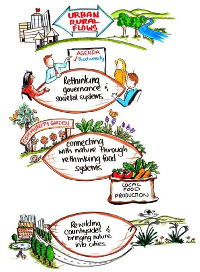
development of positive visions of nature and their associated storylines. It followed an approach designed to produce bottom-up, divergent visions of the future (Pereira, Hichert, Hamann, Preiser, & Biggs, 2018). The approach was selected with the intention of creating a space in which participants could think creatively to develop an inspired and powerful set of visions, grounded in existing 'Seeds' (see Box 1). The workshop process consisted of four steps (see Figure 2 and Lundquist et al., 2017, Appendix A2 for a detailed description of the workshop methodology). It is important to note that even though there was an explicit desire to include as many perspectives as possible, there is a clear bias in that only individuals who in some way prioritize and value nature are inclined to spend a full week formulating positive nature futures. The concerns of adequate representivity in a global undertaking such as this are paramount and will be picked up in the discussion.

The aim of the *first step* of the workshop was to set the scene and organize participants into thematic groups. In breakout groups, participants discussed themes that should be captured in future nature scenarios and then in plenary agreed on seven thematic, self-organized groups on freshwater, food, inclusive economics, urban–rural flows, indigenous and local knowledge, nature's dynamics and oceans. As these themes were brainstormed with the participants, they emphasize what those in the room thought were the most important thematic areas for discussion. Extending away from the thematic areas of focus into more holistic narratives for the development of scenarios was therefore acknowledged as a challenge that the team would face further into the process.

During the *second step* of the workshop, participants constructed scenario skeletons using three existing initiatives ('Seeds') that they believed would contribute to a better future that reversed the negative trends in their respective themes (Bennett et al., 2016, Box 1). In the *third step*, participants worked on fleshing out the narratives and exploring possible pathways to achieving the visions using the Three Horizons approach (Sharpe et al., 2016; Figure 6). This process was used to refine the visions, but did not develop specific timelines for change. As a result of these three steps, seven visions (i.e. potential Nature Futures) emerged (Table 1). These visions differ from scenarios in that they are representations of explicitly desirable futures, but do not describe pathways by which they each emerged from a baseline. As the method was designed to emphasize desirable futures, none of the descriptions are dystopian; rather different aspects of nature and its contributions to people emerge across the different visions.

Desired futures of peoples' relationship with nature varied substantially across these visions (Table 1). Some visions emphasize the indirect and intangible benefits of biodiversity, such as in *Urban Rural Flows*, *Nature's Dynamics* and *Culture*, while others emphasize the direct uses of nature, such as in *Food Production*. Acknowledging local ecosystem service flows and the development of multifunctional landscapes is an important component of *Urban Rural Flows*, *Water*, *Culture* and *Prosperity*. Others emphasize the management of global ecosystem service flows or the segregation of spatial uses of ecosystems, such as *Urban Rural Flows*, *Nature's Dynamics* and *Marine*.

TABLE 1 Seven visions of positive Nature Futures that emerged from the Auckland workshop (adapted from Lundquist et al., 2017)

Name of vision (shortened title)	Description	Image of seeds (Source: Mary Brake, Reflection Graphics; Dave Leigh, Emphasise Ltd.; Pepper Lindgren-Streicher, Pepper Curry Design)
Nature-based inclusive prosperity (Prosperity)	This vision illustrates a world based on reconstructing global governance and institutional mechanisms in order to recharacterize economic drivers to include externalities and incentivize sustainable and natural resource use and sustain richly diverse cultures, societies and nature into the future	
Sustainable food systems (Food Production)	This vision illustrates a world where global food production systems are re-engineered, emphasizing sustainable supply chains and benefit sharing mechanism in place between producers, traders, transporters and retailers, grounded on biodiversity-rich food production that supports local and indigenous communities	
ReFooding and ReWilding the urban Rural flows (Urban Rural Flows)	This vision illustrates a world where urban and rural communities are reconnected with nature, achieved through ReGoverning to improve governance systems, ReFooding to reinstate localized ecosystem service flows and ReWilding solutions to free up space for nature across rural and urban areas	

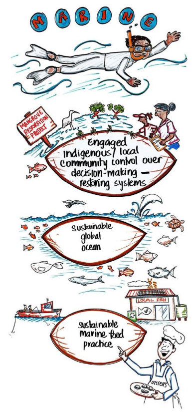
(Continues)

TABLE 1 (Continued)

Name of vision (shortened title)	Description	Image of seeds (Source: Mary Brake, Reflection Graphics; Dave Leigh, Emphasise Ltd.; Pepper Lindgren-Streicher, Pepper Curry Design)
Healthy Social–Ecological Freshwater Systems (Water)	This water-centric vision illustrates a world where innovative technologies and circular economies support efficient water use, extraction and recycling at localized scales,and legal rights and incentives are awarded to rivers as living systems	
A tasty World with values (Culture)	This vision illustrates a world where values of reciprocity, harmony and relationality drive humans' relationships with nature at all levels of human organization, where bio-culturally diverse and autonomous local food systems dominate, where there is respectful sharing among diverse knowledge systems and where governance systems recognize the rights of local producers and indigenous peoples with respect to territories, resources and knowledge	
Dancing with Nature (Nature's Dynamics)	This vision illustrates a world where nature is at the centre, and human societies both accommodate and benefit from natural environmental fluctuations. Dynamic societies and infrastructure emerge, with technological innovations that enable people and nature to adapt to the challenges of the Anthropocene	

(Continues)

TABLE 1 (Continued)

Name of vision (shortened title)	Description	Image of seeds (Source: Mary Brake, Reflection Graphics; Dave Leigh, Emphasise Ltd.; Pepper Lindgren-Streicher, Pepper Curry Design)
Healthy oceans, happy communities (Marine)	This ocean-centric vision illustrates a world where the high seas are closed to resource extraction, and coastal ecosystems provide a wealth of ecosystem services, supported by long-term sustainability strategies by governments and businesses that empower local-based sustainable co-management practices. Novel technologies support behavioural change to lower impact diets and increase food production	

During the *fourth and final step*, participants re-organized themselves into different sub-groups to map the visions across topics that they decided were the most relevant for identifying similarities and differences between the visions. These topics included (Lundquist et al., 2017; Table S1):

- State of biodiversity
- Value of nature
- Management of nature
- Governance systems
- Production and consumption of ecosystem services
- Socio-economic development
- Use of technology
- Lifestyles

The sub-groups mapped the visions across the different topics, which helped to identify commonalities and differences between them (see examples of use in Figure 3; Table S1). The visions were then compared across regions (Africa, Asia, Europe and North America, Latin America, Oceania), so that the experts present from these regions could reflect on how existing positive actions for biodiversity, infrastructure or other social, political or economic actors specific to a region might facilitate or impede the implementation of particular visions (Table S2).

Shared themes across multiple visions include green infrastructure (see Tzoulas et al., 2007), a circular economy (see Korhonen, Honkasalo, & Seppälä, 2018), context-dependent learning to inform environmental governance (see Armitage et al., 2018) and the equalization and reduction of humanity's global footprint (see Hoekstra & Wiedmann, 2014)—overall a more 'responsible stewardship' relationship between people and nature. All of the visions require a societal paradigm shift and significant changes in values, echoing the call for transformative change necessary for the sustainable use of natural resources (IPBES, 2019). The seven Auckland visions became starting points to inform the rest of the scenario development process, but required a lot of refinement before they could be adapted, including moving away from some of the thematic foci to more holistic descriptions of nature.

3.2 | Phase ii: Elaboration of the visions through stakeholder engagement

As the Auckland visions were developed by a small group of stakeholders, a series of further stakeholder engagement processes were conducted. The main aim of these sessions was to test how well the visions resonated with a broader group of people, how best to communicate the visions in engagement processes and to get feedback as to what the gaps or potential inconsistencies were in the visions so that these could be accounted for in the development of the scenario narratives. These stakeholder engagements took place through ad hoc engagement in IPBES events, such as Plenaries and other meetings that brought together diverse groups of stakeholders, as described below. More information is available in Supporting Information A: Methods.

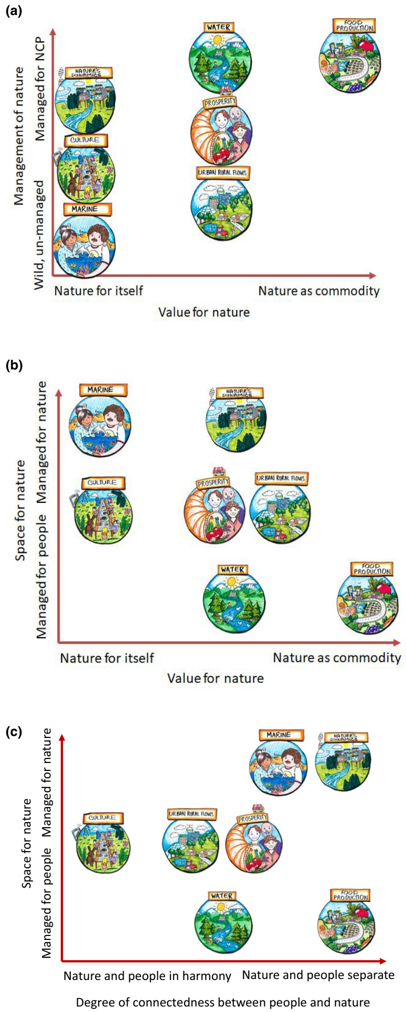


FIGURE 3 Mapping the visions across different dimensions. The axes capturing a range of values of nature from use to non-use including: (a) management of nature (y) and value for nature (x), (b) space for nature (y) and value for nature (x) and (c) space for nature (y) and degree of connectedness between people and nature (x). (Adapted from Lundquist et al., 2017)

3.2.1 | IPBES 6: Stakeholder day and plenary

In the margins of the sixth session of the IPBES Plenary (IPBES-6) and IPBES Stakeholder Day (Medellin, Colombia; 17–24 March 2018), a targeted survey was conducted to increase the 'reach' of our consultation activities. Two methods were used to generate further inputs, and materials were visualized and accessible both online and offline to facilitate accessibility and participation:

- An exhibition booth where visitors were able to add new ideas, identify gaps in visions and themes and modify or give feedback on the existing visions (Figure 4) by means of a paper survey.
- An online survey announced through both in person and social media channels.

All information from these stakeholder engagements were recorded to be used in the scenario narrative development process (Table S3).

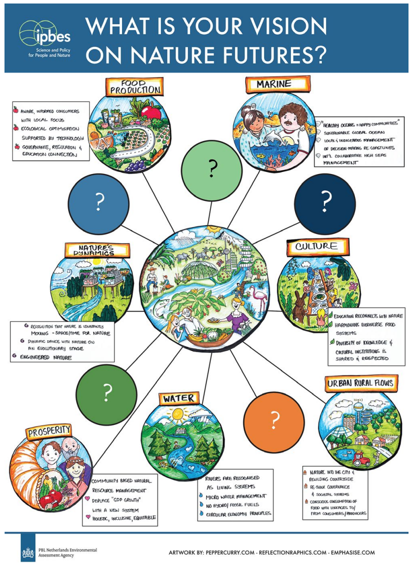


FIGURE 4 Poster used for IPBES 6 to illustrate and explain the current visions and to encourage people to suggest new areas or themes for exploration. (Source: Authors' own and images from Mary Brake, Reflection Graphics; Dave Leigh, Emphasise Ltd.; Pepper Lindgren-Streicher, Pepper Curry Design)

3.2.2 | Natural Capital Symposium 2018

The seven visions were also presented at the Natural Capital Symposium, held during 19–22 March 2018 at Stanford University, where the results of the visions from the Auckland workshop were presented to attendees. This annual symposium attracts global participants from a variety of sectors and disciplines, including NGOs, business, government and academia. Key learnings included the need for approaches to align participants in a constructive process to explore and enrich visions even when time is limited, and to develop processes that work across different knowledge backgrounds, including those with limited familiarity with scenario approaches. Not all the visions resonated with stakeholders equally and it was not easy to explain the main differences between the seven visions because of the high degree of overlap in some instances. The need to differentiate between aspects of the visions was an underlying rationale in the development of the NFF in the next phase and was also a core aspect for consideration in the scenario development process.

3.3 | Phase iii: Formulating the Nature Futures Framework

In June 2018, an expert meeting was organized in The Hague (PBL, 2018). The objective was to develop a plan for formulating scenarios across scales based on the prior visioning process in Auckland, and to identify concrete tasks for engaging both the expert community and broader stakeholders in further co-development of the visions. In response to the feedback from the stakeholder engagement processes in Phase ii, the expert group decided that it was necessary to map out the seven visions that had been developed in Phase i to see what the fundamental overlaps, similarities and differences were. A group of scientists spent 3 days analysing the visions coming out of Phase i, and the elaborations that resulted from Phase ii, testing different parameters for mapping and categorizing them in a meaningful way (see PBL, 2018 for a full account of the workshop process). Considering that all visions were intentionally desirable visions of future human–nature relationships, and that some were narrower in geographical or ecosystem scope (e.g. covering freshwater or marine systems), it was clear that the parameters for separating them would need to be clear and consistent. After many discussions the experts came to realize that underpinning the visions were three value perspectives for how people relate to nature (Figure 5).

Building on the IPBES guidance on multiple values that identify intrinsic, instrumental and relational values for nature (IPBES, 2015), but seeking to find short and descriptive names for these perspectives they were called:

- *Nature for Nature*, in which nature has value in and of itself, and the preservation of nature's diversity and functions is of primary importance;
- *Nature for Society*, in which nature is primarily valued for the benefits or uses people derive from it, and which could lead to an optimization of multiple uses of nature and
- *Nature as Culture*, in which humans are perceived as an integral part of nature, and therefore what is valued is the reciprocal character of the people–nature relationship.

The NFF builds on the three values of Nature (relational, instrumental and intrinsic values) identified by the IPBES and repurposes it to make it actionable for the modelling and scenarios community.[1] According to the IPBES guidance on multiple values of nature, intrinsic values refer to non-anthropocentric values associated with nature and its contributions to people and are independent of any human experience and evaluation (IPBES, 2015). Referencing Pascual et al. (2017), they refer to the inherent value of nature and its components, which is not generated by human beings. Instrumental

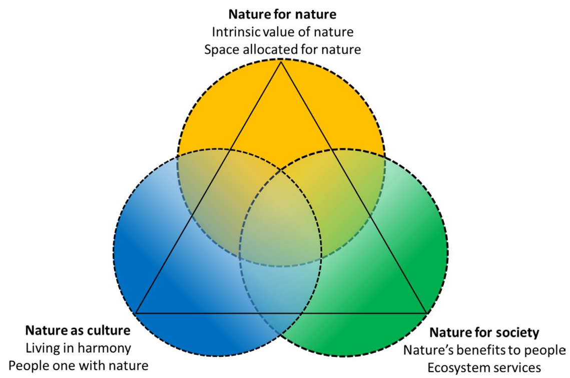


FIGURE 5 The Nature Futures Framework triangle with a list of some possible synonyms for the value perspectives that are used by various actors. (Source: PBL, 2018)

values often relate to NCP and refer to the value attributed to something as a means to achieve a particular end. Finally, relational values reflect relationships 'with natural entities to the extent that such relationships are embedded in people's identity and every day' (IPBES, 2015).

The expert group recognized the importance of elaborating on what futures in the corners and along the sides of the triangle look like (scenarios), and of identifying the transformative changes required to achieve them (pathways). The corners would therefore serve as reference points for analysing differences and convergences in actions motivated by the value positions. When combined, these plural value perspectives are more likely to be situated closer to the middle of the triangle in a way that appreciates all perspectives, and is not just dominated by one perspective. However, in reality, in order to strike that balance whilst maintaining diversity, it was recognized that some areas of the triangle will be emphasized more by some people in certain times and places compared to others. Understanding how people understood and appreciated this nuance and flexibility of the NFF was essential to the process and so further stakeholder engagement was undertaken. Important to note is also that all three value perspectives illustrate positive visions of the future human–nature relationship. The common situation of undervaluing nature that is prevalent in many societies today is not visible in the NFF.

3.4 | Phase iv: Further refinement of the NFF through stakeholder engagement

Before moving on to develop scenario narratives for modelling using the NFF triangle, it was necessary to test how stakeholders received the framework as a clear and understandable heuristic, and whether it was a useful way to frame the complex discussion about plural nature-society value relations and whether we could start to populate scenarios of what a world would look like that emphasized aspects of the triangle's value perspectives. We thus developed a set of participatory processes for testing the NFF with a diverse group of the biodiversity community. The description of the Triangle exercise that took place in October 2018 in Bonn, Germany with a group of 42 attendees, in the margins of IPBES meetings is explained in Supporting Information S2. The aim of that exercise was to develop a method for allowing people to engage with the NFF and to see whether it was understandable to a diverse group of people. Below we describe a process undertaken during the 14th Conference of the Parties (COP) of the Convention on Biological Diversity (CBD) in 2018.

3.4.1 | CBD COP 14: Three horizons approach

Further stakeholder engagement was held during an interactive workshop in the Rio Conventions Pavilion at the CBD COP in Sharm El-Sheik, Egypt on 20 November 2018. Results are extracted from materials made available in the public domain by the International Institute of Sustainable Development (IISD) based on verbal consent provided by participants on-site during the event (IISD, 2018). The group exercises followed the three horizons approach (Figure 6), where participants were invited to discuss future visions and pathways to achieve them (Curry & Hodgson, 2008; Sharpe, 2013; Sharpe et al., 2016). Participants began by creatively envisioning a more desirable future for their thematic areas (Horizon 3) and then working back to the present system (Horizon 1). Discussing Horizon 2 was the final step, representing the transition zone between the present and the future where different pathways can be articulated. The questions asked in the process were:

- **Horizon 3**: *What is the desirable state for this value perspective in the marine/rural/urban ecosystem?*

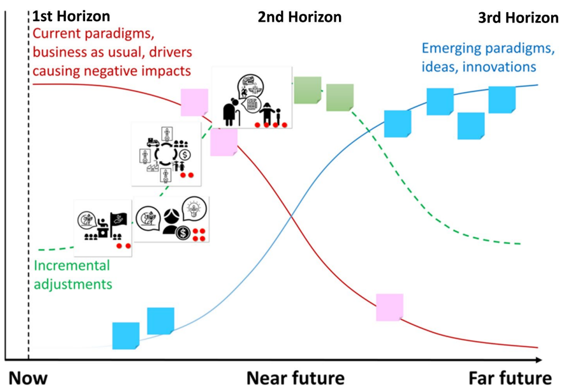


FIGURE 6 Three Horizons heuristic tool used as a method in the CBD COP 14 workshop. The red line of Horizon 1 represents the current paradigms, business as usual and drivers causing negative impacts. The blue line of Horizon 3 represents emerging paradigms, ideas and innovations for a desirable future. The green line of Horizon 2 represents the necessary actions and adjustments that are required to move from the present to the desired future. (Source: Authors' own)

- **Horizon 1**: *What are the most important direct and indirect drivers of change in nature, and what barriers prevent us from reaching that desirable state in the marine/urban/rural ecosystem?*
- **Horizon 2**: *What actions or policy interventions could address the obstacles and allow transitions towards the positive Nature Futures of the third horizon?* (bearing in mind the drivers and barriers identified in Horizon 1)

The discussions were facilitated using a poster-sized template of the three horizons and participants were invited to note down their ideas on post-its or to use the predesigned icons and add them to the template to record their discussions (Figure 6).

This interactive exercise brought together 39 participants from 22 nations. These participants produced three sets of posters focusing on each of the three perspectives of the NFF in a marine, rural and urban environment. Based on the group discussions on the three horizons approach, Table 2 summarizes the group discussions of what a positive future for the three sectors could look like if diverse values for nature were explicitly recognized. The information from these processes were recorded (Table S3) to be used in the elaboration of the scenarios in Phase iv.

Overall, these exercises demonstrated that even when starting from different values perspectives, convergence and synergies can occur when considering the pathways towards the desired futures with the NFF. Synergies across different groups included sustainable consumption, deepening the role of technology within nature while also encouraging living in harmony with nature, and emphasizing the co-evolution of humans with nature. Participants stated that using the NFF as a starting point to make different value perspectives explicit was helpful for policymakers as it allowed them to consider different options and alternative sustainability trajectories.

3.5 | Phase v: Towards a first set of Nature Futures Scenarios

The 7th session of the IPBES Plenary (IPBES-7, April–May 2019 in Paris, France) decided to establish a task force on scenarios and models to advance work on scenarios and models of biodiversity and ecosystem functions and services, as part of the new IPBES work programme up to 2030, which IPBES-7 approved. The mandate of the task force is to advise IPBES experts working on assessments on the use of scenarios, and to catalyse the further development by a variety of stakeholders including the modelling community, of scenarios and models for future IPBES assessments. The task force is following up on the work performed by the expert group on scenarios and models during the first work programme of IPBES (2014–2018). In order to fulfil this objective, the task force is currently developing a package of NFF-related material. A process is now underway to develop six illustrative scenarios of futures based on an extreme interpretation of the three value perspectives and the edges where they intersect. A core aspect of this process is to ensure that there is maximum diversity between the different scenarios so that we are able to capture a wide spectrum of possible futures based on plural value perspectives. Engaging the broader scientific community in these endeavours is of great importance and this will be discussed below in Section 4.3.

3.6 | Limitations and lessons

The Nature Futures process required dealing with changes, including a change in membership of the expert group when it became an IPBES task force on scenarios and models in November 2019. Although there are multiple benefits from being able to associate with an intergovernmental platform such as IPBES, the fact that the project is not set up as a

TABLE 2 Key highlights from the discussions in the six groups (see Table S3 for a full description)

Value perspective	Marine	Rural	Urban
Nature for Society	Stronger enforcement of laws and regulations as an important step towards achieving the desired vision of plastic-free, healthy oceans, serving as a source of jobs and clean energy	The potential contribution of blockchain technology and the adaptation of agricultural practices to overcoming some of the negative drivers such as bad practices in agricultural production	The need for a circular economy, increased blue/green infrastructure, ecotourism and incentives for urban farming, which would require alignment of priorities across different institutions charged with urban planning
Nature for Nature	Ideal future is one of healthy oceans, healthy coastlines and healthy ecosystems, but corruption and overfishing are major impediments to this realization	There is a possibility of envisioning a future that excludes humans from rural areas (Half Earth), but the preferred focus is how to achieve a well-functioning ecosystem with clean air and water. A decrease in monocultures and pollution are ways to contribute to this goal	Sustainable cities with organic local food production and increased overall connectivity with nature as the desirable future, which would require new laws tax reforms, and better spatial planning to ensure connectivity between rural and urban areas
Nature as Culture	People's perception of oceans as being the root of sustainability problems, and the need to shift away from seeing oceans as a property that can be exploited as amusement parks, and instead revive the spiritual connections with them	The need for a change in lifestyle and education, and better management, with more food diversity, eco-friendly farming and increased engagement of youth. The role of technology in overcoming these challenges, and closing the gap between urban and rural areas is key	More equity in access to biodiverse urban spaces, green buildings and community gardens. There is a need for new social norms, mindsets and standard-setting initiatives that connect cities to nature

regular research project brings constraints. These constraints include the specific protocols for convening groups: whilst it is extremely helpful to be able to draw on the large IPBES stakeholder community, sometimes the rules can be difficult to implement and it can become expensive to generate co-funding for non-supported members to attend meetings. As this process sits outside of a dedicated research project, the ability to mobilize funding to host stakeholder engagements has been a big limiting factor. The mandate of the task force being to 'catalyse' work means we depend on interactions with other researchers and stakeholders, and the fact that the expert group is voluntary and cannot dedicate excessive amounts of time and resources to the process are further constraints.

Within this context, a chief lesson is that creating a new generation of scenarios and models requires a commitment to participatory processes that makes those involved feel comfortable to express their viewpoint openly (Hebinck, Vervoort, Hebinck, Rutting, & Galli, 2018). The management of group dynamics, especially across disciplines, cultures and languages must therefore acknowledge power differentials and the pluralities associated with cultural contexts (Marshall, Dolley, & Priya, 2018). A core aspect of the approach was to ensure co-production of knowledge through approaches such as employing a cultural guide to help with workshop planning, taking time to establish ground rules with local facilitators, a strong focus on creating a sense of community and mutual respect among the participants in the process, employing techniques such as Chatham House Rules, and negotiating the confidentiality of data. These methods support trust building and represent an investment in social capital, which is needed to progress any collective effort.

4 | DISCUSSION

The ultimate aim of the Nature Futures endeavour is to develop a process for creating multiscale scenarios of desirable futures for nature, which have been legitimized through a co-production process that includes a plurality of perspectives. The IPBES expert group embarked on an iterative process that resulted in the development of the NFF as a tool for engaging a pluralistic set of positive perspectives on human–nature relationships and as a framework for constructing multiscale scenarios. The NFF serves as a boundary object that provides a platform for practitioners, natural and social scientists, policymakers and modellers to reflect on and compare which types of values and which types of relationships with nature are being analysed, discussed and compared. We believe that the use of the NFF within the overall framework enables more nuanced and relevant dialogue around what possible futures for nature can be created. It also forms a foundational framework from which further scenario work can be undertaken. This is discussed more in Section 4.3.

As such, we argue that the contribution of the NFF is twofold:

1. Its ability to hold a **plurality** of perspectives on what is **desirable**, which enables the development of joint goals and visions and recognizes the possible convergence and synergies of measures to achieve these.
2. Its **multiscale** functionality for elaborating scenarios and models that can inform decision-making at relevant levels, making it applicable across specific places and knowledge systems.

4.1 | Holding a plurality of values and perspectives on desirable futures

4.1.1 | Desirable futures

The world needs desirable visions, including targets to stimulate action towards achieving them, as illustrated by the normative power of the SDGs and the well-below 2°C target of the Paris Agreement (UNEP, 2019). However, discussions on such desirable futures around biodiversity and particularly the post-2020 agenda in the CBD have tended to accentuate the perceived conflict between diverse perspectives of what a desirable future for nature looks like, problematizing the diversity of underlying values of the human–nature relationship. Many players in the science–policy arena actively lobby for implementation of alternative ideas, but often these ideas do not align, especially when they are popularized and differences are emphasized, which can result in tensions that potentially undermine a collective effort. A clear example is the land-sparing (high-yielding agriculture with a small land footprint) versus land-sharing (low-yielding, wildlife-friendly agriculture on larger tracts of land) debate that offers two alternative pathways for agricultural and urban development to enable better outcomes for local and global biodiversity (Kremen, 2015; Loconto, Desquilbet, Moreau, Couvet, & Dorin, 2018). The concept of 'Half-Earth' introduced by the naturalist E.O. Wilson has gained significant traction (Büscher et al., 2017; Kopnina, Washington, Gray, & Taylor, 2018; Wilson, 2016), while other groups advocate for 30% of the ocean to be protected (Dinerstein et al., 2019). An altogether different solution is found in green growth for sustainable development, celebrating natural capital accounting, nature-based solutions and payment for ecosystem services schemes (Bull & Strange, 2018; Mandle, Ouyang, Salzman, & Daily, 2019; Russi & ten Brink, 2013; TEEB, 2010, 2018). Other research articulates the need for a look at alternative economic models for a flourishing nature (D'Alessandro, Cieplinski, Distefano, & Dittmer, 2020; Otero et al., 2020).

There is a diversity of perspectives in the global conservation community on how to conserve nature (Mace, 2014; Sandbrook, Fisher, Holmes, Luque-Lora, & Keane, 2019). Mace (2014) proposed four stages in the evolution of the nature conservation paradigm, from 'nature for itself' to 'nature despite people' to the 'nature for people' approach embodied in the Millennium Ecosystem Assessment (2005). A fourth stage posits that a more nuanced 'nature and people' approach has recently been taken up that recognizes the dynamic relationship between people and nature. These different framings have implications for environmental management and have led to some tensions in the conservation community

(Sandbrook et al., 2019). Sandbrook et al. (2019) argue that future debates and policy processes should emphasize working through the more contentious issues, and ensure inclusion of the perspectives of under-represented groups in conservation who may not share the views of those in more powerful positions. To this end, the NFF as a heuristic device that has been developed in an interdisciplinary process with widespread stakeholder engagement, can potentially facilitate constructive dialogue to identify and focus on shared ambitions for collective action. By focusing on the positive relationships (i.e. not emphasizing the 'nature despite people' perspective, but including it in the nature for itself value), the NFF work can help to identify and bridge dominant perspectives in the world of nature conservation.

4.1.2 | Value pluralism

The embracing of value pluralism makes it possible to fit the NFF to different contexts and identify different behavioural changes associated with particular political, legal and socio-cultural perspectives. By enabling the identification of more diverse types of policy responses and actions that can restore the living world and focusing on the variation among people's relationships to nature, the NFF highlights that acknowledging people's diverse relationships with nature is essential for discussing nature futures and coming to an agreement on ways to achieve a more desirable future. Often, assessments of nature focus on natural sciences or economics and do not consider why and how people care about nature (IPBES, 2019; Millennium Ecosystem Assessment, 2005; UNEP, 2019). In contrast, the NFF approach focuses on reciprocal relationships between people and nature (within the whole of the triangle space) rather than only people's impact on nature, or nature's impact on people. It emphasizes the importance of a pluralistic notion of values compared with monistic approaches to human–nature relationships dominated by a single worldview (that might overemphasize only one target, such as the conservation of biodiversity, economic growth, social development or poverty alleviation, the inclusion of indigenous knowledge) as discussed in the IPBES conceptual framework (Díaz et al., 2015; IPBES Plenary, 2016; Pascual et al., 2017).

The IPBES values framework, referring to intrinsic, instrumental and relational values for nature that are captured in the NFF, and builds on an ongoing scholarship that engages with the need for a diversified framing on values of nature (Chan et al., 2016; Chan, Gould, & Pascual, 2018; Chan, Satterfield, & Goldstein, 2012; O'Connor & Kenter, 2019; Piccolo, 2017). Chan et al. (2016) build on the IPBES guidance and emphasize the importance of the relational values approach, arguing that recognizing these values is critical to the genuine inclusion of diverse groups in environmental stewardship. Piccolo (2017) has added to this debate by arguing that depicting intrinsic values as part of a dichotomy between anthropocentric and ecocentric values is unhelpful and that any attempt to reframe the discussion about values and environmental protection through more formal recognition of relational values will need to more clearly address how relational and intrinsic values coexist. Together with colleagues, he goes on to call for ecocentric values to be a core aspect of the transformation of human's relationship with nature and argues that conservation used to be at the forefront of this approach (Piccolo, Washington, Kopnina, & Taylor, 2018). Extending the discussion of intrinsic values of nature, O'Connor and Kenter (2019) use the life framework for values to make the case for integrating the more-than-human components of intrinsic values that goes beyond classifications of ecosystem services and NCP.

While the NFF builds on the relational, instrumental and intrinsic values, the three perspectives do not map unequivocally to these values and allow for their coexistence, addressing some of the criticisms of Piccolo (2017). Nature for nature represents both intrinsic values and instrumental values such as existence values and non-material benefits from nature. Nature for society is dominated by the use and indirect use of a subset of instrumental values, while nature as culture captures the relational values, but also the non-material benefits associated with cultural construction and interpretation of nature. The NFF approach is being developed to support scenarios and therefore is closer to stakeholder perspectives than conceptual classifications of the types of nature values. In addition, it recognizes that most stakeholders will find themselves in intermediate positions of the preference space, where all values and perspectives coexist.

4.1.3 | NFF as a boundary object

Reinforcing the call by Tadaki, Sinner, and Chan (2017) to move away from theoretical gridlock within the environmental values debate and into a space where the valuation of diverse values of nature can be means of citizen empowerment, the methodological approach of the NFF is an attempt to create a boundary object for bringing different disciplinary perspectives and worldviews together. The creation of a boundary object in the scientific process can be a useful strategy for reconciling tensions between different viewpoints and translating between them so that progress can be made (Star & Griesemer, 1989). As such, boundary objects must be both adaptable to different viewpoints whilst also being robust enough to maintain identity across them (Star & Griesemer, 1989). In the biodiversity conservation context, boundary objects have proved to be important tools for navigating different scalar perspectives for improved decision-making (Gray, Gruby, & Campbell, 2014). The IPBES Conceptual framework itself has been described as a boundary object for opening up the science–policy interface for broader engagement with plural ontologies and epistemologies (Borie & Hulme, 2015; Scarano et al., 2019). Based on the stakeholder engagements described in Section 3.3, we argue that the NFF triangle has turned out to be useful as a boundary object for bridging multiple disciplines and stakeholder perspectives. As the final outputs of the Nature Futures process must be relevant for a wide audience, including the modelling community, having a common conceptual lynchpin in the NFF has been critical for creating buy-in and understanding across different groups.

The aim of the NFF is not to replace the frameworks described above, but to provide a heuristic that can hold these different conceptualizations in order to provide a simple, but effective, tool for the creation of multiscale, plural biodiversity scenarios. As such, it is intended to be used as a heuristic device for holding ongoing engagements between diverse perspectives. As intergovernmental assessment processes have a strong influence on how the spatial dimensions of environmental problems are designated and thus how power relations are accordingly reconfigured across different scales and levels (Beck, Esguerra, & Goerg, 2017), a tool through which to unpack these relations and empower different spatial scales can be an important offering. By capturing diversity in an accessible heuristic, the NFF has the potential to support IPBES assessment work by operationalizing the platform's principles: promoting a collaborative approach; facilitating an interdisciplinary and multidisciplinary approach; engaging with different knowledge systems, including indigenous and local knowledge; and ensuring full, effective balanced participation across national, sub-regional and regional levels. The NFF approach also complements ongoing IPBES work, especially that of the Values Assessment which will be considered by the 9th session of the IPBES Plenary in 2022. Future assessments, including those on transformative change, the nexus of biodiversity, water, food and health and business and biodiversity, will be able to utilize the NFF as an overarching framework around which to organize the analysis of scenarios and models that deal with these topics.

4.2 | Multiscale functionality to inform decision-making at relevant levels

Although a growing body of literature has identified the challenges and possibilities associated with developing cross-scale scenarios (Biggs et al., 2007; Kok, Biggs, & Zurek, 2007; Mason-D'Croz et al., 2016; Mistry et al., 2014; Palazzo et al., 2017; Zurek & Henrichs, 2007), it has mostly focused on rescaling global scenarios for regional and local use using various algorithms (Häyhä, Lucas, van Vuuren, Cornell, & Hoff, 2016; Kok, Pedde, Gramberger, Harrison, & Holman, 2019; Kok et al., 2016; Mason-D'Croz et al., 2016; Palazzo et al., 2017). Effective multiscale, and particularly cross-scale analysis is difficult, and it is not only a challenge of scenario planning. Disciplinary research often re-emphasizes the problems of scale: ecologists and social scientists traditionally frame their research questions at different scales and consider different facets of natural resource management, setting different objectives and using different language (Montana & Borie, 2016; Stevens, Fraser, Mitchley, & Thomas, 2007), which makes it difficult to connect scales. Within disciplines, scale remains a problem, due to the scale bound nature of research problems and data collection (Levin, 1992).

The NFF has been explicitly designed by an interdisciplinary group of researchers to be used across multiple scales, potentially, but not necessarily, combining scales in the same framework within a cross-scale approach. Overcoming philosophical and disciplinary challenges and embracing the plurality of knowledge systems that lies at the heart of IPBES, were central goals of the expert group as they developed the NFF. Bridging interdisciplinary barriers is required to be able to incorporate more diverse knowledge systems into environmental assessments (Obermeister, 2017). Although not perfect, the group made a lot of effort to embrace a diversity of knowledges, methods, research and discussion styles and this resulted in the NFF triangle operating as a boundary object that can work not only across disciplines, but also across scales.

It is important to point out that packaging and providing knowledge for policy is not a neutral activity, especially when navigating across scales of relevance that requires translating the global environmental knowledge of assessments into a form that is usable by decision-makers that operate at a different level, usually that of a nation state (Turnhout, Dewulf, & Hulme, 2016). The NFF is not a neutral object that was developed with buy-in from the whole world, and this must be fully acknowledged. A key rationale for the development of this paper is for the NFF development process, with all its associated challenges, to be transparently laid out for all to be able to engage with the process, critique it and improve on it in future iterations. Such epistemological agility is necessary when co-producing knowledge with diverse peoples across different scales (Haider et al., 2017), as highlighted by the work on the multiple evidence base that conceptually informs the NFF as a tool to feed into intergovernmental processes like IPBES and the CBD (Tengö et al., 2017). Finally, the flexibility of the NFF to work across multiple different contexts and with a variety of stakeholders requires it to be relatively simple and this means that it can lose a lot of the nuance and subtlety that is sometimes of great importance when engaging diverse perspectives. This is a core constraint of the NFF, however, its work as a boundary object can alleviate some of this simplification.

4.3 | Next steps in the Nature futures scenarios process

In order to broaden the engagement with the NFF and to get wide buy-in to its adoption as an actionable framework by diverse researchers, it is imperative that future steps in the process seek actively to involve more people and expertise. The next steps in the scenario development process are to extend the use of the NFF in multilevel case studies to test its relevance across diverse ecosystems, bio-cultural regions and geographical scales. This will involve both the development of new scenarios based on the framework (discussed in Section 4.3.1) as well as the analysis of existing scenarios within the NFF framework. The articulation of variables and indicators that can be quantified by the biodiversity modelling community is also needed. It is hoped that the insights from the case studies will be input for further refinement of the global scenarios, as well as for developing more diverse sets of indicators to assess the progress towards the goals for nature that incorporate more diverse value perspectives (IPBES/7/INF/11[2]).

To be most effective, the development of the multiscale scenarios needs to be coordinated across work that is underway

elsewhere. Linking to ongoing work on global scenarios connected to the IPCC and UNEP's Global Environment Outlook and Global Biodiversity Outlook, as well as to business and government scenarios, and to the increasing number of local, national and regional social–ecological scenarios, is crucial to gain traction in the user community. This requires strategic planning and innovative communication platforms that engage busy people across a range of interests and scales. Such work can help to catalyse greater societal support for enhanced conservation of nature, but it requires an ongoing commitment of resources, particularly in terms of time and funding. As such, we set out the following two key processes in which we invite interested research and practitioner communities to help take part in furthering.

4.3.1 | Multi-level case studies

To better represent the global diversity of values, ecosystems and local contexts, a broader engagement is needed with a wider range of stakeholders situated in different contexts, and including groups such as indigenous peoples, the youth and the private sector. These engagements could be undertaken with support from several IPBES task forces, including the capacity-building task force that has already organized a youth engagement around the NFF and futuring processes (IPBES Capacity Building, 2019) as well as the indigenous and local knowledge task force that convenes dialogues with indigenous peoples and local communities for ongoing IPBES assessments. Mobilizing the research community to use the NFF in their own work is critically important to provide a richness of different case examples. Innovations in research methods can also allow a large group of people from around the world to engage with the scenario process by using online methods that allow many people to contribute their perspectives and narratives. For example, SenseMaker® uses an online application to capture a variety of perspectives and narratives (Van der Merwe et al., 2019). These are just some of the options that we encourage the research community to undertake with us in moving forward the nature futures agenda.

The aim of having a set of case studies is to populate the triangle with examples of how nature values are represented in different locations, across different spatial scales and how these could change into the future (Figure 7). For example, people's relations to nature will vary between the residents of the city of Singapore, Siberian reindeer herders and communities in the south of France. For clarity, it is important to demonstrate that there are two different ways of using the NFF triangle to visualize nature futures in case studies. The first is by identifying a position within the NFF triangle space that represents the relative emphasis of the three value perspectives. The second is represented in Figure 7, where the desired state of the system is represented by a space connecting three points along each of the triangle's vertices, indicating how well that particular value perspective is achieved. This approach is more appropriate for a bottom-up approach to global scenario narratives as it is easier to amalgamate the desired state space rather than a point within the triangle.

The goal of such efforts is to identify key variables and indicators for different nature perspectives that can help the community operationalize this framework in a way that is both globally comparable and locally relevant, as well as identify commonalities and differences among desired visions of nature around the world. Comparison of such case studies can also be used to identify shared drivers, and ignored or hidden teleconnections between local places (Martín-López et al., 2019). This type of comparison is necessary to

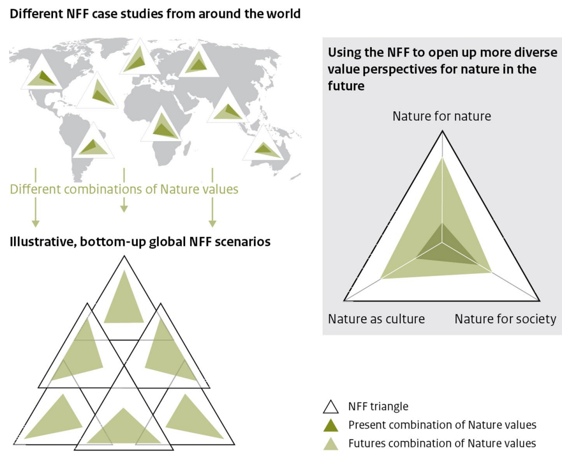


FIGURE 7 Local NFF case studies that engage a variety of actors in different social, geographic and ecological contexts are vital for understanding how global change varies from place to place, the diversity of nature values and how local places connect to global processes. When scaled to the global level, the richness of this bottom-up information can be combined to showcase a diversity of options of what desirable futures for nature could look like globally, based on different emphasis on the nature value perspectives. The use of the NFF enables an opening up of the value perspective space when describing possible nature futures as compared to the present state. (Source: Authors' own)

ensure that global analyses adequately identify the cross-scale dynamics that are shaping the world.

Having the NFF as a clear common framework linking these case studies will be important for consistency, especially for providing inputs for the modelling community. We therefore encourage those who are interested in applying the NFF in their context to undertake scenario processes using the NFF as a foundation to ensure consistency and comparability of the findings. Existing examples include a youth workshop organized in Brazil by the IPBES task force on capacity building as well as a case study in the National Park Hollandse Duinen in The Netherlands. More substantial guidelines on how to get involved are also being developed.

As with all participatory visioning and scenarios processes, issues of power, politics and representation, come to the fore (Hebinck et al., 2018; Oteros-Rozas et al., 2015; Pereira et al., 2018). Recognizing inherent biases whilst trying to foster a wide range of perspectives is also a methodological challenge (Schirrmeister, Göhring, & Warnke, 2020). Navigating these dynamics in a global, participatory process is particularly challenging as it will never be fully representative of the whole world. Furthermore, in asking for the research and practitioner communities to undertake case studies, there is no systematic plan for ensuring representativeness. However, we hope that by encouraging the involvement of the wider community, by leveraging the diversity of stakeholders in the IPBES process and by actively targeting our own research to ensure the views of under-represented groups such as indigenous knowledge holders, are included, that this process will be a significant step towards a new set of globally relevant, but locally applicable desirable nature scenarios.

4.3.2 | The application of the NFF for the modelling community

Given the complexity of dynamic social–ecological systems, which encompass interconnected natural and human systems that are multi-dimensional with countless feedbacks within and between systems, integrative modelling of environmental scenarios has been a challenge (Pereira et al., 2010; Rosa et al., 2017). In Nature Futures modelling, connecting the visions to the ongoing and emerging work of modelling groups will require substantial investment in modelling capacity and capability associated with participatory modelling, social–ecological feedback modelling, cross scale modelling and understanding leverage points for transformative change (Leclere et al., 2018). The application of the NFF requires a modelling capability for assessing interlinked impacts of dynamic nature on societies as well as transformative change processes, with better integration of the feedbacks within linked human–environment systems.

A considerable number of indicators have been selected for use in IPBES regional and global assessments as documented by the IPBES task force on knowledge and data.[3] However, there are substantial gaps in modelling elements and indicators for socio-economic elements and human well-being, and few available indicators that are relevant to the Nature as Culture value perspective (Mastrángelo et al., 2019; PBL, 2018). In particular, having reviewed the findings of the IPBES regional and thematic assessments, Mastrángelo et al. (2019) emphasized that a limited understanding remains of the role that indigenous and local knowledge plays in sustaining the co-production of NCP. Other gaps include the relationships between multiple dimensions of NCP and good quality of life, the temporal dynamics of nonlinear social and ecological change, social–ecological feedbacks including how changes in people's preferences and quality of life influence governance and other indirect drivers, trade-offs between NCP, the influence of institutions in the social distribution of NCP and the effectiveness of governance systems to promote necessary transformations (Mastrángelo et al., 2019). Filling these gaps requires knowledge sharing across disciplines (e.g. modelling, natural and social science, ILK). We encourage the modelling community as well as all other researchers interested in furthering this component to engage with us in developing this body of work.

5 | CONCLUSION: REFRAMING NATURE FUTURES

As the IPBES Global Assessment (2019) has shown that Nature is declining globally at rates unprecedented in human history and makes it clear that transformative changes are needed to get us onto a more sustainable trajectory for the planet. Under the current socio-economic trajectory, the world will miss most of the Sustainable Development Goals (SDGs), and so we need to initiate changes in our economies, technologies and societies if we are to shift onto a more sustainable global development pathway (Naidoo & Fisher, 2020). The development of the NFF rests on the assumption that there is a critical need to develop positive nature-people scenarios for the future of our planet, particularly at such a moment when we need to act now to prevent irreversible environmental devastation with severe consequences to humanity (Steffen et al., 2018; Wyborn et al., 2020).

The year 2019 saw a diversity of perspectives on how to address the environmental challenges of our time. Examples include Extinction Rebellion[4] that argues that the global environmental crisis is an emergency marked by abrupt climate breakdown and mass extinctions and a global youth movement to avert a climate disaster, sparked by teenager Greta Thunberg, which resulted in mass climate protests and climate strikes by children around the world, referencing #FridaysfortheFuture[5] (Almeida, 2019). The World Economic Forum is advocating for a New Deal for Nature (Lambertini, Polman, & Børge, 2019), and the Global Deal for Nature has been proposed by the biodiversity research community (Dinerstein et al., 2019). Politicians are forming alliances with researchers and activists to propose interventions like The Green New Deal[6] led by United States Representative Alexandria

Ocasio-Cortez and Senator Ed Markey. In the context of such diversity, the NFF allows for a standardized approach to appreciate a plurality of NCP over time and space and allows for a more nuanced approach to pathways development that is more relevant for actors operating within specific jurisdictions. Given the need for negotiating a new deal for nature in the post-2020 CBD agenda (Dinerstein et al., 2019; Lambertini et al., 2019), the NFF could create a space wherein a discussion on reversing the degradation of nature and declines in NCP could be held between actors as diverse as politicians and young climate activists.

All the necessary groundwork is currently being laid for the negotiations at CBD COP-15 on the post-2020 biodiversity framework and the global goals on nature to replace the Aichi biodiversity targets. As we navigate the next chapter in global biodiversity governance, the NFF makes a unique contribution towards improving the science–policy interface that can enable a better future for people and nature. However, this cannot be an isolated endeavour. We call on the research community to join us in testing and improving the framework in diverse contexts and where appropriate to use it in their work. In this way, together we can move towards a more desirable and hopeful future for people and the planet.

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CONFLICT OF INTEREST

The authors have no conflict of interest with regard to the publication of this manuscript.

AUTHORS' CONTRIBUTIONS

For the Auckland workshop, L.M.P., C.J.L., H.M.P. and G.P. conceived the ideas and designed methodology; C.J.L., R.A. and H.M.P. acquired funding; L.M.P., G.P., H.M.P., K.K.D., C.J.L., F.R., S.K.-V., R.A., N.K., S.C.R., J.H., E.d.B., T.L., A.G., facilitated the Auckland workshop; S.O., M.S., E.d.B., H.K., C.J.L. and J.J.K. collected and analysed the data from the workshop and subsequent stakeholder consultations and expert group meetings; L.M.P. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

All data are available in the cited reports and in Tables S1, S2 and S3 (source: Lundquist et al., 2017).

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ENDNOTES

1 https://ipbes.net/diverse-values-valuation
2 https://ipbes.net/sites/default/files/ipbes-7-inf-11_scenarios.pdf
3 https://ipbes.net/core-indicators
4 https://rebellion.earth/
5 https://www.fridaysforfuture.org/
6 https://theintercept.com/2019/04/17/green-new-deal-short-film-alexandria-ocasio-cortez/

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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Current Opinion in Environmental Sustainability

Emerging response options and scenarios of slow onset events related to climate change in Southeast Asia

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The negative effects of slow onset events (SOEs) related to climate change are already affecting developing countries, with the resulting impacts likely to increase significantly. With an increasing urgency to act on SOEs, this paper systematically reviewed and synthesized literature on SOEs in Southeast Asia (SEA), which is a region of several highly climate vulnerable countries. With a focus on scenarios and emerging response options by affected sectors such as agriculture, fisheries, and forestry, we found that the drivers of SOEs in SEA are both indirect and direct and have confounding impacts. Only a few researches used scenarios and models for assessing SOEs in SEA, a majority of which use Representative Concentration Pathways and Shared Socioeconomic Pathways. The impacts of SOEs range from environmental, ecological, economic, and social factors and require integrated response options including mitigation or adaptation that pay attention to the complexity of the intersection between human and natural systems.

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This review comes from a themed issue on **Slow onset events related to climate change**

Edited by **Susana Adamo**, **Riyanti Djalante**, **Prabodh GD Chakrabarti**, **Fabrice G Renaud**, **Amsalu Woldie Yalew**, **Doreen Stabinsky**, **Zinta Zommers** and **Koko Warner**

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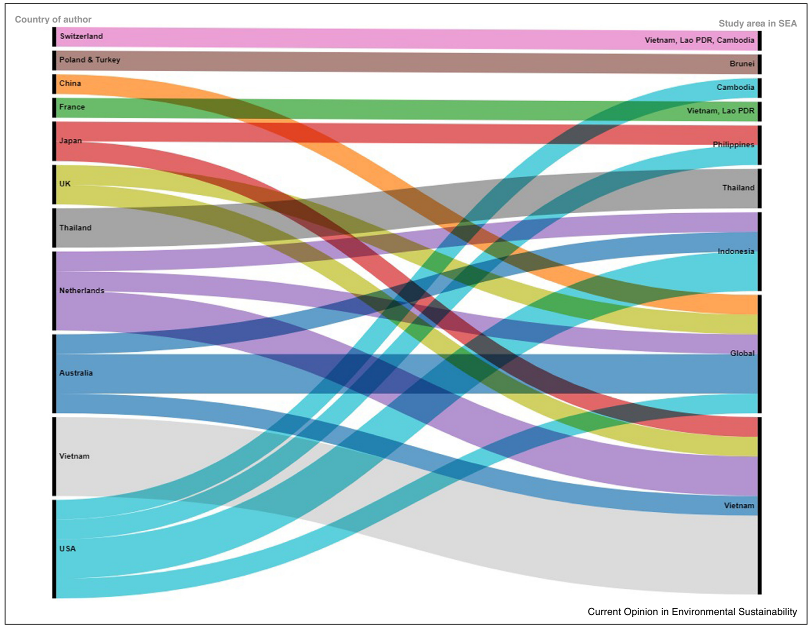
Introduction

Climate change manifests itself not only through rapid onset events such as typhoons but also through slow onset events (SOEs) that have incremental and creeping impacts. The United Nations Framework Convention on Climate Change (UNFCCC) defines SOEs as increasing temperatures, desertification, loss of biodiversity, land and forest degradation, glacial retreat, ocean acidification, sea level rise (SLR), and salinization [1]. SOEs are already affecting developing countries and often impact key development sectors such as agriculture or fisheries [1]. However, there is a lack of scientific research on SOEs in developing regions such as Asia, Africa, or Latin America especially on its social implications [2]. With SOEs already affecting developing countries, there is a need to study the impacts and consequences of SOEs to inform response options [1]. One way of assessing how climate change impacts and corresponding response options could unfold in the future are through scenario development and analysis. Several environmental assessments such as the Intergovernmental Panel on Climate Change (IPCC) or the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) have used scenarios to assess different interventions and their future trajectories. In this paper, we present results of a systematic literature review on scenarios of SOEs in Southeast Asia (SEA) from 2016 up to early 2020 (see SM1 for search terms). The search resulted in 29 peer-reviewed articles

Figure 1



Country of authors and study area in Southeast Asia (SEA).
The countries on the left represent the countries of the first authors and the countries on the right represent the study areas in SEA. (Source: Authors).

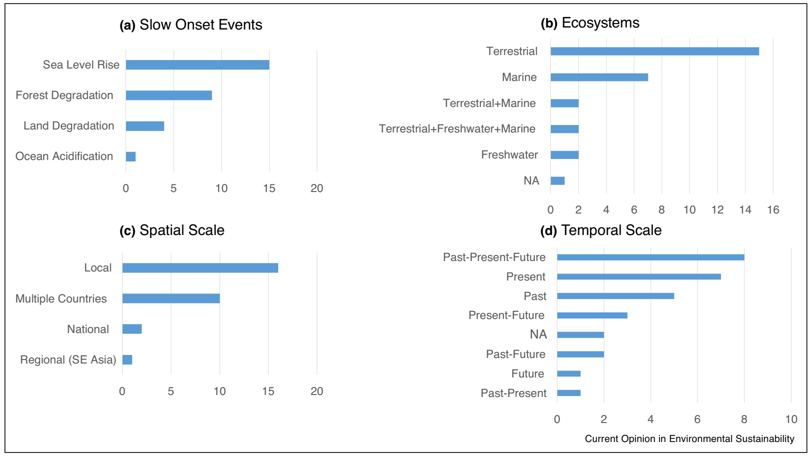
that discuss climate-related SOEs in SEA and utilize scenarios as tools for generating response options.

Trends of SOE research in SEA

Majority (66%) of the articles reviewed were published in 2018–2019, with several articles (31%) published in 2016–2017. A few number of articles (3%) published in 2020 were also included. Most articles were case studies (93%) (e.g. Refs. [3,4•,5]) with more than half at the local scale (55%) and one third in multiple countries (34%) (e.g. Refs. [3,6,7]). Majority of the studies (76%) were conducted by first authors from developed countries with only 36% of these studies having a co-author from the country of study (e.g. Refs. [8–11]). Among all SEA countries, Vietnam was the most studied country (31%) (Figure 1). These trends show the need for more SOE research in other SEA countries, and specifically locally led research that is transdisciplinary in nature. Such an approach could allow a more accurate assessment of SOE as it will include insights from vulnerable communities as well as local science-policy interfaces [12].

Most of the publications studied sea level rise (SLR), forest degradation, and land degradation with some studies covering salinization (e.g. Refs. [10,13,14]) and ocean acidification (e.g. Ref. [8]) (Figure 2). Most of the impacts of SOEs are on the terrestrial ecosystem, followed by the marine ecosystem. The most negatively impacted sectors are agriculture and fisheries, which are the backbone of most SEA economies (Figure 3). This highlights the urgent need to address SOEs in SEA and their confounding drivers (Figure 5). More than half of the studies noted

Figure 2



Summary of slow onset events, ecosystems, and the spatiotemporal scales considered across the 29 papers reviewed.
The x-axis represents the number of papers while the y-axis represents the classification categories. (Source: Authors).

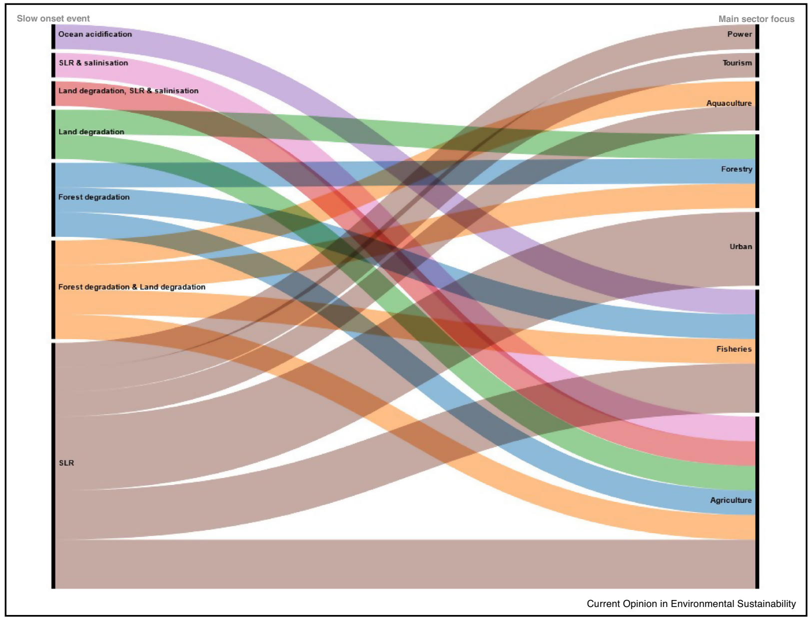
indirect drivers of SOEs such as policies, governance systems, and institutions (52%), economic drivers (34%), and demographic drivers (24%). The direct drivers of SOEs covered in these studies are climate change and variability (72%), land use and land cover change (41%), and natural resource use and exploitation (21%). These drivers form the basis of exploratory scenarios, which evaluate a range of plausible futures by looking at the trajectories of indirect and direct drivers [15]. We find that SOEs in SEA are driven by multiple drivers and, as such, should have response options that concurrently address these drivers.

Accessibility of tools for national policy making process with scenarios and models

Majority (59%) of the papers we reviewed used exploratory scenarios, while around 17% of the papers did not use scenarios (Figure 4a). Several papers (24%) also used target-seeking and policy-screening or retrospective policy evaluation scenarios. A large majority of papers that provided specific scenarios and storylines adopted and modified the IPCC's Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) (38%), with the remaining papers using either customized scenarios and storylines that were related to climate change, land use change, incentives, and implementations of the program on "reducing emissions from deforestation and forest degradation in developing countries" (REDD+) (27%) (Figure 4b). Several papers (35%) did not provide specific scenario storylines. For those with scenario analyses, the development of scenarios was mostly done by experts without stakeholder participation (52%) while about 28 percent were done in collaboration with various stakeholders. Several of the papers (69%) used models and employed a wide array of modeling tools such as ecological models (14%), hydrodynamic models (11%), spatial and land-use models (13%), various forms of socio-economic models (11%) or others such as system dynamics, equilibrium, indicator-based, and integrated models (Figure 4c).

The SOEs that were evaluated using scenarios and modeling tools were mostly focused on projected SLR (52%), forest and land use degradation (44%), and ocean acidification (4%). Given that the majority of the scenarios evaluated relate to IPCC RCPs and SSPs, most of the direct drivers that were incorporated in the modeling were related to climate change drivers, land use, and

Figure 3

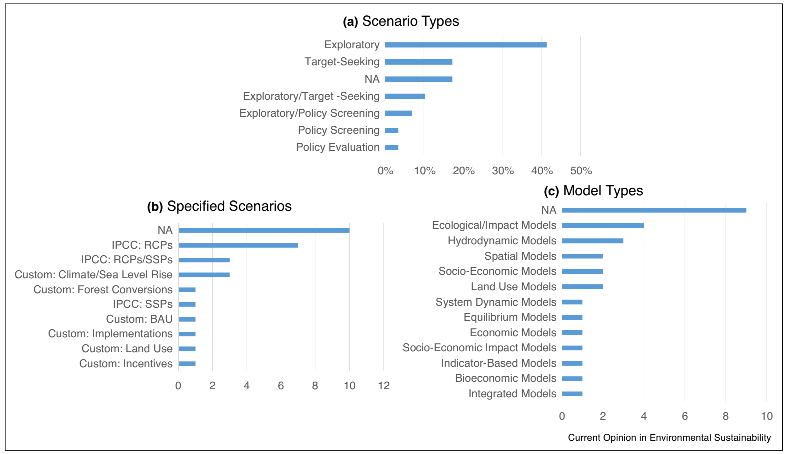


Slow onset events and sectors considered.
The left-hand side represents the slow onset events studied and the right-hand side represents the sectors studied within each slow onset event.
SLR stands for sea level rise. (Source: Authors).

natural resource use and exploitation (Figure 5a). On the other hand, the majority of the indirect drivers incorporated in the modeling were related to governance, various demographic and socio-economic drivers, and few technological drivers (Figure 5b). The ecosystems that were modeled were mostly terrestrial (54%), followed by marine (25%), then interactions among terrestrial, freshwater, and marine ecosystems (14%), with the remaining papers focusing on freshwater systems (7%) (Figure 2b). Less than half of the 29 papers assessed and modeled SOEs into the future up to the year 2050 or 2100 (48%), and the rest did not provide futures assessments, but focused their analyses on the present time or on a historical trend from the past to the present time (Figure 2d). Overall, the use of scenarios and models for assessing SOEs in SEA is still limited in Southeast Asian countries except in Vietnam where a large majority of the papers were focused on.

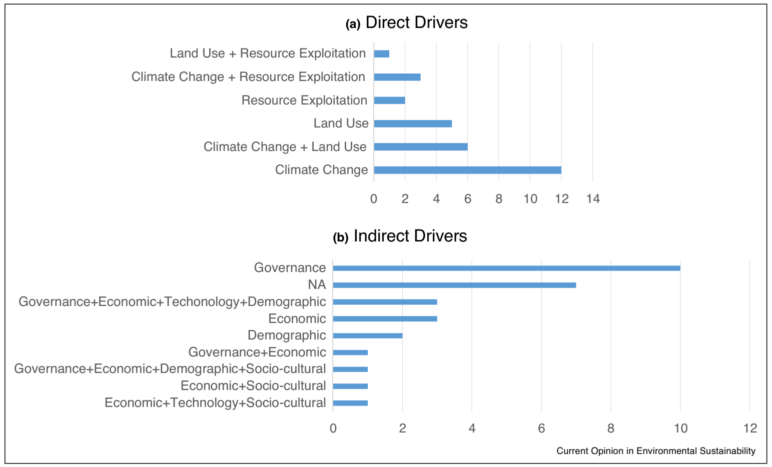
The papers that used scenarios and models to assess the impacts of SLR, generally suggest that beach loss and coastal inundation [9,16••,17•], saltwater intrusion of freshwater and farmlands [10], mangrove loss [18•], and flooding and storm surge will increase in many of the modeled areas in Southeast Asia [18•,19], most especially under higher climate change scenarios such as RCP 8.5, and even for lower RCPs or climate change scenarios. For terrestrial areas, the combination of natural resource use and exploitation, land use and land conversions, and impacts of climate change such as drought [20], changing

Figure 4



Summary of scenarios and modeling characteristics across the 29 reviewed papers. (Source: Authors).

Figure 5



Summary of direct and indirect drivers that were considered in the scenario/modeling across the 29 papers reviewed. (Source: Authors).

Table 1

Impacts of SOEs

Slow onset event	Environmental and ecological impact	Economic impact	Social impact
Sea level rise	Arsenic levels [23]		
	Mangrove loss [18•]	Gross Domestic Product (GDP) at risk [18•]	People at risk [18•]
	Salinity [13]	Rice yield [13]	
	Sea level increase, water availability, energy demand [4•]	Crop yield variation [4•]	Human health [4•]
		Damage to assets, GDP [19]	Casualties, demographic growth [19]
	Water flow, quality, nutrients, and so on [20]		
		Changes in monetary value of coastal ecosystem services [17•]	
	Coastal erosion, beach lowering, and so on [6]		
		Property values [32]	Dislocation/displacement of urban poor population; Government distrust, and so on [32]
	Beach loss [16••]		
Sea level rise; salinization	Salinity; freshwater availability [14]		
Forest degradation	Loss of forest due to large-scale land acquisitions [29•]	Timber exports [29•]	
	Biodiversity loss due to conversion [31]		Human welfare; indigenous and local people's knowledge and rights [31]
	Carbon emissions [28•]	Stakeholder profits, incentives, and so on [28•]	
	Emission reduction [33•]		
Land degradation	Carbon stocks/emissions [21]		
		Cost of REDD+ [34]	Impact on local livelihood [34]
Land degradation; desertification	Sparse vegetation [11]		
Land degradation; forest degradation	Ecological disruptions and losses [3]	Crop yields [3]	Threats to human well-being [3]
	Impairment of photosynthesis [27]		
	Sea water intrusion, coastal floods, and so on [22]	Agricultural disaster [22]	
	Carbon emissions, deforestation [26]		Impacts on people, affected population [26]
Ocean acidification	Coral mortality, reduced fish habitat, and so on [24]	Abundance decline [24]	

Different SOEs have multiple environmental, economic, and social impacts.

precipitation patterns [21], and desertification [26] are all aggravated under higher RCPs and even in lower RCPs or climate change scenarios. Overall, there are still major gaps in our current understanding of SOE impacts in Southeast Asia based on the use of scenario and modeling approach. The fact that many countries in the region have no published peer-reviewed literature on futures of slow onset events under different scenarios could mean that more work needs to be done on this subject in the region.

Impacts and risks associated with slow onsets with response options

SOEs have broad ranging impacts including environmental, ecological, and socio-economic impacts that result in changes in livelihood, economic opportunities, and health and well-being of peoples (Table 1). Of the 29 reviewed literature, three (10%) publications covered all categories of environmental and ecological, economic, and social impacts. The rest either covered one to two impact categories or none at all. For literature covering several categories, the combination of environment and economic impacts appears to be the most prevalent. It is followed by the combination of environment and social impacts and then by socio-economic impacts. Single impact literature largely focuses on environmental impacts (68%), while economic impacts (31%) and social impacts (24%) trail behind.

Almost all of the reviewed literature recommend interventions and response options through either climate

Table 2

Response options

SOE	Mitigation responses	Adaptation responses
Sea level rise	Role of microbial communities in contaminated soils [23]	Abiotic controls in contaminated soils [23]
	Irrigation water management, Land use planning [13]	Natural or assisted migration of mangroves [18•]
	Environmental risk assessment on coastal ecosystems [17•]	Salinity control strategies, climate-smart agriculture [13]
	Integrated participatory appraisal of coastal freshwater systems [14]	Elevate areas at risk; dry proof buildings [19]
	Increase community participation in planned measures [8]	Socio-technical flood risk management system [5]
	Mangrove reforestation [22]	Financial and technical support for autonomous and community-based adaptation [8]
	GHG emissions reduction including through wetland conservation [7]	Installation of wall against coastal erosion [22]
		Conventional structures (e.g. dykes) with ecological engineering (e.g. mangroves) for coastal protection [9]
		Environmentally and socially just planned retreats or relocations [32]
		Construction of seawalls, dykes or supplementing beach nourishment [16••]
		Consider all causes of change such as subsidence [7]
Land degradation	Combination of land sharing and land sparing [3]	Water resources management (e.g. sustainable irrigation systems) [11]
	Regulate land transactions and monitor implementation for agricultural production [26]	
Land degradation; forest degradation	Increase in ecosystem carbon in rangelands, wastelands and other land uses spared from intensive crop production [6]	
Forest degradation	REDD+ [29•,30,33•,34]	Monitoring, reporting, and verification (MRV) [28•,31]
	Peat fire suppression [21]	
	REDD + safeguards information system [31]	
	Long-term measurements of integrated solar radiation and temperature in understory [27]	
	Providing an incentive for transactions costs for REDD+ [28•]	
Loss of biodiversity; sea level rise	Compliance with Paris Agreement; Estimate budget pressures [4•]	
	Effective management of coral reef and marine biodiversity [24]	
Salinization	Land use planning [10]	Alternate Wetting and Drying (AWD) to save irrigation water [10]
		Converting farm model [10]
		Selecting salt tolerance varieties [10]
		Adding rich Ca^{2+} fertilizers to increase salt tolerance [10]

The literature has both mitigation and adaptation responses per SOE.

change mitigation or adaptation. The number of response options are more or less equally divided between mitigation (51%) and adaptation (49%), with most addressing SLR in Southeast Asia. The majority of mitigation responses are environmental (61%) in nature as compared to adaptation, which are dominated by technological options. Disaggregating the response options per slow onset event (Table 2), we found that SLR had the broadest range of interventions whether mitigation or adaptation. With most of the research on SLR focused on adaptation, research on the benefits of climate change mitigation especially in coastal zones is limited [7]. The adaptation responses to SLR outnumber mitigation responses, which are mostly social-ecological in nature. Ecological mitigation responses focus on ecosystems such as mangroves or wetlands and their conservation [7,22]. Mitigation responses involving the life sciences have also been mentioned, specifically the role of microbial communities in contaminated soils, which pose risks of contaminant mobility due to SLR [23]. This is particularly notable in Southeast Asia, which has elevated levels of geogenic and anthropogenic arsenic along its coasts similar to South Asia and the mid-Atlantic coast of the United States [23]. An adaptation measure for such impact from SLR is the use of abiotic controls such as precipitation or temperature to understand the mechanism for the release of soil contaminants such as arsenic [23]. The other adaptation responses for SLR are mostly technological in nature such as engineering fixes through construction of dykes, seawalls, and other conventional structures [9,16••,19,22]. Ecological engineering through mangroves is also suggested as coastal protection against SLR [9]. In both mitigation and adaptation responses to SLR, social approaches have been mentioned such as increased and integrated community participation in mitigation measures [14,24]. In adaptation, one publication

highlighted the need for environmentally and socially just approaches especially to planned relocations [25]. Not least, one publication suggested the need for financial and technical support for community-based adaptation [8].

Publications dealing with land degradation mostly had mitigation responses, which touches upon both land sparing and land sharing [3,21]. One mitigation response also calls for policy interventions such as regulating land transactions and monitoring implementations for agricultural production, which can drive land use changes [11]. In connection with this, a sustainable irrigation system is suggested as an adaptation measure to alleviate negative effects of desertification [11]. Forest degradation also mostly had mitigation responses, with REDD+ suggested by most of the publications. There were mitigation responses that call for the improvement of REDD+ such as instituting a safeguards information system or a measurement, reporting, and verification (MRV) system for carbon emissions reductions. In addition, a more technical intervention has been undertaken to establish longer-term measurements of the integrated solar radiation and temperature in the understory of tropical forests; this could be used to confirm a decreasing leaf area index (LAI) as a lower LAI allows more sunlight to reach the forest floor and accelerates the drying of soil [27]. Finance in the form of incentives for REDD+ investors is also mentioned as a mitigation intervention [28•]. Apart from REDD+, peat fire repression is also suggested as a mitigation response to forest degradation [21]. Papers dealing with loss of biodiversity together with SLR only had mitigation responses, which is to effectively manage coastal biodiversity and comply with the UNFCCC Paris Agreement target to hold the increase in the global average temperature below 2.0°C above pre-industrial levels and to pursue efforts to limit temperature increases to 1.5°C above pre-industrial levels [4•]. Publications dealing with salinization mostly had adaptation responses for the agriculture sector and recommended land use planning as a mitigation measure.

Conclusion

Our systematic review of available literature on scenarios and SOEs associated with adverse impacts of climate change in the SEA region reveals several key insights for designing future response options. The literature on SOEs were skewed towards (i) impacts (e.g. of climate change on ecosystem services, on GDP and economic gains from complying with the Paris Agreement, and others); (ii) assessments ranging from vulnerability of freshwater systems and land desertification on the local scale such as whether there is now a vegetation collapse in Borneo, which is a center of biodiversity shared by three countries in Southeast Asia (Brunei, Malaysia and Indonesia); (iii) uncertainty in estimates, incentives, and emissions reduction under the REDD+ program, plausible future storylines (notably of how the world would look like in terms of global GDP and economic gains), and a global climate economy model, including REDD+; and (iv) responses (e.g. adaptation in low-lying islands, planned retreat as an adaptation measure to SLR in Global South cities, and mitigation that is mainly emissions reduction through REDD+). The quantification of impacts also included environmental and ecological losses from potential SLR and, more importantly, that of responses such as the socio-economic outcomes of large-scale land transactions as a consequence of REDD+ project activities. On spatial scales, studies from SEA ranged from global (a future world in 2050 as a consequence of complying with the Paris Agreement) to regional (transboundary displacement of deforestation) to national (evaluation of progress in REDD+, focusing on social protection in Indonesia). There were a number of local studies that covered impacts of climate change on natural and human systems and some adaptation and mitigation responses, although not discounting confounding factors where development trends are most important. There are, however, notable gaps in the distribution of studies on SOEs in the SEA countries, with most focusing on Vietnam. Another important gap is the limited study on ocean acidification, a climate change-driven SOE that could potentially translate to considerable environmental and economic losses even in the near future. Finally, this study takes note of one recommendation, which states that it is imperative to pay attention to the complexity of the intersection between human and natural system, an example of which is the wide range of potential environmental, ecological, and socio-economic costs and benefits of land-use transitions to meet the needs of the agriculture, fisheries and, to a certain extent, forestry at multiple regional levels.

Conflict of interest statement

Nothing declared.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.cosust.2021.04.004.

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- • of special interest
- •• of outstanding interest

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Supplementary Material

Search terms on Web of Science of literature until 17 February 2020

((TS=(("Future impact*" OR "Future response*" OR "Future effect*" OR "scenario*" OR "vision*" OR "trajector*" OR "pathway*") AND ("slow onset" OR "slow onset event" OR "forest degradation" OR "salini*ation" OR "sea level rise" OR "ocean acidification" OR "land degradation" OR "desertification") AND ("climate change" OR "climate") AND ("Southeast Asia" OR "Brunei" OR "Cambodia" OR "East Timor" OR "Timor Leste" OR "Indonesia" OR "Laos" OR "Malaysia" OR "Myanmar" OR "Philippines" OR "Thailand" OR "Vietnam")) AND SU=((Agriculture OR Environmental Sciences & Ecology OR Biodiversity & Conservation OR Fisheries OR Forestry OR Marine & Freshwater Biology OR Meteorology & Atmospheric Sciences OR Oceanography OR Acoustics OR Social Sciences Other Topics) NOT Biochemistry))) AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article) Indexes=SCI-EXPANDED, SSCI, A&HCI, ESCI Timespan=2017-2020

Summary of literature (N=29) review with number of observations (N) per criteria

Criteria	Classification	N
Year of study	2018	11
	2019	8
	2017	7
	2016	2
	2020	1
Type of paper	Case study	27
	Review	2
Spatial scale	Local	16
	Multiple countries	10
	National	2
	Regional	1
Temporal scale	Past	19
	Present	16
	Future	14
	Past, present, future	8
Slow onset event	Sea level rise	14
	Forest degradation	11
	Land degradation	9
	Salinization	3
	Ocean acidification	1
Sector	Forestry	11
	Agriculture	6
	Fisheries	4
	Urban	3
	Water	2
Ecosystem	Terrestrial	19
	Marine	11
	Freshwater	4
Indirect drivers considered	Policies, governance systems and institutions	15
	Economic drivers	10
	Demographic drivers	7
	Science and technology	3
	Socio-cultural drivers	3
Direct drivers considered	Climate change and variability	21
	Land use and land cover change	12
	Natural resource exploitation	6
Linkage considered	Direct drivers to state of nature	16
	Indirect drivers to state of nature	10
	State of nature to benefits to humans	9
	Response to drivers	2
	Indirect drivers to benefits to humans	1
	Benefits to humans to response/governance	1

Summary of trends of SOE impacts

Impacts	**N**	**% Share**
Environment	19	66%
Economic	12	41%
Social	8	28%
Econ-Envi-Social	3	10%

Summary of trends of SOE impacts and models

Nature of Impacts	**With model**	**Without model**
Environmental Impacts	14 (48%)	6 (21%)
Economic Impacts	7 (24%)	2 (7%)
Social Impacts	6 (21%)	1 (3%)

D. Curriculum vitae

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Technical Support Unit for IPBES Knowledge and Data Task Force

Statistics Korea Statistical Research Institute — Daejeon, Korea
Research Contractor, Trend Analysis Unit — Feb – Aug 2014

UNESCO, *Education for All Global Monitoring Report* — Paris, France
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Fellowship & Secondment

Intergovernmental Platform on Biodiversity and Ecosystem Services Bonn, Germany
Fellow on development of scenarios on nature and its contributions to people Mar 2019 to now

Yale University, Jetz Lab & Map of Life New Haven, USA
Secondment of IPBES Knowledge and Data Technical Support Unit Oct – Dec 2016

Awards & Grants

Mar 2019	EU Directorate-General CLIMA Climate Change Modelling Information Expert Support Fund (for Denver Scenarios Forum 2019)
Nov 2018	iDiv Female Scientist Career Fund (CBD COP14)
Sept 2018	Student Conference on Conservation Science (SCCS) bursary (SCCS Europe 2018)
Dec 2017	iDiv Science Policy Committee Shadowing Program Fund (CBD SBSTTA21)

Reviews Activities

Proposals for German Ministry of Science and Research BMBF (Dec 2019, April 2021)
Journals *Sustainability Science, Conservation Biology, Environmental Science and Policy*

Leadership & Membership

GLASSNET Local-Global-Local Analysis of Systems Sustainability, member	Since 2021
UN SEEA Indicators Working Group, member	Since Oct 2020
IPBES Scenarios and Models Taskforce, fellow	Since April 2019
GEO BON Policy Taskforce, member	Since June 2017
iDiv Science Policy Committee, member	Since 2017
iDiv Integrative Synthesis Club, co-founder and member	2018-2019
iDiv yDiv Integrative Biodiversity Science Course Taskforce, PhD rep.	2018-2019

Halle (Saale), den 10.02.2022

HyeJin Kim

E. List of publications and conference contributions

Publications in Dissertation

- "A protocol for an intercomparison of biodiversity and ecosystem services models using harmonized land-use and climate scenarios". *Geoscientific Model Development*, 11, 4537-4562. 2018. https://doi.org/10.5194/gmd-11-4537-2018.
- "Global trends in biodiversity and ecosystem service from 1900-2050" by Henrique M. Pereira et al. (in review) https://doi.org/10.1101/2020.04.14.031716
- "Towards a better future for biodiversity and people: modelling Nature Futures" by HyeJin Kim et al. (in review.) https://osf.io/preprints/socarxiv/93sqp/

Publications in Peer-reviewed Journals

- "Nature futures for the urban century: Integrating multiple values into urban management." Andressa V. Mansur et al. *Environmental Science & Policy*, *vol. 131:46-56*. 2022. https://doi.org/10.1016/j.envsci.2022.01.013
- "Biodiversity post-2020: Closing the gap between global targets and national-level implementation." Andrea Perino et al. *Conservation Letters.* 2021. https://doi.org/10.1111/conl.12848
- "Emerging response options and scenarios of slow onset events related to climate change in Southeast Asia." Margaret Matias et al. *Current Opinion in Environmental Sustainability, 50, 175-184.* 2021. https://doi.org/10.1016/j.cosust.2021.04.004
- "Developing multi-scale and integrative nature-people scenarios: the IPBES Nature Futures framework." by Laura Pereira et al. *People and Nature.* 2020. https://besjournals.onlinelibrary.wiley.com/doi/full/10.1002/pan3.10146
- "Conservation goals in international policies" by Aletta Bonn et al., a book chapter in Conservation Research, Policy and Practice by William Sutherland et al. Cambridge University Press. April 2020. https://doi.org/10.1017/9781108638210.015
- Ch. 4 Plausible futures of nature, its contributions to people and their good quality of life. In: IPBES Global Assessment on Biodiversity and Ecosystem Services. https://ipbes.net/global-assessment
- "Challenges in producing policy-relevant global scenarios of biodiversity and ecosystem services". *Global Ecology and Conservation, vol. 22. 2019*. https://doi.org/10.1016/j.gecco.2019.e00886
- "Monitoring biodiversity change through effective global coordination". *Current Opinion in Environmental Sustainability*, *29, 158–169.* 2017. https://doi.org/10.1016/j.cosust.2018.02.005.
- "Multiscale scenarios for nature futures". *Nature Ecology and Evolution. 1 (10), 1416 – 1419.* 2017. https://doi.org/10.1038/s41559-017-0273-9.
- "The Biodiversity Informatics Landscape: Elements, Connections and Opportunities". *Research Ideas and Outcomes, 3, e14059.* 2017. https://doi.org/10.3897/rio.3.e14059

Invited Presentations at Conferences and Meetings

- Enhancing Data Interoperability through Essential Variables and Biodiversity Observation Networks." 6th Expert Forum of the UN System of Environmental Economic Accounting. December 2021. Virtual.
- "Enhancing the role of biodiversity scenarios in policy development and implementation for sustainable and positive futures: Connecting and interweaving multiscale perspectives and processes." Biodiversa BiodivScen Interim Conference. October 2021. Virtual.
- "External Review of the Nature Futures Framework." A webinar for the Social Science and Humanities Stakeholder Network of IPBES ONet. October 2021. Virtual.
- "Enhancing policy relevance of modelling and indicators through framework and data connectivity and cyberinfrastructure: recent developments in biodiversity and ecosystem services from IPBES and GEO BON." GLASSNET Workshop on Cyberinfrastructure. September 2021. Virtual.
- "Role of indicators in modelling scenarios using the Nature Futures Framework Part II: Potential role of Essential Biodiversity Variables and Essential Ecosystem Services Variables". IPBES workshop on modelling Nature Futures scenarios. January 2021. Virtual.
- "Nature Futures scenarios and modelling & the role of SSH scholars". IPBES Social Science and Humanities (SSH) Community of Practice Seminar. November 2020. Virtual.
- "Linking data and indicators with the SEEA EA – An overview of GEO BON EBV & EESV framework". Virtual Expert Forum on SEEA Experimental Ecosystem Accounting 2020. November 2020. Virtual.
- "EBVs-based analysis using the Intervention-Nature-Benefit framework for CBD Post-2020 Global Biodiversity Framework". GEOBON EBV2020 2nd Workshop. Feb. 2020. Leipzig, Germany.
- "Nature Futures, and the relevance of Essential Biodiversity of Variables (EBVs)." GEOBON EBV2020 1st Workshop. Oct. 2019. Washington, D.C., U.S.A.
- "Re-viewing the Concept of Biodiversity and Nature's Contributions to People." Structuring Nature: An Interdisciplinary and Intercultural Summer School. Aug. 2019. Berlin, Germany.
- "Integrated modelling for multi-scale nature futures." 2019 iDiv Conference. Aug. 2019. Leipzig, Germany.
- "Enhancing biodiversity conservation through the use of scenarios and models in informing societal decisions."
  - 2018 iDiv Annual Conference. December 2018. Leipzig, Germany
  - 2018 Student Conference on Conservation Science Europe. September 2018. Tihany, Hungary.
- "Shared Socioeconomic Pathways on Biodiversity and Ecosystem Services for IPBES Global Assessment". UN Convention on Biological Diversity SBSTTA22. July 2018. Montreal, Canada.
- "Nature Futures: IPBES multi-scale, multi-sectoral visions for biodiversity conservation". 2017 iDiv Annual Conference. December 2017. Leipzig, Germany
- "Current use and future needs of scenarios and models". Workshop on Biodiversity and Ecosystem Services Scenarios for IPBES using the Shared Socio-economic Pathways. October 2017. Leipzig, Germany

Halle (Saale), den 10.02.2022

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F. Authors' contributions

Chapter 2

Kim, H.J., Rosa, I., Martins, I.S., … Pereira, H.M. (2018) A protocol for an intercomparison of biodiversity and ecosystem services models using harmonized land-use and climate scenarios. *Geoscientific Model Development*, 11, 4537–4562.

Protocol design: Alkemade, R. (40%), Leadley, P. (40%), Pereira, H.M. (20%), other authors (input)
Writing: Kim, H.J. (70%), Rosa, I. (10%), Martins, I.S. (10%), Pereira, H.M. (10%), other authors (edits)

Chapter 3

Pereira, H.M., Rosa, I., Martins, I.S., **Kim, H.J**., et al. *In review.* Global trends in biodiversity and ecosystem service from 1900-2050

Design: Kim, H.J. (10%), Rosa, I. (20%), Martins, I.S. (20%), Pereira, H.M. (50%)
Analysis: Kim, H.J. (30%), Rosa, I. (30%), Martins, I.S. (30%), Pereira, H.M. (10%) other authors (input)
Writing: Kim, H.J. (15%), Rosa, I. (15%), Martins, I.S. (15%), Pereira, H.M. (55%), other authors (input)

Chapter 4

Kim. H.J., Peterson, G., Cheung, W., Ferrier, S., … Pereira, H.M. *In review*. Towards a better future for biodiversity and people: modelling Nature Futures

Design: Kim, H.J. (50%), Peterson, G. (10%), Cheung, W. (10%), Ferrier, S. (10%), Pereira, H.M. (20%), other authors (input)
Analysis: Kim, H.J. (70%), Pereira, H.M. (30%), other authors (input)
Writing: Kim, H.J. (80%), Pereira, H.M. (20%), other authors (edits)

Chapter 5

Kim, H.J., Pereira, H.M. et al. *In preparation.* Performance of terrestrial protected areas under the Nature Futures prism.

Design: Kim, H.J. (80%), Pereira, H.M. (20%), other authors (datasets and input)
Analysis: Kim, H.J. (90%), Pereira, H.M. (10%), other authors (datasets and input)
Writing: Kim, H.J. (90%), Pereira, H.M. (10%), other authors (datasets and input)

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G. Eigenständigkeitserklärung

Hiermit erkläre ich, dass die Arbeit mit dem Titel „Enhancing the use of scenarios-based biodiversity information in conservation policies and practice“ bisher weder bei der Naturwissenschaftlichen Fakultät I Biowissenschaften der Martin-Luther-Universität Halle-Wittenberg noch einer anderen wissenschaftlichen Einrichtung zum Zweck der Promotion vorgelegt wurde.

Ferner erkläre ich, dass ich die vorliegende Arbeit selbstständig und ohne fremde Hilfe verfasst sowie keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe. Die den Werken wörtlich oder inhaltlich entnommenen Stellen wurden als solche von mir kenntlich gemacht.

Ich erkläre weiterhin, dass ich mich bisher noch nie um einen Doktorgrad beworben habe.

Halle (Saale), den 10.02.2022

HyeJin Kim

Appendix II

A. Supplementary Material of **Chapter 2**. A protocol for an intercomparison of biodiversity and ecosystem services models using harmonized land-use and climate scenarios

Supplement of Geosci. Model Dev., 11, 4537–4562, 2018
https://doi.org/10.5194/gmd-11-4537-2018-supplement

Geoscientific
Model Development
Open Access

Supplement of

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

HyeJin Kim et al.

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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 (ºC)	Nitrogen deposition (IMAGE model) Roads (GRIP dataset, Meijer et al., 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., 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): $$ii_{s,r,t'} = \frac{E_{s,r,t'} - E_{s,r,t}}{\sum_{r=1}^{\lvert R \rvert} E_{s,r,t}}$$ *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 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

BES-SIM model	Description
	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 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

BES-SIM model	Description
	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). 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:

BES-SIM model	Description
	$$p_i = \left[\frac{\sum_{j=1}^{n} s_{i_{present} j_{future}} c_{j_{future}}}{\sum_{j=1}^{n} s_{i_{present} j_{present}}}\right]^z$$ 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 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

BES-SIM model	Description
	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).
Ecosystems-based model of biodiversity	

BES-SIM model	Description
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.
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

BES-SIM model	Description
	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 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

BES-SIM model	Description
	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 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)

BES-SIM model	Description
	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 changes in cropland extent under the different scenarios. Yield was expressed in terms of caloric content based on

BES-SIM model	Description
	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	10^9KCal	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

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B. Supplementary Material of **Chapter 3**. Global trends in biodiversity and ecosystem service from 1900 to 2050

Supplementary Materials for

Global trends in biodiversity and ecosystem service from 1900 to 2050

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Materials and Methods

This study was conducted under the auspices of the Expert Group on Scenarios and Models of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). The detailed protocol of this multi-model study was published in (*17*). Below we summarize the main methodological aspects.

Scenarios

All models used the same set of scenarios: SSP1 with RCP2.6 ("global sustainability" with low land-use pressure and low level of climate change, (*36*)), SSP3 with RCP6.0 ("regional rivalry" with high land-use pressure and intermediate level of climate change, (*37*)), and SSP5 with RCP8.5 ("fossil-fueled development" with intermediate land-use pressure and high level of climate change, (*38*)) – to assess a broad range of plausible futures (Table S1). We used land-use projections for these scenarios ignoring the impacts of climate change, although the deployment of land-based climate mitigation strategies is considered in connection to each of the SSP-RCP combinations. Land-use projections for SSP3xRCP6.0 were not available, so we chose the closest land-use projections available, SSP3xRCP7.0.

Land use data

All models used the Land Use Harmonization (*39–43*) version 2 dataset (LUH2, see http://luh.umd.edu/data.shtml for data). LUH2 provides global gridded land-use datasets at 0.25° resolution with annual time-steps comprising estimates of historical land-use change (850-2015) and future projections (2015-2100) under the assumptions of each Shared Socio-economic Pathway (SSP) (*44*). The 12 land use categories (Table S3) include the separation of primary and secondary natural vegetation into forest and non-forest sub-types, pasture into managed pasture and rangeland, and cropland into multiple crop functional types (C3 annual, C3 perennial, C4 annual, C4 perennial, and C3 nitrogen-fixing crops). The LUH2 dataset also computes all transitions between these 12 land use types, resulting in over 100 possible transitions per grid cell per year (e.g., crop rotations, shifting cultivation, agricultural changes, wood harvest) as well as various agricultural management layers (e.g., irrigation, synthetic nitrogen fertilizer, biofuel crops). Due to specific model parameterizations, each biodiversity and ecosystem service model used its own aggregation of the land use categories (see (*17*) for more details).

Climate data

Models used historical climate data and future projections associated with each SSPxRCP combination (*20*) from CMIP5 / ISIMIP2a (*45*) or its downscaled version from the WorldClim (*46*), or the projections from MAGICC 6.0 (*47*, *48*). Most models used the IPSL-CM5A-LR (*49*) projections which are mid-range across the 5 GCMs in ISIMIP2a (*50*) – that includes 12 climate variables at 0.5° resolution on daily time steps from the pre-industrial period 1951 to 2099 (*45*). The WorldClim downscaled dataset has 19 bioclimatic variables monthly from 1960 to 1990 and multi-year averages for specific points in time (e.g., 2050, 2070) up to 2070 at 1km resolution. MAGICC 6.0 climate data (*47*, *48*) in the IMAGE model framework (*51*) was used for the GLOBIO model.

Biodiversity models

All models have been published in peer-reviewed journals, although in some cases modifications have been made to the original model (see (*17*) for details in modifications). In total, 8 spatially-explicit models were used (Table S2), these include three species distributions models - AIM-biodiversity (*52*), InSiGHTS (*53*, *54*), MOL (*55*, *56*); and five community models (cSAR-iDiv (*57*), cSAR-IIASA-ETH (*58*), BILBI (*59*), PREDICTS (*60*, *61*), GLOBIO (*62*, *63*). Three of these models, BILBI, PREDICTS and cSAR-iDiv share coefficients for the impacts of land-use on biodiversity from the PREDICTS database (*61*). The biodiversity models have different methodological approaches, taxonomic groups, spatial resolution and output metrics (Table S2), but they were harmonized as described below.

Ecosystem services models

For ecosystem functioning and services, five spatially-explicit models were used. They include three process-based DGVM models – LPJ-GUESS (*64–66*), LPJ (*67*, *68*), and CABLE-POP (*69*) – and two ecosystem services models – InVEST (*70*) and GLOBIO-ES (*71*, *72*)). These rely on different modelling approaches to estimate a wide range of biophysical outputs, which were harmonized as described in the next sections (see Table S2 for a summary of the models, details available in (*17*)).

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

Model outputs were produced at three spatial scales: one-degree grid cells (α metrics), at the regional level (regional γ metrics) for the 17 IPBES sub-regions (*73*), and at the global level (global γ metrics). The methodology adopted by each modelling team to aggregate from the original resolution of the model to one-degree cells was the arithmetic average of the values in the original resolution.

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

Biodiversity metrics

Outputs of each biodiversity model were assigned to one or more of the following harmonized biodiversity metrics (Table S2): species richness (S), mean species habitat extent ($\dot{H}$), and species-abundance based biodiversity intactness (I). While all metrics were reported as proportional changes relative to the beginning of a time period, intactness was also reported as a score relative to a pristine baseline. For mapping purposes, local changes in proportional species richness were converted in normalized changes in absolute species richness (ΔSS), by multiplying by the number of species in each cell divided by the number of species in the richest cell. Global spatial averages of the local metrics were calculated across all terrestrial one-degree cells and are denoted with an overbar (e.g. $\overline{\Delta S_\alpha}$) to distinguish it from averages of a metric across species ($\dot{H}$).

In the end, the harmonized metrics analyzed were:

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

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

In addition, global spatial averages for α metrics where calculated as follows:

- $\overline{\Delta S_{\alpha}} = \sum_{x,y}\frac{\Delta S_{\alpha}(x,y)}{n}$
- $\overline{\Delta \dot{H}_{\alpha}} = \sum_{x,y}\frac{\Delta \dot{H}_{\alpha}(x,y)}{n}$
- $\overline{I_{\alpha}} = \sum_{x,y}\frac{I_{\alpha}(x,y)}{n}$

where *n* is the number of terrestrial one-degree cells.

The harmonized biodiversity metrics need to be interpreted with care as the original model outputs mapped to the same harmonized metric can differ in some technical details. For instance, the GLOBIO model (*62*, *63*) 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 (*74*) 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 both metrics have been harmonized as representing species-abundance based intactness (*I*), they are calculated differently in the models (i.e., the former is the average of abundance ratios while the latter is the ratio of the sums). Similarly, models based on the species-area relationship (*75*) produced similar metrics (relative change in species richness) but covered different taxonomic groups (Table S2).

Ecosystem services metrics

A similar effort was made to assign the metrics outputted by the ecosystem function and services models to a set of harmonized metrics (Table S1). We used the typology of the IPBES Nature’s Contributions to People (NCPs) (*19*) to classify material and regulating services. For each of the following ecosystem services we assigned one biophysical metric from one or more models, sometimes changing the sign of the reported metric for consistency: bioenergy production; food and feed production; timber production; ecosystem carbon; crop pest control (more is better control); coastal resilience (more is greater resilience); pollination; soil protection; nitrogen retention (more is higher water quality).

The dynamic global vegetation models (DGVMs) tend to output similar metrics and have similar assumptions (*76*), but the two ecosystem service models (GLOBIO and InVEST) tended to output different metrics for the same service. DGVMs have been used in the climate change modeling community for decades so they benefit from a long history of multi-model inter-comparison (*77*). Therefore, while for certain metrics, such as ecosystem carbon pool, the metrics are calculated in a similar way and use equivalent biophysical units (e.g. Kg C), for other metrics, e.g., pollination, direct comparison of absolute values was not feasible. For instance, GLOBIO-ES (*72*, *78*) defines their metric of pollination services as “the fraction of cropland potentially pollinated, relative to all available cropland”, but in InVEST (*79*) defines it as “the proportion of agricultural lands whose pollination needs are met”. As for biodiversity metrics, this problem was addressed by using proportional changes of each metric in each model at each scale of analysis.

Comparison of biodiversity, regulating and material ecosystems services

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

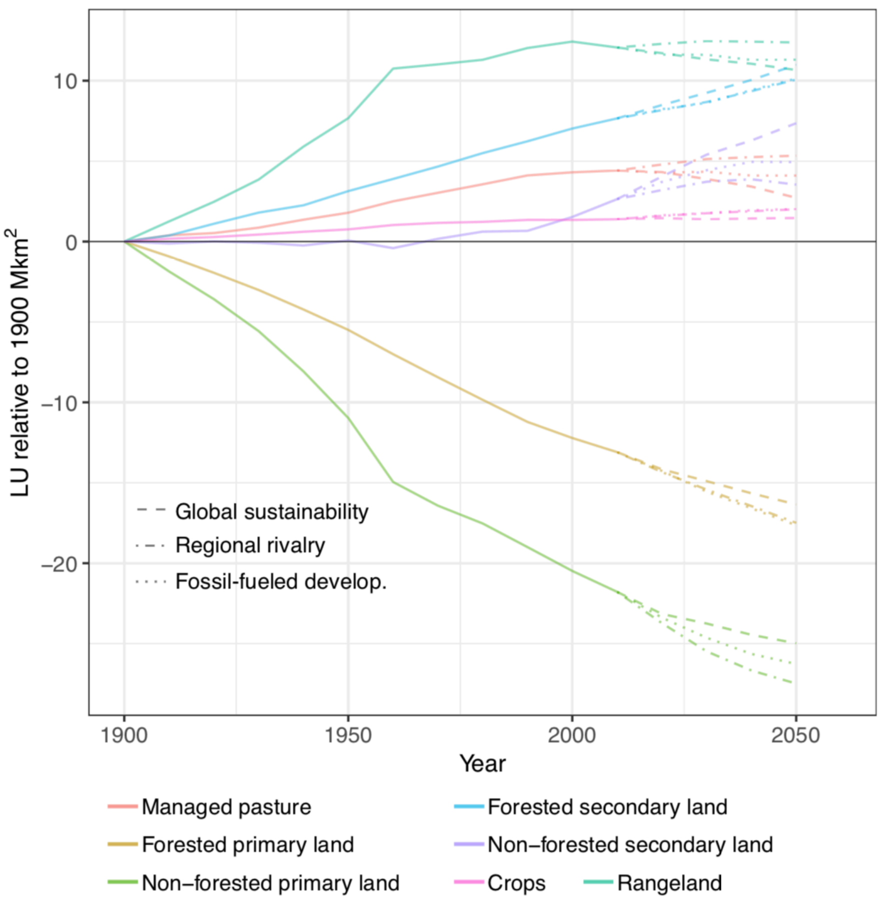

Fig. S1. (a) Global historical trends (1990-2015) in land-use and projected trends for each scenario (2015-2050). Lines correspond to absolute area changes relative to the year 1900. The original area covered by each land-use in 1900 was: forested primary land (36.0 Mkm^2), non-forested primary land (50.7 Mkm^2), forested secondary land (6.3 Mkm^2), non-forest secondary land (11.8 Mkm^2), managed pasture (3.5 Mkm^2), rangeland (12.9 Mkm^2), cropland (9.5 Mkm^2).

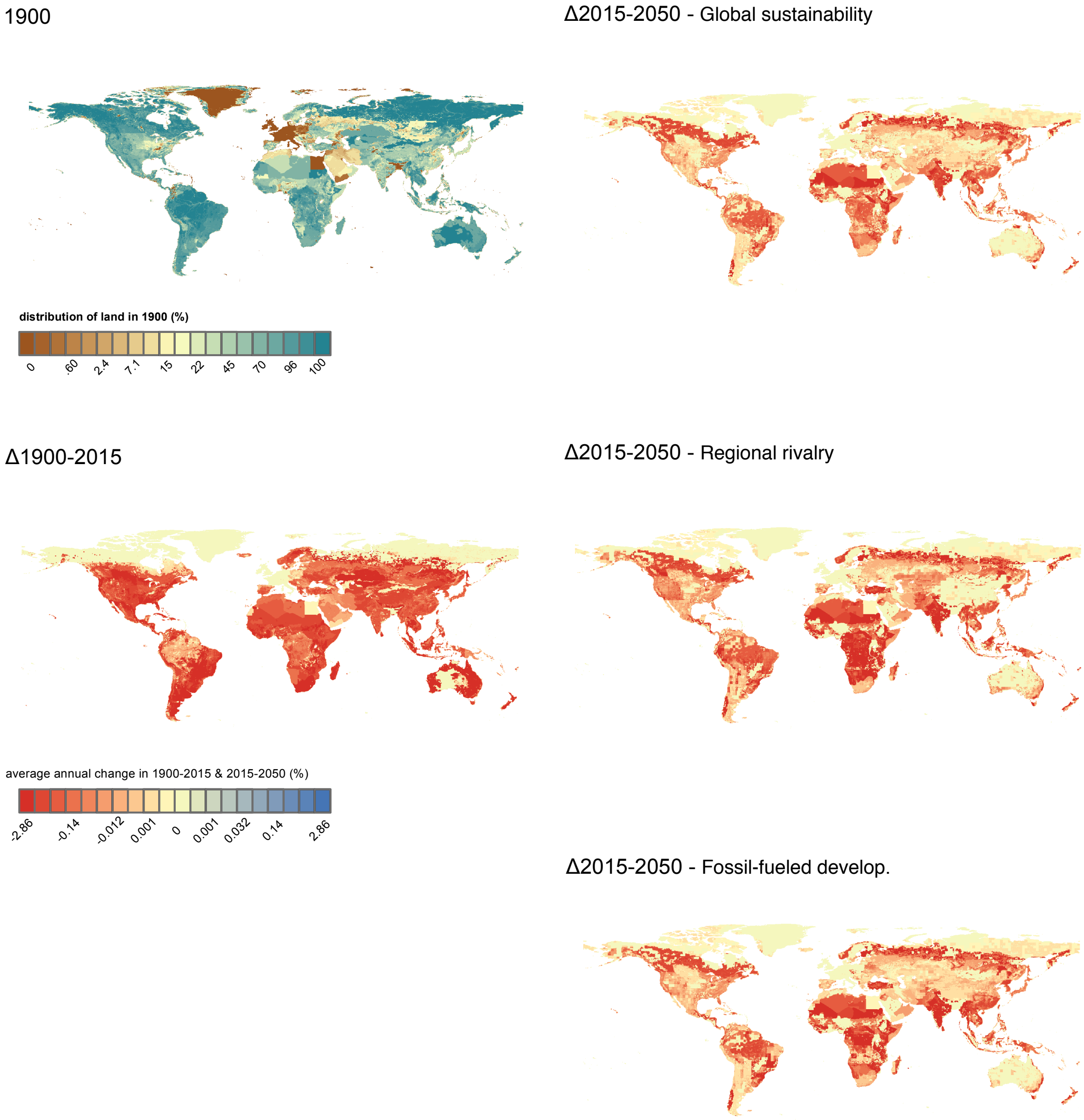

Figure S1 (b) Distribution of primary land (forest & non-forest) in 1900, historical changes (1900-2015) and future changes (2015-2050) in each scenario. Please note that changes are reported in absolute percentage points (i.e., y_{t1}-y_{t0} where y is the percentage of the area in a cell covered by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

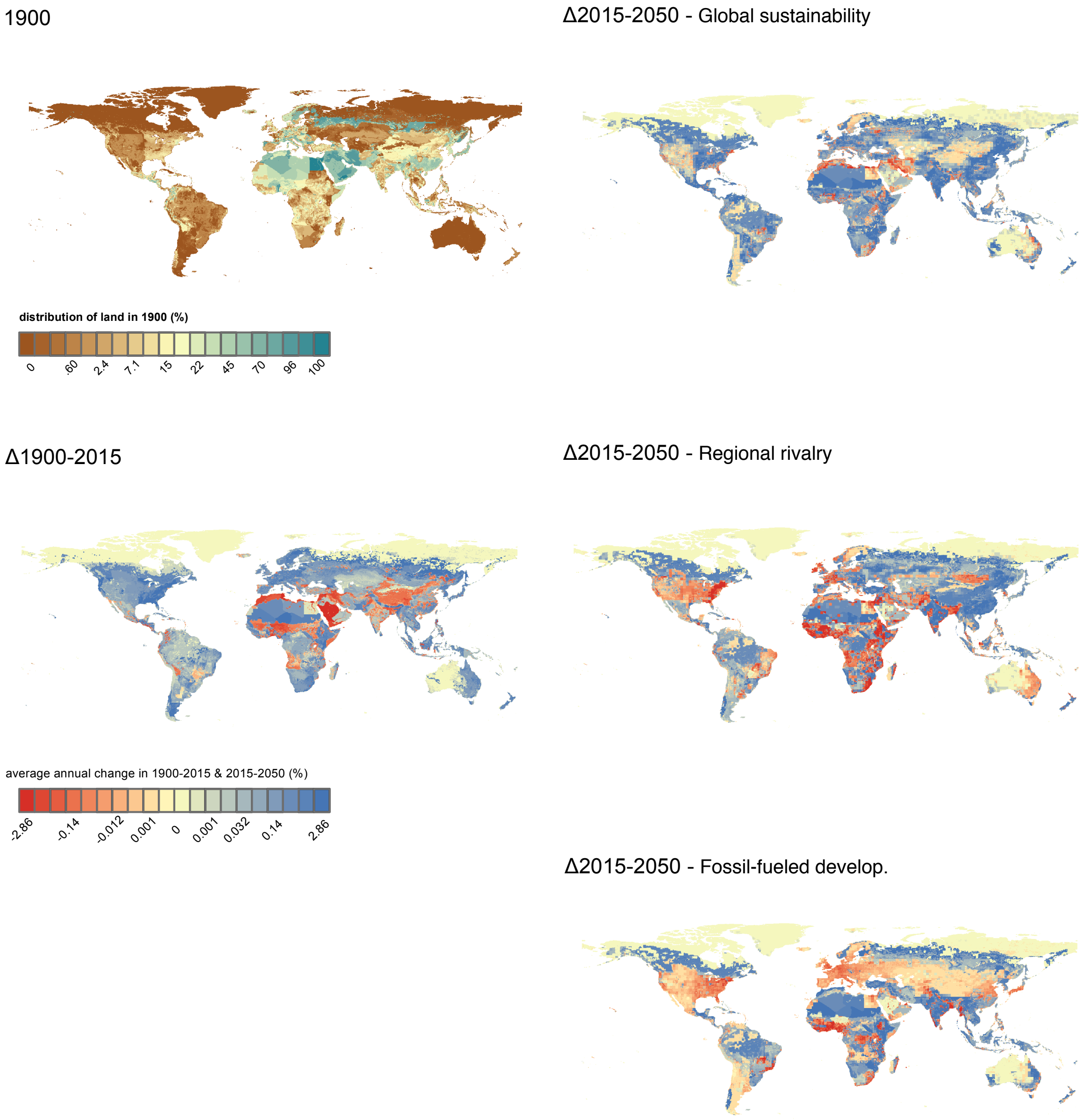

Figure S1 (c) Distribution of secondary land (forest & non-forest) in 1900, historical changes (1900-2015) and future changes (2015-2050) in each scenario. Please note that changes are reported in absolute percentage points (i.e. y_{t1}-y_{t0} where y is the percentage of the area in a cell covered by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

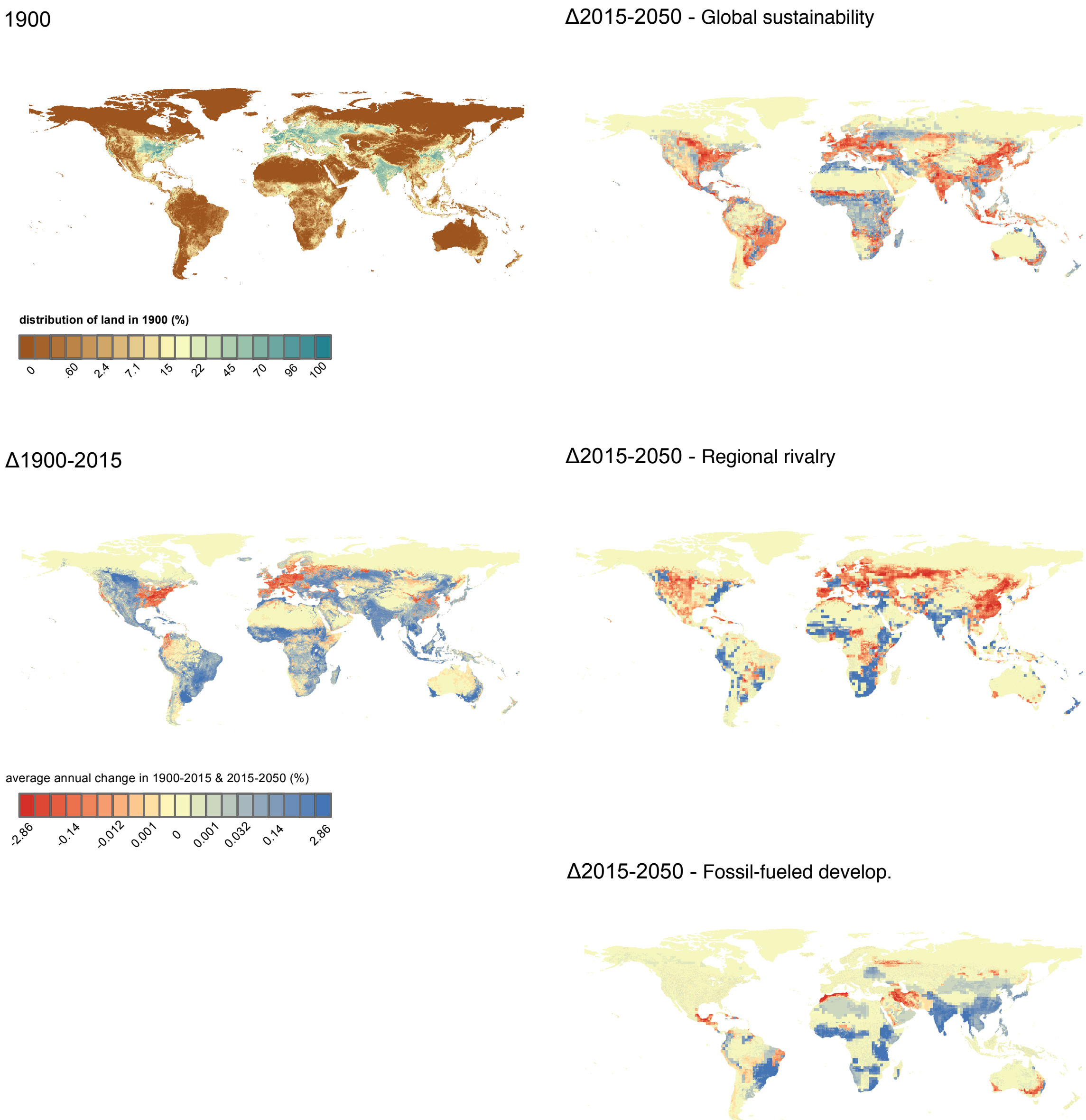

Figure S1 (d) Distribution of cropland (C3 & C4) in 1900, historical changes (1900-2015) and future changes (2015-2050) in each scenario, in percentage. Please note that changes are reported in absolute percentage points (i.e. y_{t1}-y_{t0} where y is the percentage of the area in a cell covered by that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

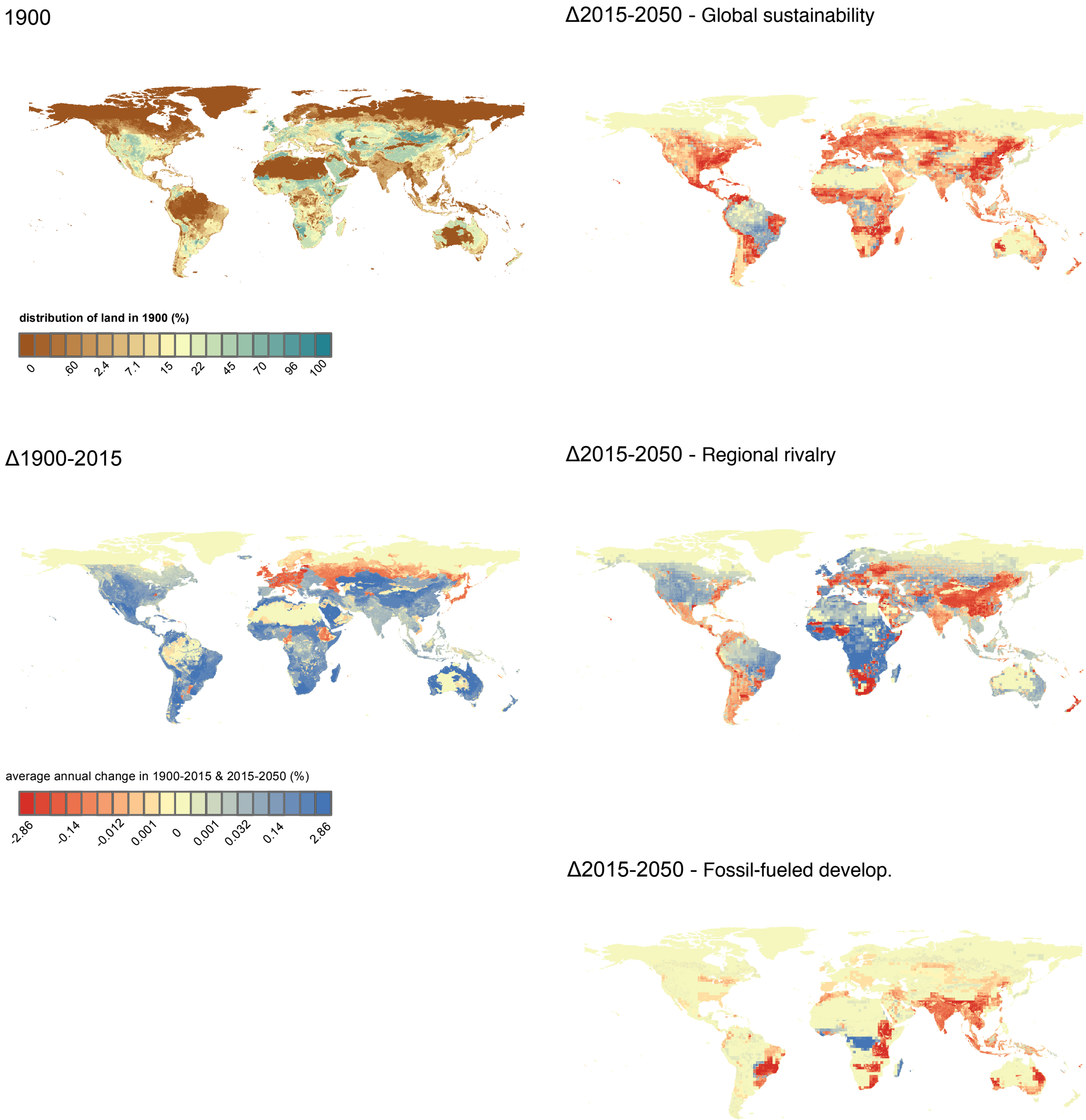

Figure S1 (e) Distribution of pasture and rangeland in 1900, historical changes (1900-2015) and future changes (2015-2050) in each scenario, in percentage. Please note that changes are reported in absolute percentage points (i.e. y_{t1}-y_{t0} where y is the percentage of the area in a cell covered by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

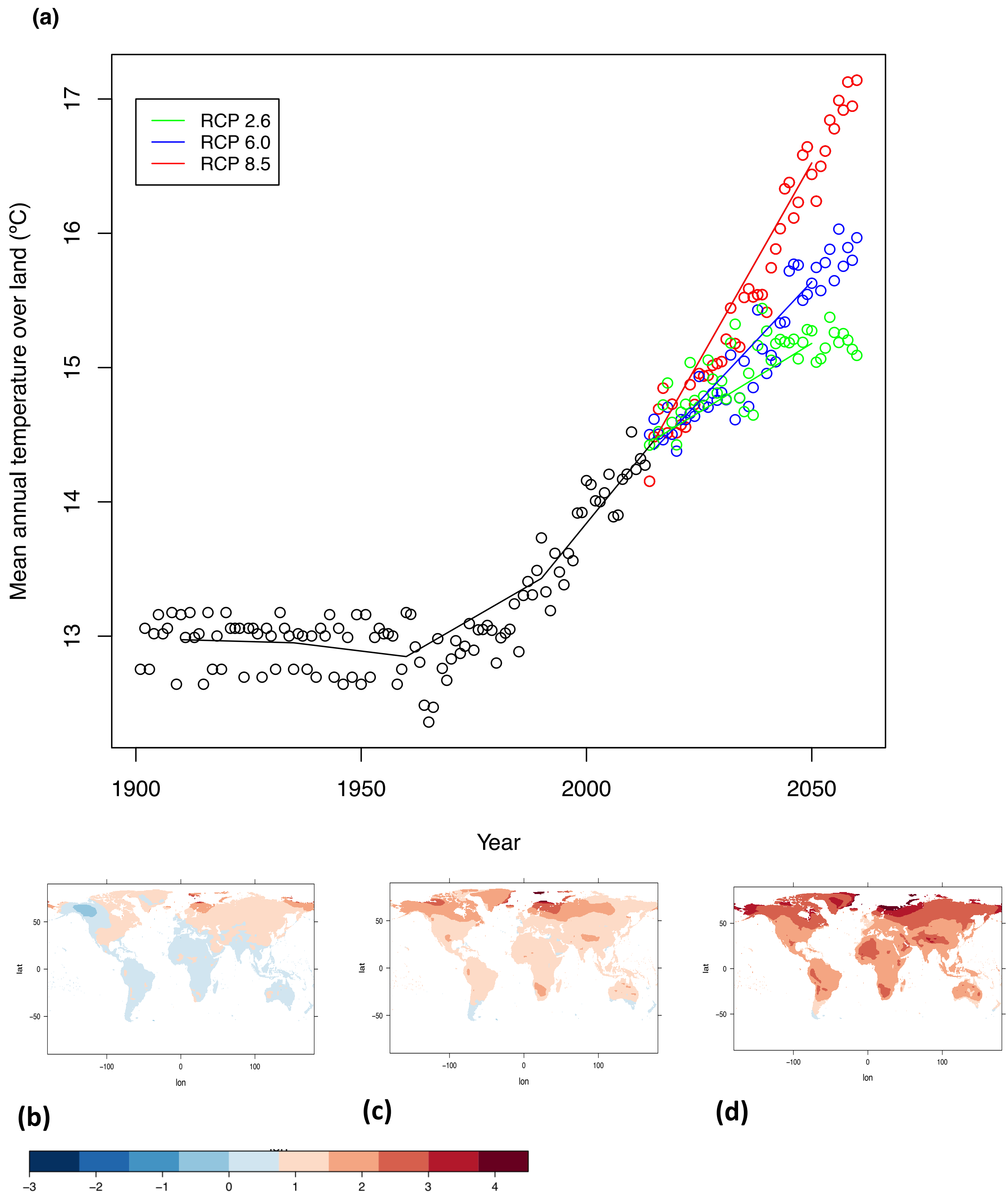

Fig. S2. (a) Global historical trends (1990-2015) in mean annual temperature and for each scenario (2015-2050). Spatial distribution absolute changes in mean annual temperature in each scenario (2015-2050): **(b)** global sustainability - RCP2.6, **(c)** regional rivalry - RCP6.0, **(d)** fossil-fueled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

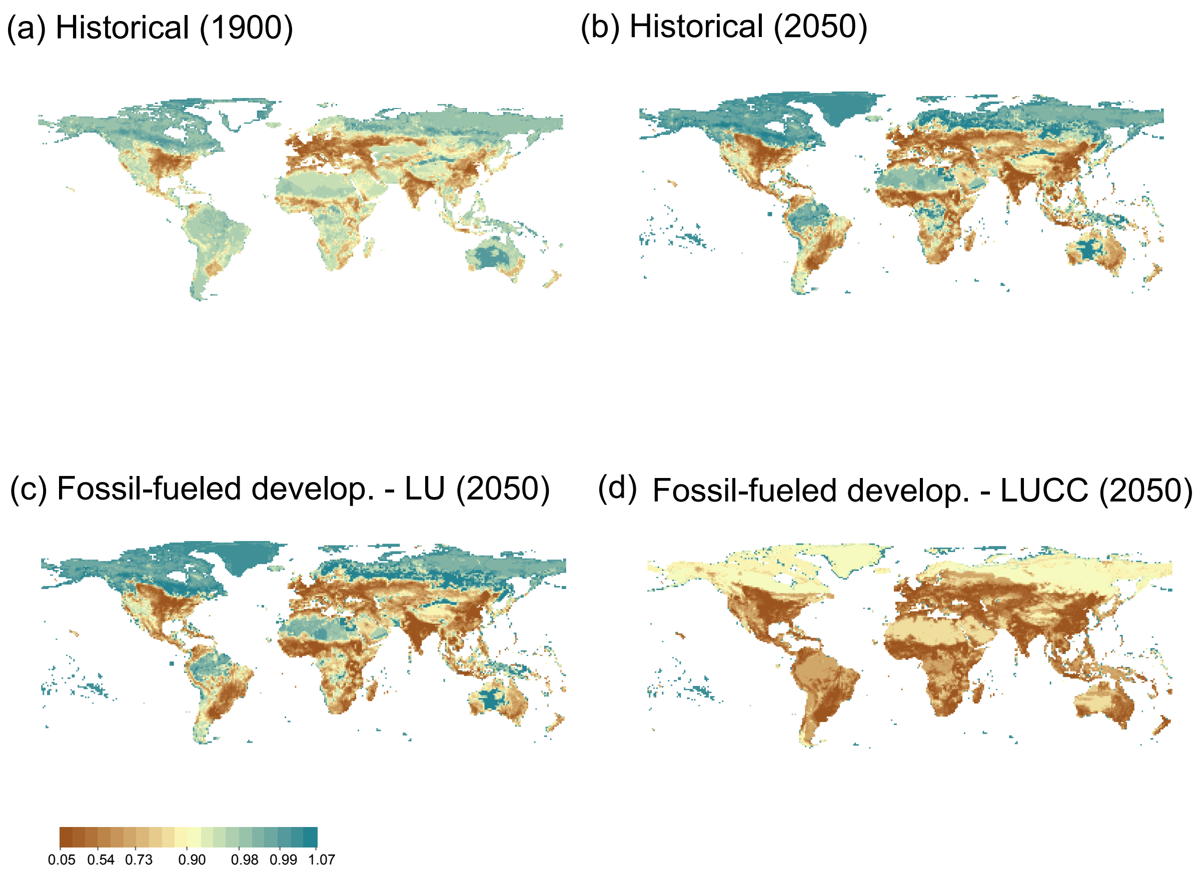

Fig. S3. Spatial distribution of intactness (*I*): **(a)** year 1900; **(b)** 2015; **(c-d)** 2050 in the fossil-fueled development scenario based on land-use change alone **(c)** and on the combined impacts of land-use change and climate **(d)**. Values correspond to the inter-model mean between PREDICTS and GLOBIO, except for **(d)** which is based only on GLOBIO. Values are scores relative to a pristine baseline (a score of 1 corresponds to pristine, while a score of 0 corresponds to fully degraded). Color scale is based on quantile intervals when considering all maps features.

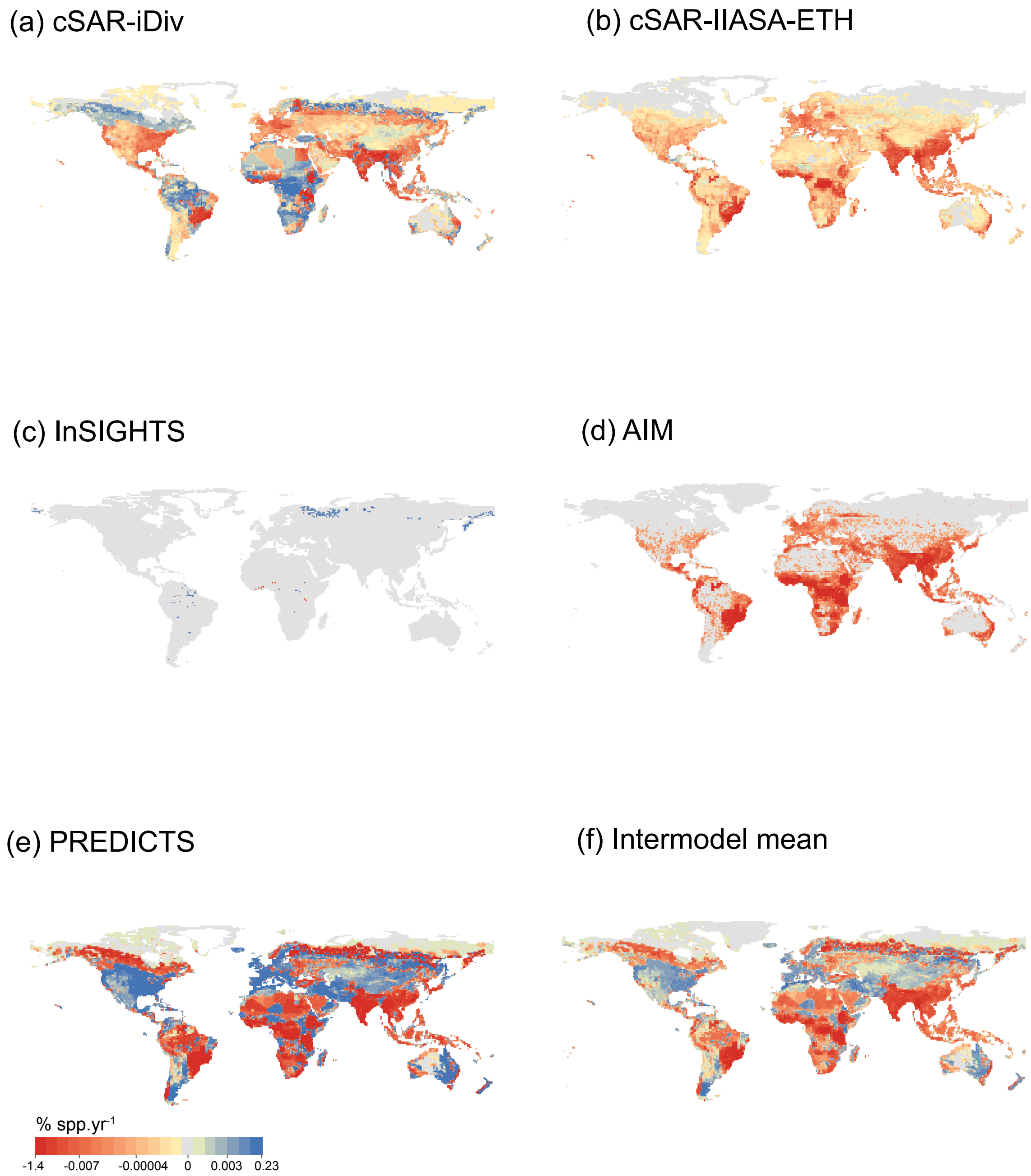

Fig. S4. Spatial agreement between biodiversity models. Projection of normalized changes in local species richness per year (ΔSS_{α}) during 2015-2050 caused by land-use change alone for the regional rivalry scenario: **(a)** cSAR-iDiv model; **(b)** cSAR-IIASA-ETH model; **(c)** InSIGHTS model; **(d)** AIM-B model; **(e)** PREDICTS model; **(f)** inter-model mean. A value of 1% yr^{-1} corresponds to a decline in the number of local species equal to 1% species of the most speciose grid cell. Color scale is based on quantile intervals when considering all maps features.

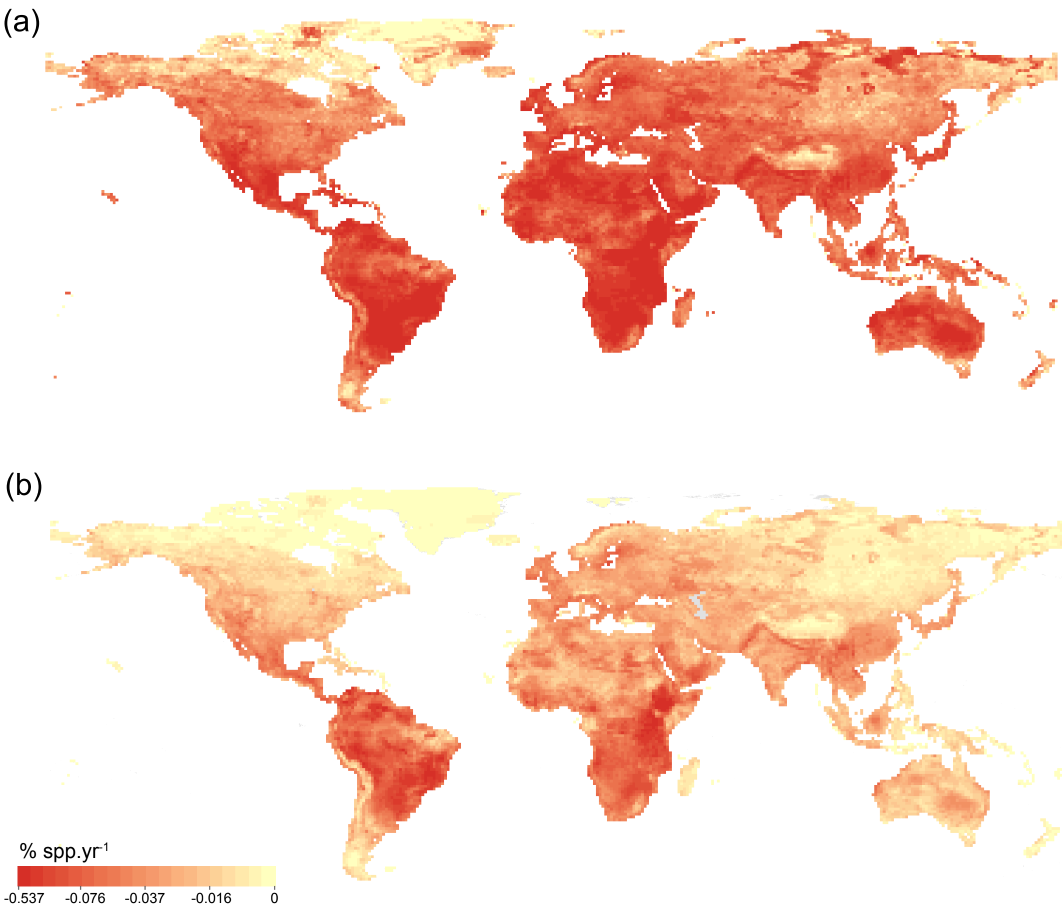

Fig. S5. Biodiversity metrics of the AIM model for the fossil fueled development scenario for 2015-2050: **(a)** proportional changes in local species richness (ΔS_{α}); **(b)** normalized changes in local species richness per year (ΔSS_{α}). Color scale is based on quantile intervals when considering all maps features.

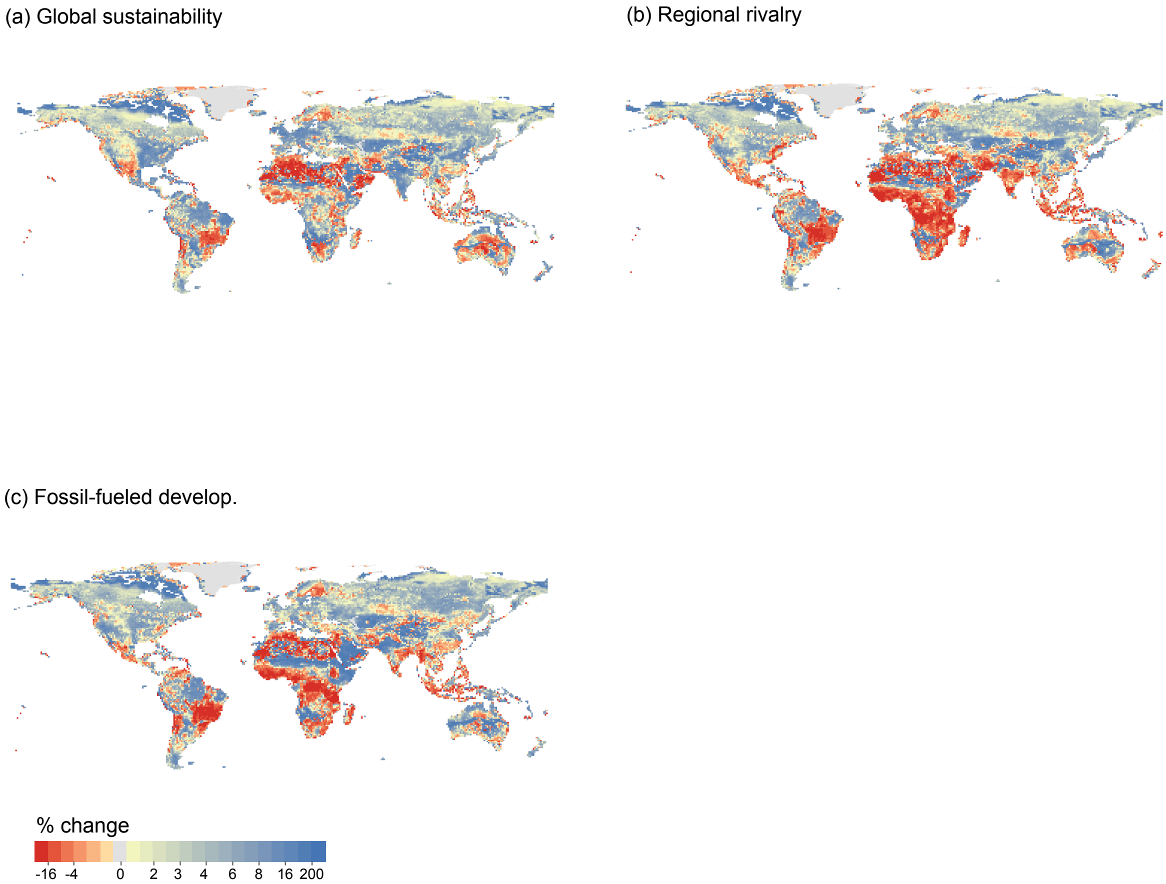

Fig. S6. Ecosystem carbon pools across scenarios. Inter-model mean of proportional changes for 2015-2050 (N=4, CABLE-POP, LPJ, LPJ-GUESS, GLOBIO-ES): (a) global sustainability, (b) regional rivarly, (c) fossil-fueled development. Color scale is based on quantile intervals when considering all maps features.

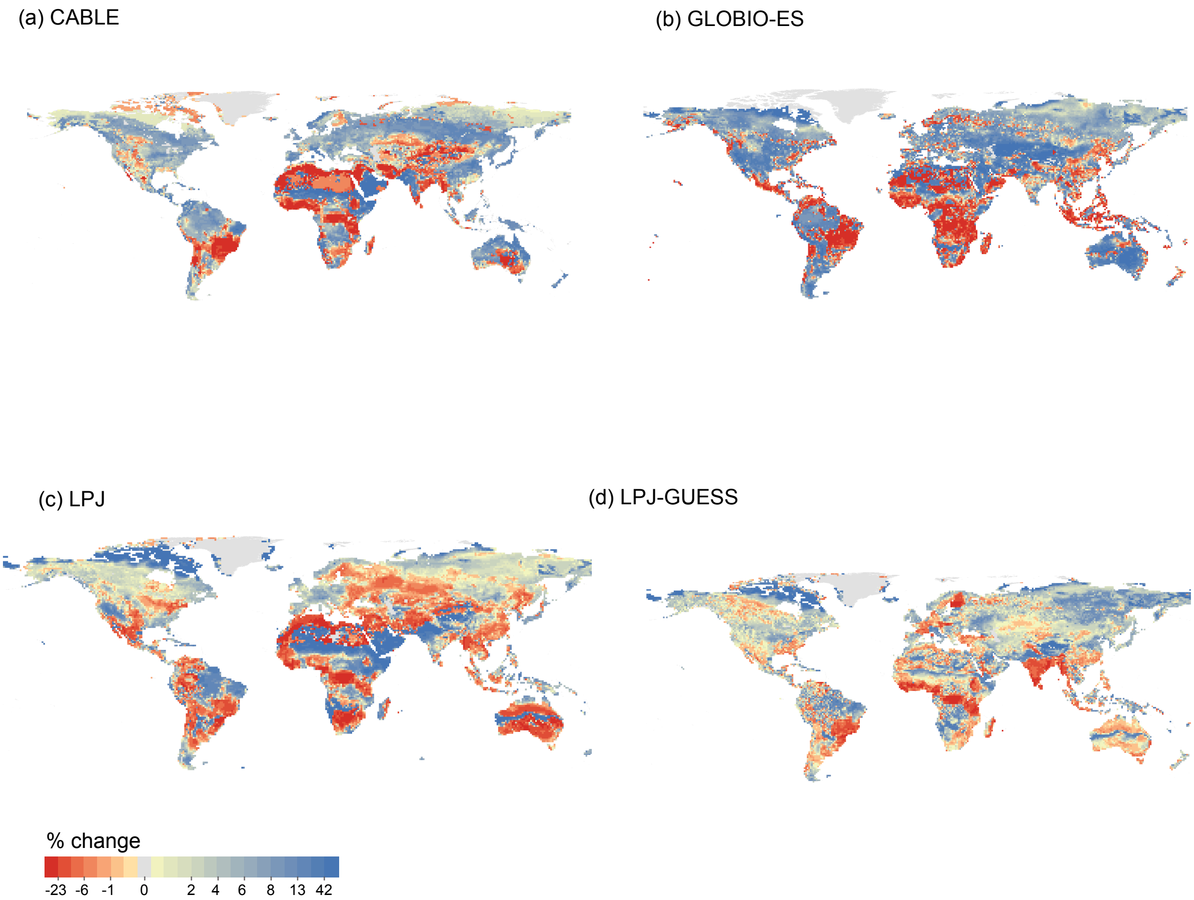

Fig. S7. Spatial agreement across models in ecosystem carbon for the fossil fuel development scenario for 2015-2050: **(a)** CABLE-POP, **(b)** GLOBIO-ES, **(c)** LPJ and **(d)** LPJ-GUESS. The inter-model mean can be found in Figure S7. Color scale is based on quantile intervals when considering all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

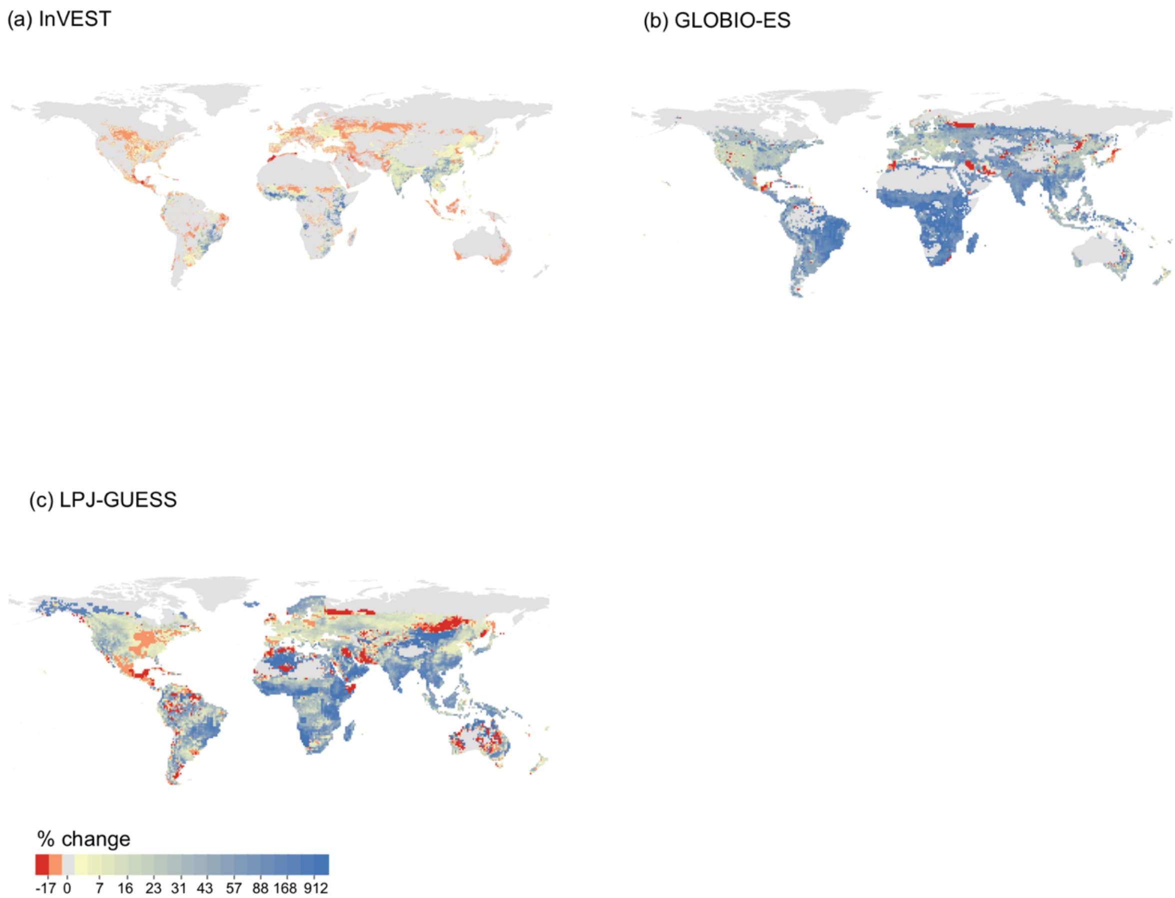

Fig. S8. Spatial agreement across models in modelled food and feed production for the fossil fueled development scenario for 2015-2050: **(a)** InVEST, **(b)** GLOBIO-ES and **(c)** LPJ-GUESS. The inter-model mean can be found in Figure S7. Color scale is based on quantile intervals when considering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

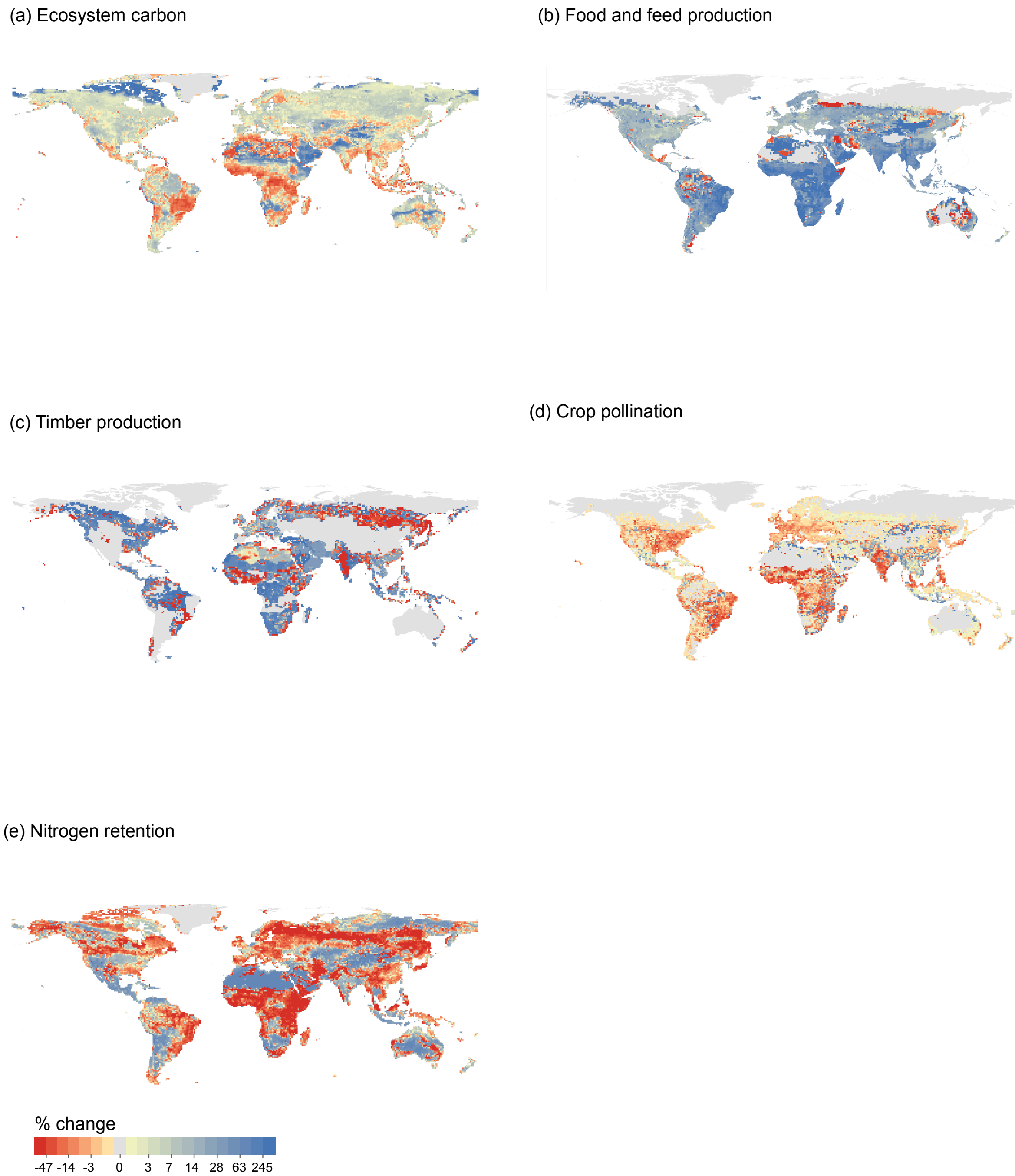

Fig. S9. Spatial distribution of ecosystem service changes. Inter-model mean projection of proportional changes (2015-2050) in the fossil fueled development scenario for: (a) Ecosystem carbon (N=4), (b) Food and feed production (N=3), (c) Timber production (N=2), (d) Crop pollination (N=2) and (e) Nitrogen retention (N=2). Colour scale is based on quantile intervals when considering all maps features.

Table S1. Characteristics of SSP and RCP scenarios (based on *(18)* and https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about**)**

	SSP1xRCP2.6 Global sustainability	SSP3xRCP6.0 Regional Rivalry	SSP5 Fossil-fueled Development
Land-use projections			
Population growth	Relatively low (8.5 billion in 2050)	Low to high (10 billion in 2050)	Relatively low (8.5 billion in 2050)
Economic growth	High to medium (284,565 GDP/PPP billion US$2005/yr in 2050)	Slow (177,284 GDP/PPP billion US$2005/yr in 2050)	High (360,926 GDP/PPP billion US$2005/yr in 2050)
Urbanization	High (92% in 2050)	Low (60% in 2050)	High (92% in 2050)
Equity and social cohesion	High	Low	High
International trade and globalization	Moderate	Strongly constrained	High
Policy focus	Sustainable development	Security	Development, free market, human capital
Institution effectiveness	Effective	Weak	Increasingly effective
Technology development	Rapid	Slow	Rapid
Land-use regulation	Strong	Limited	Medium
Agricultural productivity	High	Low	High
Consumption & diet	Low growth, low-meat	Resource-intensive	Material-intensive, meat-rich diet
Mitigation policies in land use	Full	Absent	Absent
Bioenergy	High	Low	Lowest
Climate projections			
Carbon intensity	Low	High	High
Energy intensity	Low	Intermediate	High
Radiative forcing	Peak at 3W/m^2 before 2100 and declines	Stabilizes to 6W/m^2 in 2100	Rising to 8.5 W/m^2 in 2100
Concentration (p.p.m)	Peak at 490 CO_2 equiv. before 2100 then declines	850 CO_2 equiv. (at stabilization after 2100)	>1,370 CO_2 equiv. in 2100
Methane emissions	Reduced	Stable	Rapid increase

Table S2. Model description, metrics, and scenarios

Model	Description	Taxonomic scope	Metrics	Scenarios
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. Species range shifts were projected under two commonly used dispersal assumptions: 'no' migration, which did not allow for species colonization and 'full' migration, which allowed for species colonization. Only the "no-migration" estimates were used.	Amphibians, birds, mammals, plants, reptiles	$S\alpha$ $S\gamma$ □□	Historical Land use Land use and climate
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. The model did not consider species colonization in this exercise.	Mammals	$S\alpha$ $S\gamma$ □□	Historical Land use Land use and climate
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. The model considered range loss within the currently known distribution, and not the species colonization in this exercise.	Amphibians, birds, mammals	$S\alpha$ $S\gamma$ □□	Land use and climate
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.	Birds	$S\alpha$ $S\gamma$	Historical Land use
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.	Amphibians, birds, mammals, plants, reptiles	$S\alpha$ $S\gamma$	Historical Land use
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).	Vascular plants	$S\gamma$	Historical Land use Land use and climate

Model	Description	Taxonomic scope	Metrics	Scenarios
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.	All	$S\alpha$ $I\alpha$	Historical Land use
GLOBIO	A modelling framework that quantifies the impacts of multiple anthropogenic pressures on biodiversity intactness, quantified as the mean species abundance (MSA) metric.	All	$I\alpha$	Historical Land use Land use and climate
LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator)	A big leaf model that simulates the coupled dynamics of biogeography, biogeochemistry and hydrology under varying climate, atmospheric CO_2 concentrations, and land-use land cover change practices to represent demography of grasses and trees in a scale from individuals to landscapes.	Not applicable	Bioenergy production Food and feed production Ecosystem carbon Nitrogen retention	Historical Land use Land use and climate
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.	Not applicable	Ecosystem carbon	Historical Land use Land use and climate
CABLE-POP (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, CO_2 concentrations and N-input.	Not applicable	Ecosystem carbon Timber production	Historical Land use Land use and climate
GLOBIO-E S	The model simulates the influence of various anthropogenic drivers on ecosystem functions and services.	Not applicable	Crop pest control Nitrogen retention	Land use and climate
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.	Not applicable	Coastal resilience Pollination Nitrogen retention	Historical Land use and climate

Table S3. Description of land use categories in LUH2 (based on (*39*, *42*, *80*))

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

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C. Supplementary Material of **Chapter 4.** Towards a better future for biodiversity and people: modelling Nature Futures

SUPPLEMENTARY MATERIALS

Towards a better future for biodiversity and people: modelling Nature Futures

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Appendix A. Participants' perspectives on the application of Nature Futures Framework in scenarios and models (Source: 2019 Vancouver Stakeholder Workshop(PBL, 2019a))

Question 1. *Based on your understanding of the Nature Future Framework, what new Nature Futures scenarios are needed (thinking especially of the ecosystem or area where you work, if applicable)?*

Question 2. *What are the most important dynamics, variables, processes, feedbacks or drivers that should be included in the next generation of scenarios, but are not well represented in existing scenarios?*

Responses

- Scenarios that explicitly consider indigenous and other ways of knowing
- How to overcome structural inequalities and power differentials to accommodate diversity and difference. Different ways of thinking about people, nature, and how they fit together (e.g. "Walking backwards into the future").
- Scenarios that allow for positive biodiversity options beyond 'protected areas', i.e., non-binary - e.g., better sustainable management
- Non-quantitative social and cultural ecosystem services (and societal and cultural values) - how do we model the things that we cannot quantify
- Scenarios that engage with business and industry interests and rights in ways that promote different ways of doing economy. Grounding work in practice and economy crucial for sustainability but usually not very well represented in scenarios
- Reconcile scale mismatches – especially across governance and biophysical regimes
- Shared Socio-economic Pathways (SSPs) and marine environment - how different ocean management can help us achieve different dimensions of ocean sustainability
- People interactions with oceans at regional and global scales besides fishing (e.g., pollution, recreational activities); Interaction of climate change and oceans dynamics beyond fishing (also marina pollution, deep sea fishing, recreation); Differences among regions, ways of living; Inclusion of idiosyncratic ways of living among regions
- How changes in people's behaviour could change ocean dynamics (further research) and how changes in people's experience of nature change nature (next few years).
- Scenarios that incorporate the impact of knowledge/ignorance of nature, including e.g. loss/revival of traditional knowledge; scenarios that incorporate impact of knowledge, biodiversity literacy as educational priority, feedbacks for health and nutrition, public engagement through citizen science, conservation volunteering > awareness/consciousness > mainstreaming as a political issue, culture of data/information sharing > improved science to inform nature-friendly policies. How culture of data sharing can improve production of science itself.
- Species-focused scenarios that include dynamics of ecosystems and human interactions, evolving conservation strategy, proxies to human wellbeing.
- Complex scenarios that address impact of invasive species on ecosystems and integrated to broader social-ecological scenarios.
- Scenarios that incorporate nature conservation goals and sectoral development (especially, agriculture).
- Interaction with human impact and desired transformation of human relations with nature. *(How human can transform relations with nature in order to significantly reduce negative impact)*
- "Nature for nature": Rewilding and novel Anthropocene ecosystems: need to incorporate what nature could be (not just humans doing things with/to nature or not).
- What kind of nature do we want? - learning from the past and bringing back wildness for the animals and for people in the context of the Anthropocene
- Pluralism context - Different phases in "Policy Cycle" require different types of models & scenarios but tool development heavily biased towards 'decisions'; let people who think differently about the world engage in the process, not simply focused on "decisions" (e.g., including co-management).
- Types of motivations (individual and institutional) to pursue specific types of behaviour, policies, etc. related to nature, ecosystems and biodiversity; Values underpinning decision-making processes; Link to value considerations in other IPBES processes
- Formation of the prevailing nature-related discourses due to the changes in business strategies, public opinion and the influence of opinion-makers. Influence of these discourses on indirect drivers of nature and NCP/ES change (culture, policy, diets, ...)

- Blue justice (and critical engagement with the sea as a humankind common heritage); range shifts of species, communities, fleets;
- Inclusion of fishing communities' ways of resilience, adaptation, nature conservation x industrial use of coastal and riverine zones in scenarios; different types of dependency on the natural resources; application of different governance strategies for BBNJ (and deep seabed); Incorporation of good fisheries management within EEZ (economic exclusive zones)
- Climate change; Gender, inequality
- Scenarios that explicitly address degrowth paradigm which can be defined as "'an equitable downscaling of production and consumption that increases human well-being and enhances ecological conditions at the local and global level, in the short and long term'' (Schneider et al. 2010:512).
- Scenarios that explicitly address depopulation and shrinking (compacting) cities and their impacts on NCP and human wellbeing (Aging and depopulation in rural areas; Feedback between land and ocean through nutrient and material flow incl. Pollution; Mental health and greenspace; cross cutting points: multiple-feedbacks (incl. combined feedback)).
- Scenarios explicitly addressing the linkages between peoples' relationship with nature and how they value nature - and nature outcomes such as how changes in land-use and migration reshape peoples' interactions with nature (e.g. urbanisation, intensification of land (water) use, migration to new landscapes)
- Scenarios exploring peoples' emotional relation to the 'products' of nature; the degree of materialism/consumerism across generations, socio-economic classes and value traditions and what dynamics this creates over space and time.
- Direct experiences with nature on human well-being and their feedback on value frameworks for nature; Investment in and access to education in general and environmental education in particular. Rise of populist parties, xenophobia, nationalism, lack of trust in science, human rights violations such as civic freedoms related to likelihood for pro-nature policies
- In my country the vision of "Vivir bien" has been emphasised, but this concept has not been made concrete in models or scenarios. The scenarios needed are those that measure the resilient capacity of cultures, integrate indigenous and local knowledge with scientific knowledge, address the effect of change of indigenous and local knowledge, and those that can be applied to policies affecting biodiversity and ecosystem functions in real and inclusive terms.
- These new scenarios should cover how inequality in land ownership shapes land use dynamics, including the opportunities generated for good use. They should illustrate how public policy generation and economic interests affect the resilience of local communities and society at large. They should cover transitions of realities without generalizing them and incorporate changes especially in socioeconomic terms.
- New scenarios should explicitly address revenue/earning models reshaping how chain parties interact with nature. They should address pollution by agrochemicals (pesticides, fertilizers) and show how this affects biodiversity. They should also address improvements/investments in (nature) education and technological development, as well as the role of nature education in people's experience of nature and how these change over time. We also need scenarios that address the extent to which all parties (government, chain-parties, financers, landlords etc.) facilitate, stimulate, value, and reward land-users to stimulate nature/biodiversity.
- The new scenarios should cover how pollution/agrochemicals impact biodiversity (i.e. life in soil, water natural pest control, and pollination) in terms of volume of pesticides and level of hazard. They should also indicate how changes in nature education impact people's experience of nature change, as well as how activities in the open space outside the city (infrastructure, inland waterways, energy projects, recreation, industrial) shapes biodiversity.
- It is tricky to answer the question of how to incorporate different regional and temporal scales, so this requires discussions. We need scenarios that incorporate cross-domain (land / sea) impacts and threats – including those that address some scale mismatches across those two spheres of work. We would also need new scenarios that explicitly address socio-ecological responses to cumulative impacts (different scales, over time, and multiple stressors) - e.g., sedimentation.
- We need scenarios that include land-sea interactions, such as demand for food production. For example, with a future decline in agricultural production, can the demand be covered by food production in oceans and coastal areas?
- New scenarios should measure how activities on land impact the sea life (i.e. sediment, plastic, and nutrients), and how ocean governance and international trade impact fishing patterns.
- We need scenarios that look at the interactive impact of climate change and biodiversity either of biophysical and atmospheric effect on societies, or the impact of climate mitigation and adaptation on

biodiversity – as an attempt to link two systems of models to better inform policy decisions. We also need scenarios that look at the impact of large scale collective actions (e.g. diet/consumption change), and national decisions (e.g. large scale restoration) on what is perceived to have the potential to bend the curve on biodiversity and climate change (e.g. scaling up positive seeds of Anthropocene) – scenarios and models that decision makers can understand and take to their world in governments, businesses, etc.

- New scenarios should cover the impact of collective human actions on biodiversity change, identify specific targets on indirect drivers that countries can act upon, and show the cost of implementing policy decisions or conservation interventions.
- We need scenarios incorporating as indirect drivers the key global economic trends and implications for nature at regional / local scales. This would cover trade, financing, foreign direct investments, equity considerations, and linkages between nature and cultural / language diversity.
- Examples of variables related to global economic trends are: Macroeconomic trends (GDP growth and structure), international Trade (Commodity prices / terms of trade / export value & volume), Financing (Total debt / % of GDP / % of exports), and Foreign Direct Investments (Total FDI / Structure).
- Nature as Culture would show a strengthening of cultural traditions, with people going back to traditional land management and agricultural practices. In Nature for Society/People, people move to multi-functional ways of managing the landscape, with a lot of emphasis on regulating services, but also other ecosystem services. In Nature for Nature, there will be rewilding, with forest and wildlife coming back. We need to imagine these nature futures for different landscapes and what they would mean at global level, national level and for different sectors, and link them to local biodiversity models as models used for different scales are not the same. At the global level Integrated Assessment Models, but at local level, we would need local ecosystem models and knowledge.
- There seems to be a tension between diverse values and how the scenarios are discussed, caused by wanting to quantify everything. We need to focus on scenarios that have nature as a being with which we interact, rather than nature as an object being used. Difficulty identifying places where humans have positive influence on nature, so need to uplift examples of that (People's contributions to nature rather than just nature's contributions to people). Focus on food in cities is great as it is often underrepresented, but we should also address overall consumption of materials.
- New scenarios would need to respect and illustrate diverse ways of relating to nature, rather than having a quantitative and report-based focus. Ecological Footprinting could be replaced with Eco shed. It would also need to cover co-nurturing and interdependence, and positive impacts from humans to nature, including areas of stewardship rather than "protection" or "preservation".
- We need new scenarios that address how people's specific daily actions can directly improve the outcome for biodiversity and nature, and overcome the current disconnect between people's daily actions and the environment. Scenarios should also address how Indigenous knowledge can be included in a meaningful way and highlight how leaving nature (habitat) intact can have co-benefits for climate change reduction.
- The new scenarios should measure how activities by urbanites can impact biodiversity and identify what are the main drivers/ motivation for taking action. They should also cover the feedback of how changes in environmental health affect human health, including psychological wellbeing, as well as how people value certain species or issues, and influence their outcome.
- The new scenarios need to address freshwater biodiversity, as it is not well addressed, particularly in global scenarios. They should also cover invasive species, trade and trade agreements, and the interactions between biodiversity, ecosystem function and service. This is needed in order to move beyond ecosystem structure and function, and to show the role of biodiversity itself in maintaining ecosystem function in the face of uncertainty (e.g., resilience - option and insurance value).
- I would like to know how these new nature future scenarios will align with the new generation of scenarios representing integrated pathways to the SDGs and beyond (in the TWI2050 and other contexts). I see these nature futures perspectives as kind of "archetypes" beyond Global and Regional Sustainability, beyond the SSP1 single narrative. We would need new scenarios that explicitly deal with how these three perspectives on nature affect human wellbeing. For instance: rural-urban interactions and inequality (half earth, urbanization, actors, jobs) under different perspectives of nature in considering different contexts.
- The new scenarios should cover how inequality in land ownership (concentration) shapes land use dynamics and its impacts (on health, pesticides, etc), local/global interaction and feedbacks (market certifications affecting different actors, local policies, trade, agreements, land tenure regimes, etc.) in global models and in multi-scale scenarios.

- How biodiversity is the base for ecosystem function and how it can be integrated over the long term & how it can be used to influence social policies; how to integrate BES in socio economic benefits in a way that we can use the function to influence social policies
- We need scenarios that further explore how biodiversity is the base for ecosystem functioning, and how these processes and feedback can be integrated over the Long-term.
- I consider important also to continue exploring how Biodiversity and Ecosystem Services have an underpinning role in socioeconomic development and human well-being, to Influence short and long-term policies aiming to the protection of nature.
- 1) Transformative change (not only within the system, but also to alternative systems); 2) other big societal transitions (etc. populism / nationalism / politics; and digital transformations (AI, machine learning etc) influencing energy demands, employment etc.; 3) Cross cutting issues: gender, intersectionality.
- Relationship of humans with technology
- Cross-scale dynamics
- Hybrid natures, technology that nature has, what does this look like in the future; complex dynamics, global narratives, post 2020 agenda.
- We need scenarios that explicitly address how urbanism is reshaping how people interact with nature and shape regional and global dynamics.
- We need conservative (cultural-historic identity, heritage, value - native biodiversity) AND progressive (dynamism, emergence, reorganization) nature futures scenarios.
- Integrated, spatial heterogeneous, cross-scale scenarios
- 1. Spread of invasive species - people's perceptions of "wild" versus biodiversity. 2. Assessing biocultural diversity (land as culture, culture as land). 3. Inequality and land ownership - look at failures of conservation and what can we learn from them (look beyond poverty as causes)
- Relationship B and rewilding is important to understand; tolerance from behavioural point of view is great, attractive in large parks; commonality theories of nature than recognized, land is culture, culture is land; inequality and land ownership: need to look at failures of nature conservations (poverty), big losses have to do with conservation failure to deliver on promises to people, moving people out of parks etc. (3 challenges)
- Rewilding in contrast with urbanisation
- Rural areas with high cultural and natural heritages
- Social, technical, economic innovations
- Business strategies
- Social inclusiveness
- Methodological challenges arising from discussions with modellers
- From SSPs, businesses as partners (not just ‘enemies’ of nature), role that oceans play, how indigenous knowledge is critical

Appendix B. Indicators discussed on the Nature Futures Framework

Source: 2019 Vancouver Stakeholder Workshop(PBL, 2019a)

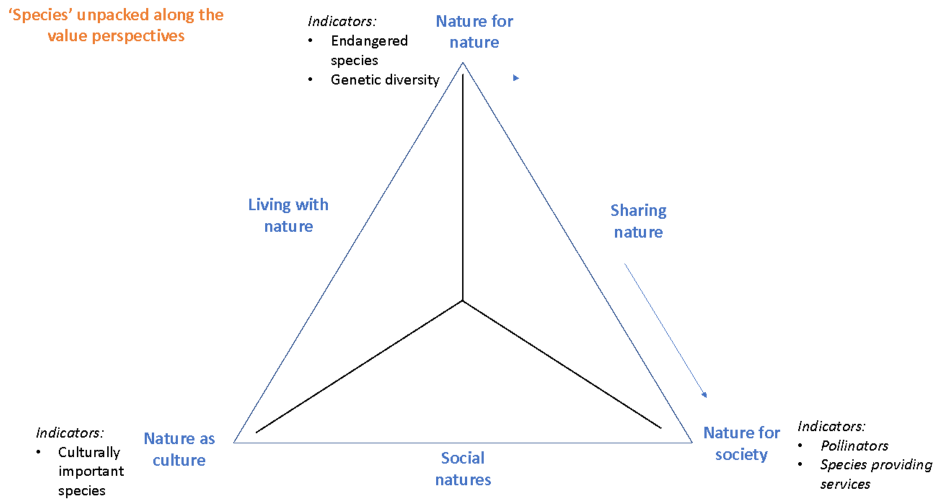
		Nature for Nature	Nature for Society	Nature as Culture
OCEAN				
Management	Total sustainable catch		↗ (1)	
	% fish from aquaculture			
	Level of management decision	Global		Local
	Area with no-take marine protected area	↗ (2) 30%		
	Area under community-based management			↗ (3)
State	% fish stocks depleted	↘(All stocks)	↘(Commercial stocks)	↘(Culturally important stocks)
	% species endangered	↘ (1)		
	Status of culturally important species	↗		↗ (2)
	Area of wetland & mangroves	↗ (3)	↗	
Benefit	Carbon sequestration		↗ (2)	
	Dietary needs met			
	Number of jobs		↗ (3)	
	Recreation in nature			
	Livelihoods			↗ (1)
	Social cohesion			↗
LAND				
Management	Level of management decision	Global		Local
	Area under community-based management			↗ (1)
	Area under rewilding	↗ (2)		
	Wilderness protected area	↗ (3)		
	Invasive species	↘(4)		
State	% endangered species	↘ (1)	↘	↘
	Status of culturally important species			↗ (2)
Impact	Clean water		↗ (1)	
	Carbon sequestration		↗	
	Soil protection		↗	
	Pollination		↗	
	Timber provision		↗	
	Local crops and breeds			↗ (3)
	Sustainable bushmeat			↗ (4)
	Dietary needs met	↗	↗	↗
	Number of jobs (ecotourism, agriculture, recreation)		↗ (2)	
	Recreation in nature		↗ (3)	
URBAN				
Drivers	Density of city	High (1)		Low
	% of people in cities	High (2)	Medium – High	Low

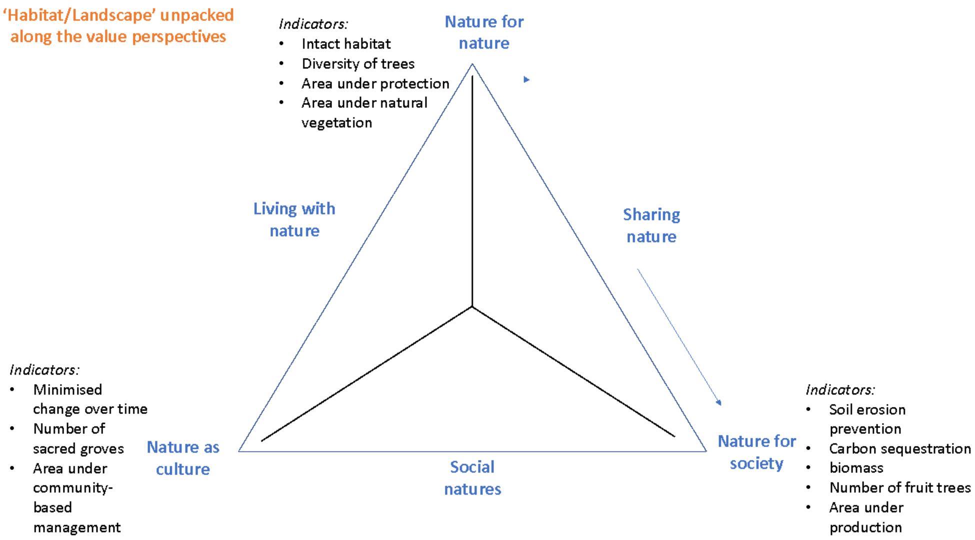
	Distribution of city SAD?	Medium	Medium	Small
	Remote responsibility	↗↗↗		
	Green spaces that are self-sustained	↗		
Pressure	Air quality regulation	↗	↗ (1)	
	Water quality regulation (waste water management)	↗	↗ (2)	
	Community gardening			↗ (2)
	Urban gardening		↗	
	Green roofs / nature-based solution		↗	
	Level of management decision	Global		Local
State	Species richness (no-take species)	↗		
	Status of culturally important species			↗
	Area of green spaces	↗ Natural green spaces	↗ Functioning green spaces (3)	↗ Cultural green spaces
Impact	Number hours commute	↘	↘	↘↘↘
	Mode of commute	Mass transportation, biking		
	Equity	↗	↗	↗
	Mode of entry supply	Central	Renewable	Local
	Accessibility to green areas	Good for large	Depends on function	Small green and close (1)
	Hours of nature education	↗ Biodiversity	↗ ES	↗ Bioculture

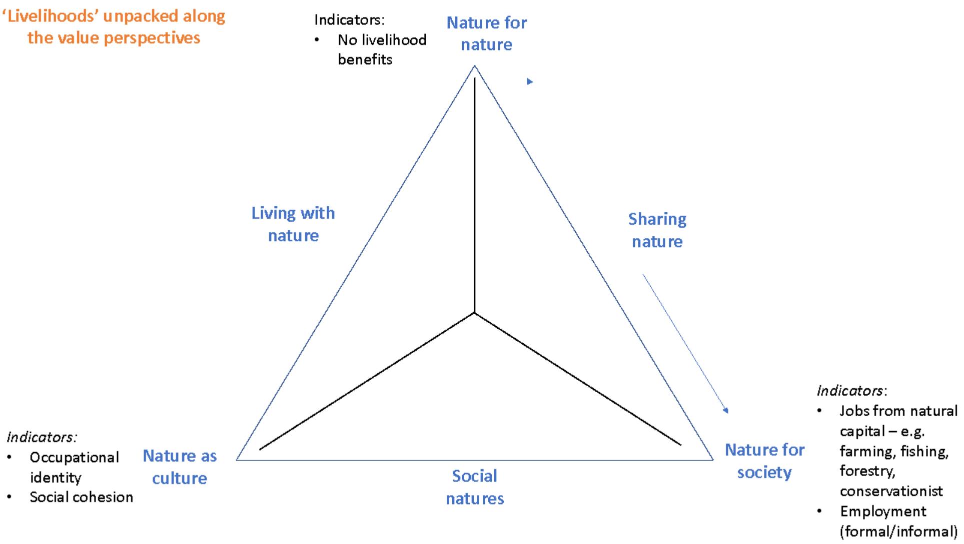
Source: 2019 The Hague Modellers Workshop(PBL, 2019b)

	Management	**State**	**Benefit**
Nature for Nature	*Indicator: Protected areas* Marine: WDPA - No take Terrestrial: WDPA 1-3	*Endangered sp. and habitat* M: Endangered species, Coral reef cover T: endangered sp., pristine forest, wetland extent apex predators; megaherbivores; "trophic rewilding"	M: diving sites T: wildlife watching
Nature for Society	*Sustainable use areas* M: Mgmt effectiveness (country level) T: WDPA 4-6	M: % depleted stocks T: CO2 sequestration, water purification, soil retention nature-based solution	M: Sustainable fish catch T: Ag production w/o erosion or water pollution, storm protection
Nature as Culture	*Comm-based mgmt* M: Comm. Based mgmt (country reports) T: WDPA Comm. Based Mgmt. Do changes relate to the perceptions/values of the governing legal/government systems rather than of the people living in a particular location? sacred forests? indigenous land	*Cultural keystones* M: status of culturally important species T: status of culturally important species, cultural landscapes social indicators; cultural support; such as cultural festivals cultural landscape certified food production - appellation UNESCO world heritage sites, *maybe MABs and indigenous reserves, certain certifications*	*# Jobs (livelihoods?)* M: number of jobs T: local livelihoods books; cultural roles; shaman; cultural activities co-management; local control over nature; social-ecological feedbacks

Appendix C. Assessing single policy using the Nature Futures Framework with indicators that measure three value perspectives (Source: 2019 Vancouver Stakeholder Workshop(PBL, 2019a))

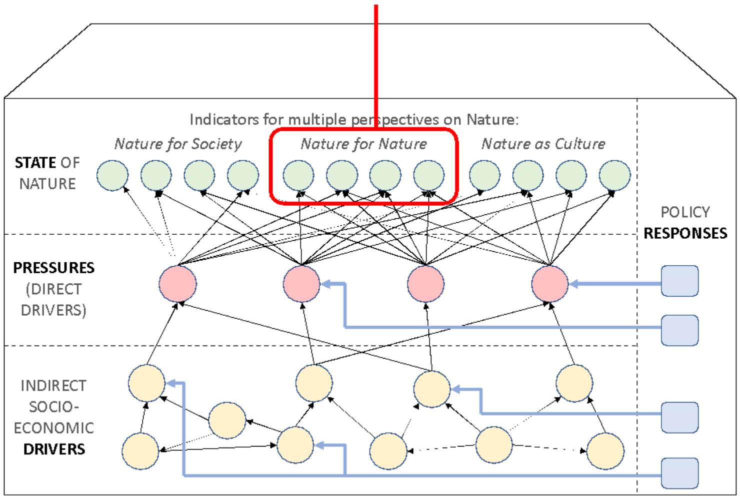




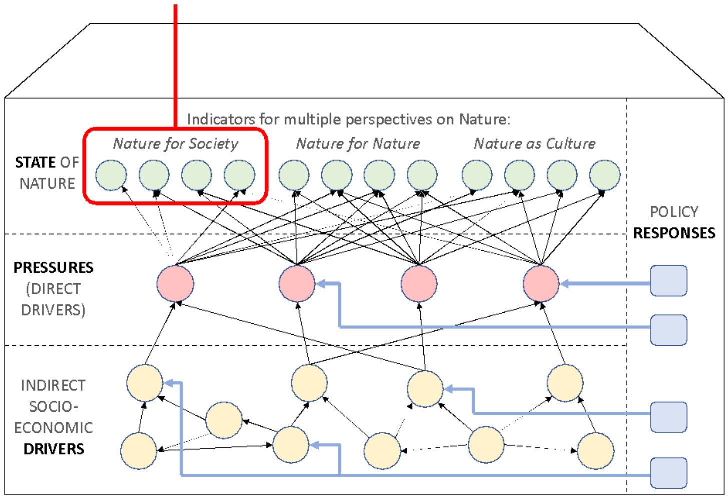


Appendix D. Assessing systems dynamics using the Nature Futures Framework and Driver-Pressure-State-Impact-Response (Source: 2019 Vancouver Stakeholder Workshop(PBL, 2019a))

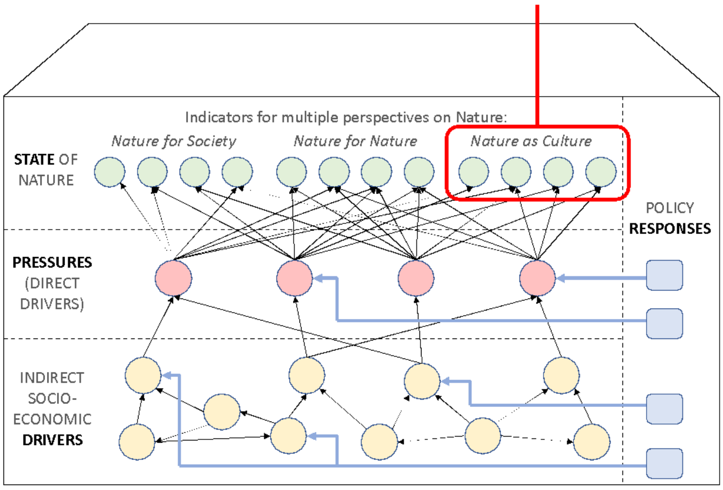
- Individual species of particular conservation concern (e.g. Red List species) ☺☺☺
- Conservation of overall species diversity ☺☺



- Particular service-providing species, or groups of species (e.g. pollinators) ☺
- Overall species diversity -> maintenance of ecosystem function/services



- Particular species of cultural significance
- Overall species diversity – cultural value?



Appendix E. Nature Futures modellable questions assessed on novelty, feasibility, scale, policy impact (Source: 2019 The Hague Modellers Workshop(PBL, 2019b))

Nature for Nature

1. Under what social-economic context/governance/climate change mitigation would protected area and other area-based conservation measures improve biodiversity and impacts/trade-offs to society in the future?

- Under what conditions (consistent with SSPs, including transboundary cooperation) would ambitious area-based conservation targets be possible?
- How protecting 50% of biomes affects biodiversity and ecosystem services?
- What has been the impact of protected areas on larger landscape biodiversity and people?
- What are the non-terrestrial tools for future conservation?

Scale: Limit to global scale
Model: Available to address this question (model intercomparison using a suite of models looking at multiple dimensions of biodiversity)
Policy impact: CBD discussion of targets and goals

2. How would the restoration of abandoned agricultural landscape increase biodiversity and their implications for sustainable food and timber production elsewhere?

- How ecological corridors around human-managed systems improve biodiversity?

Scale: Global scale and larger regional case studies
Model: In principle, existing models are possible to address this question (vegetation cover/structure linking with species composition and biome shift)
Policy impact: Yes, particularly on restoration vs afforestation and nature-based solutions; also boundary of nature for nature.

3. Would climate change over-ride the positive effects of protected area/other land/ocean policies for biodiversity conservation?
Scale: Local to global
Model: Yes, models are ready to address this question
Policy impact: Relevant to design management of protected areas and informing the level of National-Determined Contributions needed.

4. Restoration of ecosystems and effects on biodiversity

- What kind of long term forest and environment transition (restoration of forest) can reduce biodiversity loss and hasten nature's recovery?
- What are the optimal restoration mechanisms in different ecosystems? What are the cost implications in implementing them?
- How would reintroduction of species from zoos affect biodiversity?

Scale: Local to global
Model: Models are available to address the first sub-question, maybe for the second, and probably not for the third sub-question
Policy impact: Relevant to restoration-related policies.

5. Can minimizing invasive species, overexploitation and pollution prevent all species in the world from becoming endangered and maintain ecosystem integrity under projected climate change and population growth?
Scale: Global
Model: Yes, models are available
Policy impact: Yes, for global conservation policies

6. How/whether interventions related to global trade can minimize extinction risks and maintain/restore biodiversity?
Scale: Global
Model: Yes, methods/models are available
Policy impact: A range of effective conservation/trade related policies for biodiversity conservation

7. Do environmental/ecological education improve nature protection?
Scale: Local
Model: Possible qualitative social-ecological model
Policy impact: Relevant to local environmental policy

Nature for Society

1. Original: Does this perspective result in perverse biodiversity outcome?
Revised: Does managing the world for ES result in changes (increases or declines) in biodiversity, and how does that vary by types of biodiversity?
Rating: Very important, moderately difficult, dependent on ES

2. How do/can ecosystem services contribute to the regional economy?
Rating: Very important, relatively easy (if ecosystem services is known)

3. Original: Can you simulate in IAMs which landscape manages biodiversity better?
Revised: Can you incorporate a wide variety of management approaches to enhance ecosystem services (and their ecological implications) into IAMs?
Rating: Very important, difficult

4. Original: What ecosystem services can be minimized/reduced for conservation – identify over consumption areas and ecosystem service types
Revised: Trade-offs between ES and biodiversity. How can you find a combination of provisioning services while having enough regulating services?

5. Original: Can we sustainably harvest fish without any species becoming endangered and maintaining ecosystem integrity?
Revised: Can we sustainably harvest fish without any economically important species becoming endangered and maintaining ecosystem integrity such that ES are not compromised?
Rating: Important, moderately difficult

6. Original: How would improving biodiversity in the agricultural landscape impact the level, resilience, and distribution of ecosystem services?
Revised: How would improving biodiversity (crops, livestock, wild) in agricultural landscapes impact the level, resilience, and distribution of ecosystem services?
Rating: Important, difficult, some aspects (e.g., resilience), geographies, and relationships (wild biodiversity and ag.) very difficult

7. Original: What kind of ecological and economic development pathways can yield human nature outcomes congruent with all nature-based outcomes?
Revised: How do we define win-win scenarios, including more diverse social- ecological interconnections? And then, how do we identify the pathways to those solutions?
Rating: Deep interconnections: Essential, very difficult; Shallow interconnections: Important, relatively easy

8. Original: Can the ecological pressure be kept low enough in intensive systems to prevent severe feedback?
Revised: What level of ecological simplification is sustainable, and avoids undesirable human impacts?
Rating: Important, very difficult

9. Aquaculture vs wild catch
Rating: Important, not difficult

10. Original: How does/will a transition to responsible consumption affect the economy regionally?
Revised: How do changes in human behaviour (e.g., consumption) affect the regional economy, ecosystems, and land use, and thus ES?
Rating: moderately important, moderately difficult

11. Same as #10 but focusing on health and other socio-economic aspects (How does/will a transition to responsible consumption affect the economy regionally?).
Rating: Less important (for IPBES), difficult

12. Original: How would transformation to largely plant based consumption affect biodiversity and other ecosystem services?
Rating: Not essential, relatively easy

13. How do we incorporate urban areas and infrastructure into models of biodiversity and ecosystem services?

Nature as Culture

- How would diverse and locally sourced diets affect biodiversity and ecosystem services?
  - Key indicator: indicators biological/cultural/linguistic/agricultural/diet diversity
  - Diversity in agriculture (crops, livestock). Expand LU to build in diversity in crop type in IAMs as well as effects of crop type on biodiversity. PREDICTS is doing with crop management.
  - Measures of genetic diversity of crops (FAO has some info).
  - Localising diets/food miles/supply chain.
  - Maintenance of cultural/social component of diet
- How will cultural landscapes (including sacred sites) be affected by climate change and other drivers? Traditional agricultural landscapes such as landscaped terraces in Papua New Guinea, Satoyama/Japan, ancient Mediterranean cultural landscapes. Drivers: sea level rise, erosion, abandonment, rewilding
- How do traditional fisheries, maritime cultures, land-based traditional management and livelihoods affect biodiversity and ecosystem integrity? How do we model ‘partial’ protected areas/traditional land/sea management? How do global change impacts alter traditional fisheries without any species becoming extirpated and maintaining ecosystem integrity?
- How can we model cultural change and how do cultural feedbacks shape and are shaped by ecosystems?
- Is land sharing better for biodiversity and human well-being than land sparing - broader version of ‘traditional management?
- How do cultural landscapes affect different aspects of biodiversity and the ecosystem services they provide? Do we need to conserve or restore cultural landscapes?
- Can the idea of low intensity landscapes be combined with sufficient production for 9.5 billion people? [management intensity]
- Can biocultural thinking identify new global strategies or is it all context dependent?
  - Scaling up mosaic landscape on a global scale. Conceptually mosaic of multiple LU types at different scales e.g. could be communities each focussed on particular agricultural practice/strain/species.
  - Linking cultural diversity and biological/genetic diversity.
  - How different cultures react with agriculture/food?
  - More small scale/less intensive agriculture.e.g. French millet
  - Would farm-based selection of crops be an improvement vs single crop?
  - Is it important to maintain a biocultural relationship to improve/maintain biodiversity?
  - Long term resilience through potential reduction in crop yields -- probably larger footprint, less productive, but more resilience.
- What kind of societal change can contribute to sustain cultural (traditional) agricultural landscapes (e.g., ‘Satoyama’)? [Changes in dominant industrial/economic paradigm]
- How does close connection between nature and society affect human well-being? What are the well-being metrics, e.g. mental health benefits of interaction with nature vs sense of place, identity (NS hard to dissociate with NC)?
- How do changes in diversity/ecosystem health feedback on culture - feedback of nature to people, e.g. pastoral plain/organised/managed culture, like or dislike of open landscapes.
- How useful is rewilding in urban landscapes for biodiversity?

Scenario	**Feasible (1 hard, 10 easy)**	**Novelty** (1 low, 10 high)	**Interest/ Importance**
Diet: ● Diversity: maintaining genetic diversity of crops/resilience ● Locally sourced: diets/food miles/supply chain ● Traditional culture: would maintaining a traditional diet impact biodiversity	Diversity: 4 (FAO cropland genetic diversity) Local source: 6 (transport across natural boundaries., can do local region, not direct relationship between local supply and GHG footprint) Traditional culture: 1 (possibly at very local scale)	10	10
Livelihood: ● Cultural identity maintained (species still exist) ● Influence of change/drivers	Identity: 10 Drivers: 10	5	8

Cultural landscapes and biodiversity ● Provision of BES ● Resilience to drivers/climate change	Local/regional: 10 (has been done) Global: 2 (how to scale up)	Local/regional: 5 Global: 10	10
Management intensity ● Food production efficiency ● BES contributions ● Land sharing vs land sparing ● Different types of PAs ● Different spatial and temporal management regimes	10 e.g. PREDICTS differentiate GLOBIO but many lump LU	Configuration and link to cultural landscape Local: 10 Global 10	10
Leverage points for restoring and/or maintaining cultural landscapes ● Agricultural subsidies for diverse agro-cultural landscapes ● PAs that include biocultural (Medellin)	Local/regional: 9 Ocean models, econometric models (have subsidies)	5	7
Ecosystem benefits to people ● Mental health (MH) ● Sense of place/identity (SoP)	MH: nature access/distance 10 (lots of data but not in scenarios) SoP: 2	MH: 8 SoP: 10	MH: 8 SoP: 10
Impacts of greening of urban spaces ● Accounting for green space on BES .	Local: 10 Global: 8	Local: 2 Global: 10	8

Cross-cutting

Ranking of questions

		Novelty	Feasibility	Global	Local
1	How would compact cities compare with low density cities on biodiversity and ecosystem services locally and globally?	XX	XXXX	X	XX
2	How does biodiversity and ecosystem services differ in cultural landscape and sustainably intensified landscape?	XX	XXXX	X	XXX
3	What are the conditions when economic development is compatible with nature conservation (what are the tools other than protected areas and CBNRM?)?		XX	XX	
4	How does having more no-take and sustainable-take areas compare with having sustainable harvest everywhere for livelihoods and biodiversity?	X	XX	XX	X
5	How can we model pathways for nature as support for economies and people (and identify new ways key path)?	XX	X		
6	How can we model the role of global capital finance in shaping local places?	XX			XX
7	What is the role of ownership of land and land tenure/ownership in nature futures?	X			XX
8	Are any of these perspectives incompatible with “desired” growth projections (population, GDP, etc.)?	XXX	XX	XXXX	
9	How do different perspectives of terrestrial and marine systems impact/feedback on each other?	XXXX	XX	XX	X
10	What can we learn for “successes” from each perspective? What enhances? What erodes? Trade-offs, synergies.	XXXX	X		X
11	What are the missing drivers of positive ecosystem change for the future (NFF Futures)?	XXXX	X	X	X
12	What are political economies that support each or erode nature future perspective?	XXXX	X	XXX	
13	Are the pathways similar for GDP and Human Development Indices (HDI) within the 3 nature future perspectives?	XXX		XX	
14	Is it possible to fulfil the needs for 9.5 billion people on half the land?		XXXX	XXX	

Clustering of questions (possible categories):

Aerial based measures	
1	How would compact cities compare with low density cities on biodiversity locally and globally and ecosystem services?
4	How does having more no-take and sustainable-take areas compare with having sustainable harvest everywhere for livelihoods and biodiversity?
14	Is it possible to fulfil the needs for 9.5 billion people on half the land?
Process based solutions	
2	How does biodiversity and ecosystem services differ in cultural landscape and sustainable intensified landscape?
Indirect drivers	
8	Are any of these perspectives incompatible with "desired" growth projections (population, GDP, etc.)?
11	What are the missing drivers of positive ecosystem change for the future (NFF Futures)?
Social-ecological feedbacks	
5	How can we model pathways nature as support for economies and people (and identify new ways key path)?
10	What can we learn for "successes" from each perspective? What enhances? What erodes? Trade-offs, synergies.
12	What are political economies that support or erode each nature future perspective?
Biodiversity and ecosystem services linkages	
1	How would compact cities compare with low density cities on biodiversity locally and globally and ecosystem services?
2	How does biodiversity and ecosystem services differ in cultural landscape and sustainable intensified landscape?
5	How can we model pathways nature as support for economies and people (and identify new ways key path)?
Management	
2	How does biodiversity and ecosystem services differ in cultural landscape and sustainable intensified landscape?
4	How does having more no-take and sustainable-take areas compare with having sustainable harvest everywhere for livelihoods and biodiversity?
6	How can we model the role of global capital finance in shaping local places?
12	What are political economies that support each or erode nature future perspective?
State	
2	How does biodiversity and ecosystem services differ in cultural landscape and sustainable intensified landscape?
4	How does having more no-take and sustainable-take areas compare with having sustainable harvest everywhere for livelihoods and biodiversity?
9	How do different perspectives of terrestrial and marine systems impact/feed-back on each other?
Benefits	
2	How does biodiversity and ecosystem services differ in cultural landscape and sustainable intensified landscape?
4	How does having more no-take and sustainable-take areas compare with having sustainable harvest everywhere for livelihoods and biodiversity?
12	What are political economies that support or erode each nature future perspective?

Appendix F. Glossary

Co-benefits: It refer to 'the positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare' (IPCC, 2015; Mayrhofer and Gupta, 2016).

Drivers: the external factors that cause change in nature, anthropogenic assets, nature's contributions to people and a good quality of life. They include institutions and governance systems and other indirect drivers, and direct drivers (both natural and anthropogenic) (IPBES, 2016).

Feedback: The modification or control of a process or system by its results or effects (IPBES online glossary accessed 4 January 2021). A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced (IPCC, 2015)

Frontiers: Nature Futures frontiers are where different combinations of interventions achieve substantive co-benefits to reach optimal and efficient states on all three nature value perspectives (Polasky et al., 2008).

Indicators: A quantitative or qualitative factor or variable that provides a simple, measurable and quantifiable characteristic or attribute responding in a known and communicable way to a changing environmental condition, to a changing ecological process or function, or to a changing element of biodiversity (IPBES online glossary accessed 13 May 2021).

Interventions: A change in policies or management practices that are aimed to protect, enhance or restore biodiversity, ecosystem services and their contributions to people.

Modelling: Development and use of models to translate scenarios into expected consequences for biodiversity and ecosystem services (IPBES methodological guide on scenarios and models 2017)

Models: Qualitative or quantitative representations of key components of a system and of relationships between the components (IPBES online glossary accessed 28 July 2020)

Narratives (or scenario narratives): Qualitative descriptions which provide the framework from which quantitative exploratory scenarios can be formulated (IPBES glossary10).

Nature Futures: Future states of nature that "represent a wide range of human–nature interactions, based on the perspectives of different stakeholders, and include a variety of different types of human-modified ecosystems encompassing different degrees of human intervention" (Rosa et al., 2017).

Nature Futures Framework (NFF) (Lundquist et al., In preparation)**:** A heuristic that captures diverse, positive values for human-nature relationships in a triangular space.

Nature Futures value perspectives (Pereira et al., 2020): Three types of value perspectives on nature in Nature Futures Framework – intrinsic (also known as Nature for Nature), instrumental (Nature for Society), and relational (Nature as Culture) values. These nature values are not mutually exclusive and intricately intertwined by nature.

Pathways: Different strategies for moving from the current situation towards a desired future vision or set of specified targets. They are purposive courses of actions that build on each other, from short-term to long-term actions into broader transformation (Ferguson et al., 2013; Wise et al., 2014). The Three Horizons approach is often used to define such pathways in future visioning processes (Sharpe et al., 2016).

Policy space: Nature Futures policy space utilizes interventions and indicators to score and map the system across value perspectives for a point in time or progress over two time points.

Regime shift: Substantial reorganization in system structure, functions and feedback that often occurs abruptly and persists over time (IPBES online glossary accessed 4 January 2021).

Retrospective evaluation (also known as 'ex-post assessments'): is carried out to review the outcome of implemented policies and management, and can also be done through comparative scenarios or counterfactual analyses (IPBES 2016). Although valuable in enhancing transparent reporting and performance evaluation, retrospective analyses have been limited due to the challenges including environment-governance complexity, inadequate monitoring or the absence of enforcement systems (Haug et al., 2010). However, to improve the evidence base for policy decisions, retrospective evaluation is critical in informing the design and implementation of policies (Andam et al., 2008; Geldmann et al., 2019; Smismans, 2015).

Scenarios: Representations of possible futures for one or more components of a system, particularly for drivers of change in nature and nature's benefits, including alternative policy or management options (IPBES online glossary accessed 28 July 2020)

Social-ecological systems: An ecosystem, the management of this ecosystem by actors and organizations, and the rules, social norms, and conventions underlying this management (IPBES online glossary accessed 4 January 2021).

State-space: The Nature Futures state-space is where all three nature value perspectives are enhanced simultaneously from the present-day conditions.

Synergies: Synergies arise when the enhancement of one desirable outcome leads to enhancement of another. Also see definition for "Trade-offs" (IPBES online glossary accessed 4 January 2021).

Tipping points: A set of conditions of an ecological or social system where further perturbation will cause rapid change and prevent the system from returning to its former state (IPBES online glossary accessed 4 January 2021).

Trade-offs: A trade-off is a situation where an improvement in the status of one aspect of the environment or of human well-being is necessarily associated with a decline in or loss of a different aspect. Trade-offs characterize most complex systems, and are important to consider when making decisions that aim to improve environmental and/or socio-economic outcomes. Trade-offs are distinct from synergies (the latter are also referred to as "win-win" scenarios): synergies arise when the enhancement of one desirable outcome leads to enhancement of another (IPBES online glossary accessed 4 January 2021).

Value: A principle or core belief underpinning rules and moral judgments. Values as principles vary from one culture to another and also between individuals and groups (IPBES/4/INF/13). Value (as preference): A value can be the preference someone has for something or for a particular state of the world. Preference involves the act of making comparisons, either explicitly or implicitly. Preference refers to the importance attributed to one entity relative to another one (IPBES/4/INF/13, IPBES online glossary accessed 28 July 2020).

Visioning: "the process of creating a vision, i.e., a representation of a desirable future state, as opposed to scenario building (possible future states), forecasting (likely future states), and backcasting (pathways to desirable future states)" (Wiek and Iwaniec, 2014).

Visions: "Visions" are built on the different seed initiatives from which inspirational stories of sustainable, equitable futures can inspire us to move toward the values and ideals of a "good Anthropocene" (Bennett et al., 2016; Preiser et al., 2017). "Seeds" are innovative initiatives, practices and ideas that are present in the world today, but are not currently widespread or dominant (Bennett et al., 2016; Lundquist et al., 2017).

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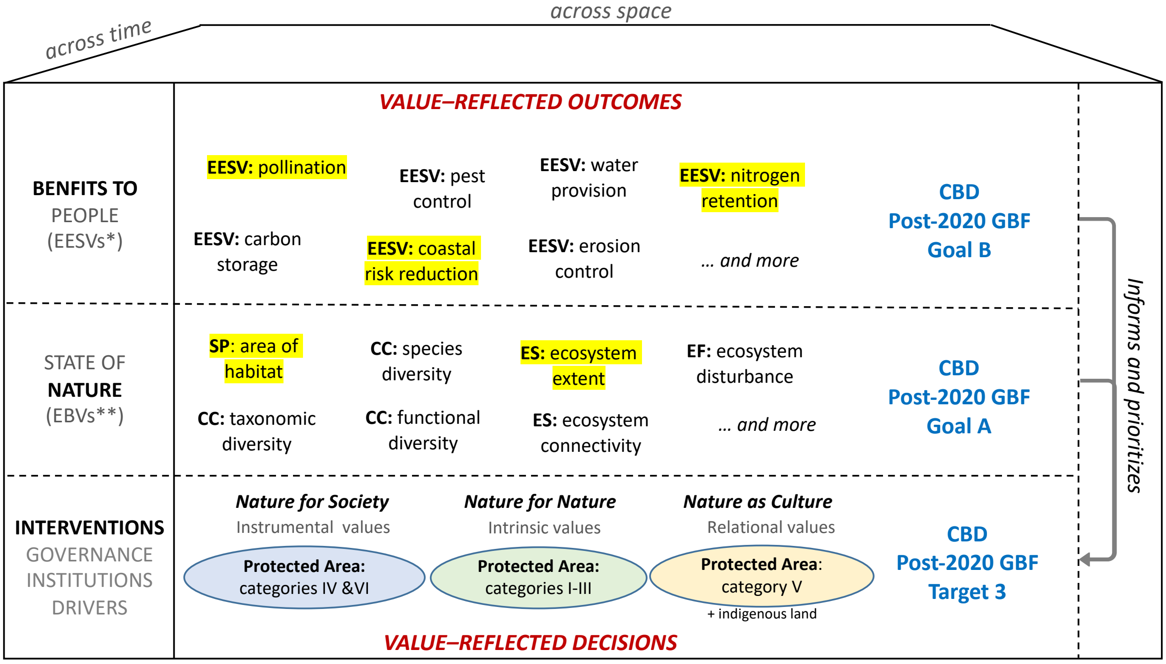
D. Supplementary Material of **Chapter 5.** Performance of terrestrial protected areas under the Nature Futures prism

Supplementary Material

Figure S1. Analytical framework of the study integrating Nature Futures Framework, CBD Post-2020 Global Biodiversity Framework and Essential Variables approaches



*Essential Ecosystem Services Variables
*Essential Biodiversity Variables - SP: Species population, CC: Community composition, ES: Ecosystem structure, EF: Ecosystem functions

Figure S2. National distribution of land across the Nature Futures protection regime

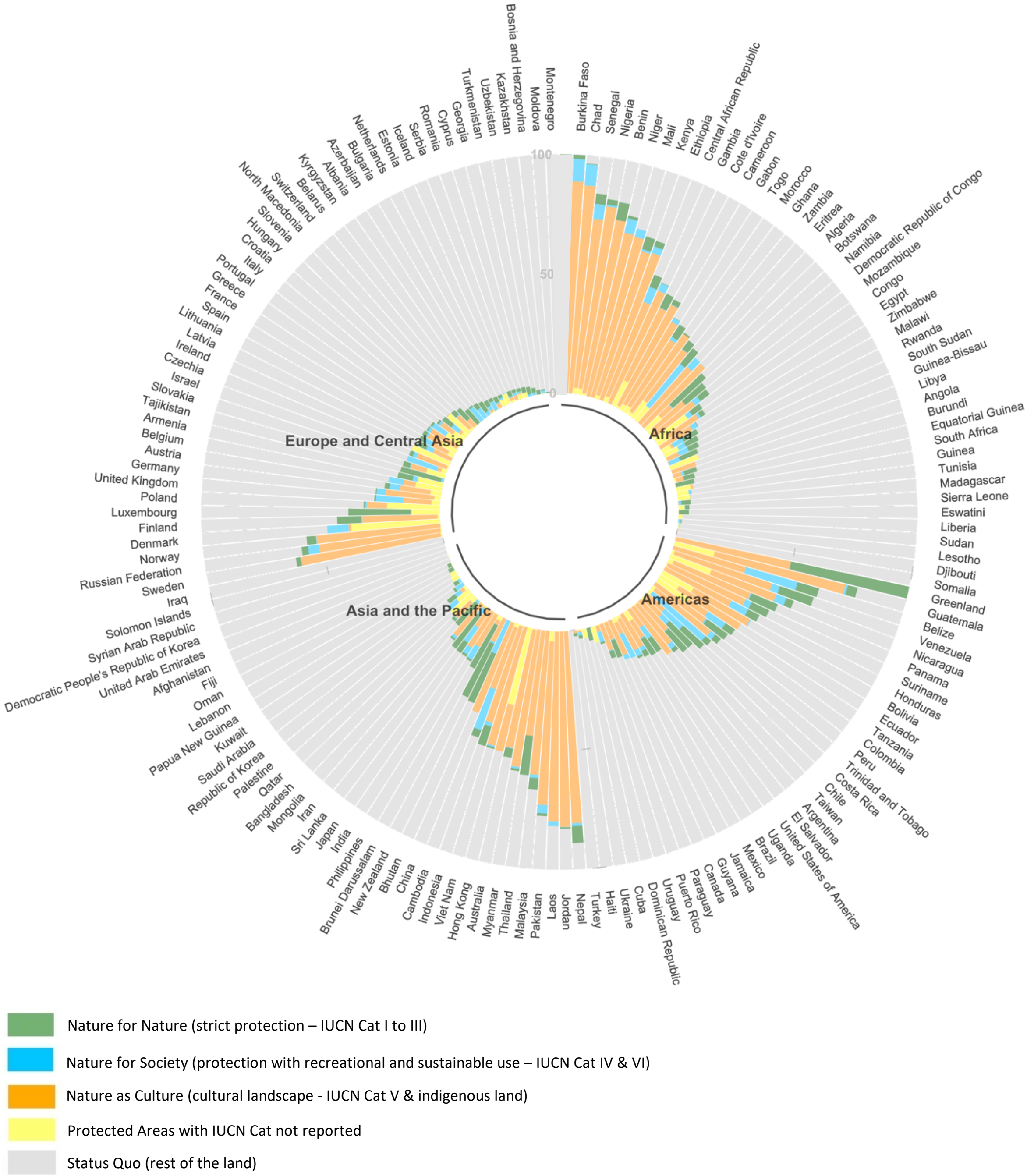
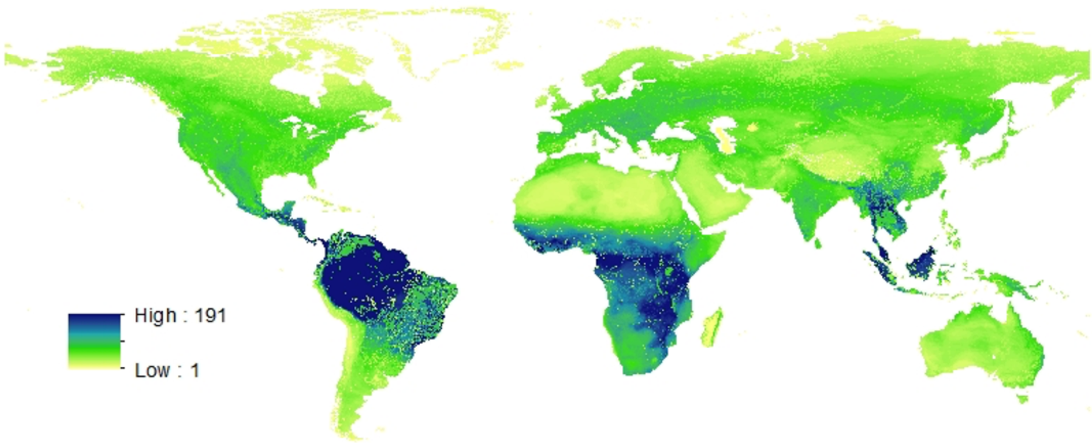
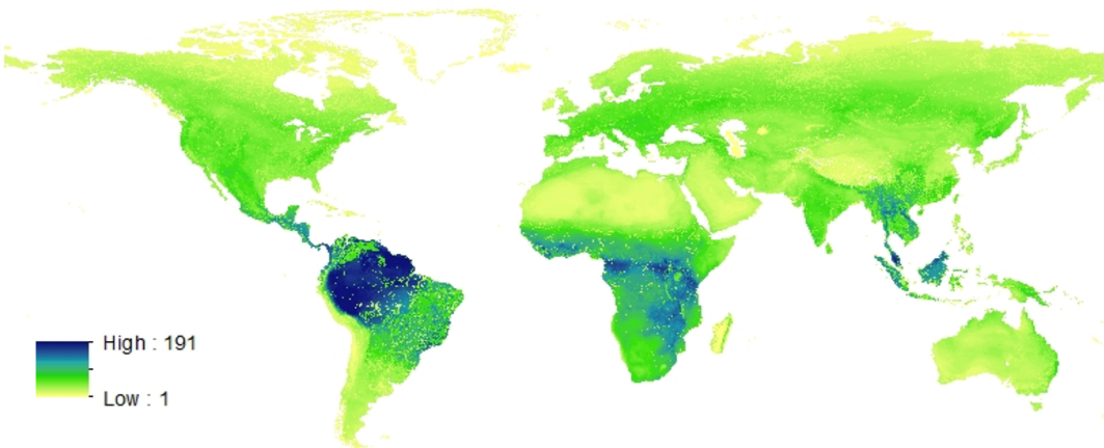


Figure S3. Maps on biodiversity

Area of habitat based species richness for mammals 2000 (number of species)



Area of habitat based species richness for mammals 2018 (number of species)



Changes in the area of habitat based species richness for mammals 2018-2000 (number of species)

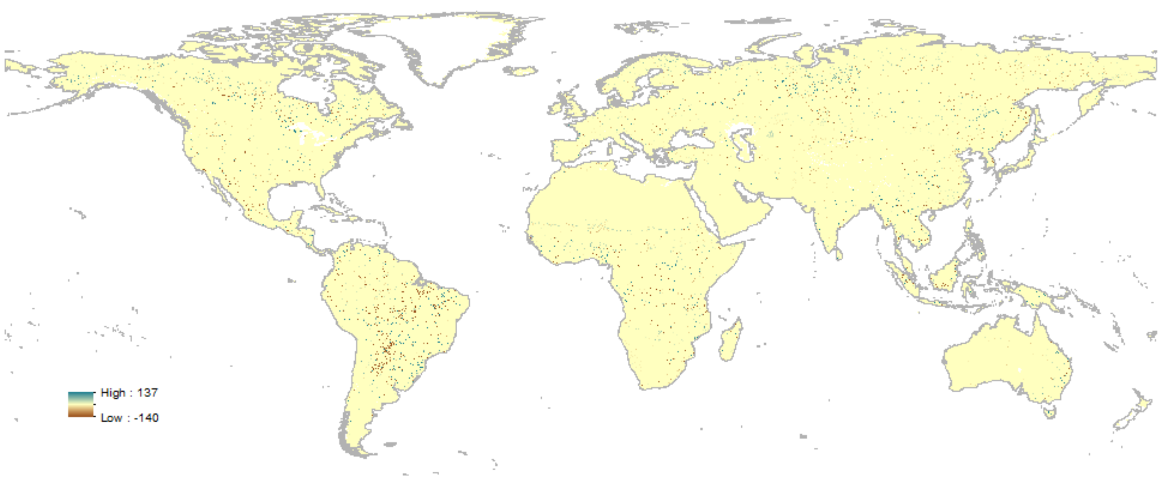
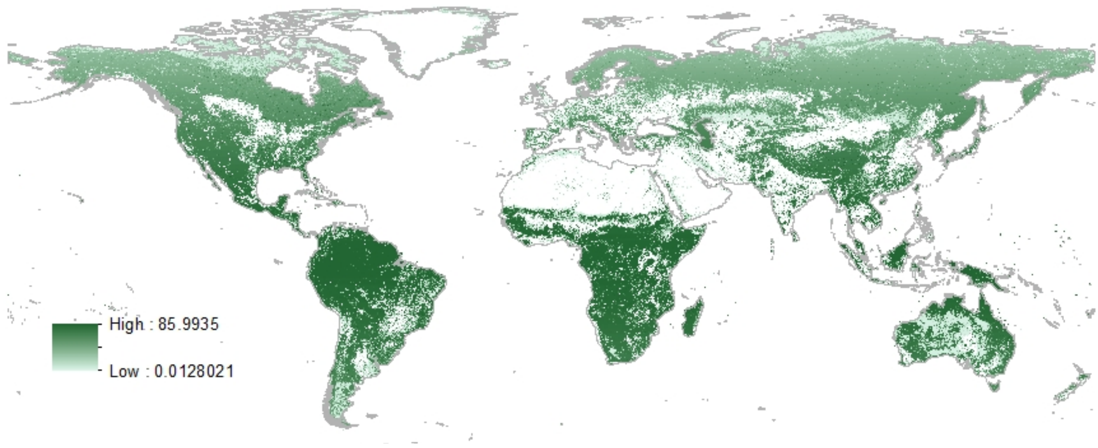
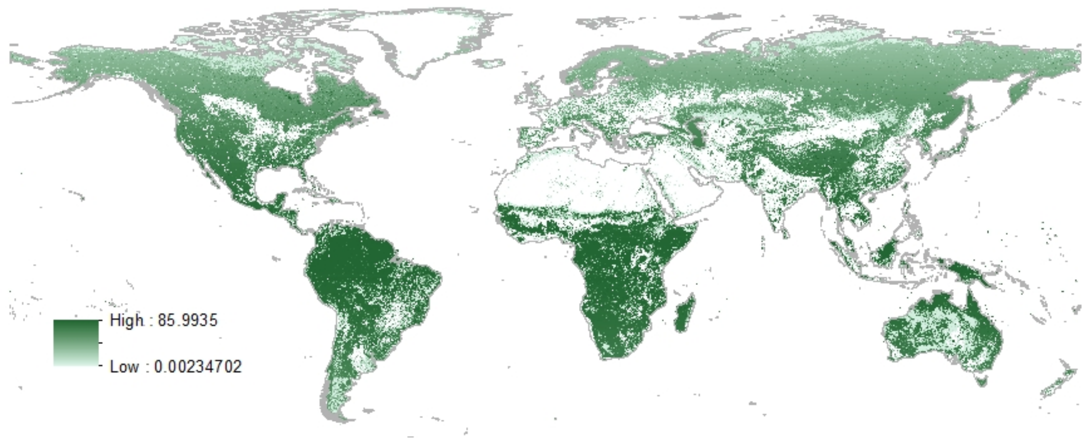


Figure S4. Maps on ecosystems

Natural and semi-natural ecosystem occupancy 2000 (hectare, max = 85.9935)



Natural and semi-natural ecosystem occupancy 2018 (hectare, max = 85.9935)



Changes natural and semi-natural ecosystem occupancy 2018-2000 (in hectare)

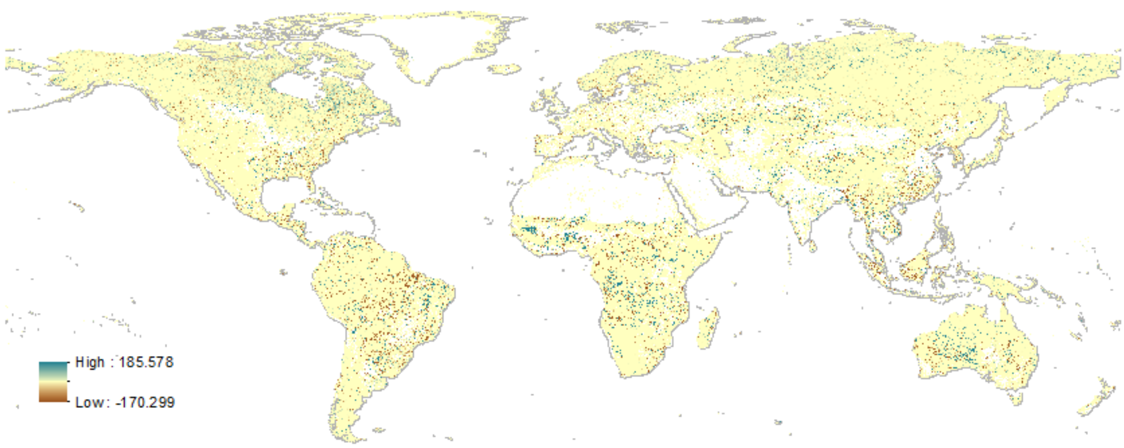
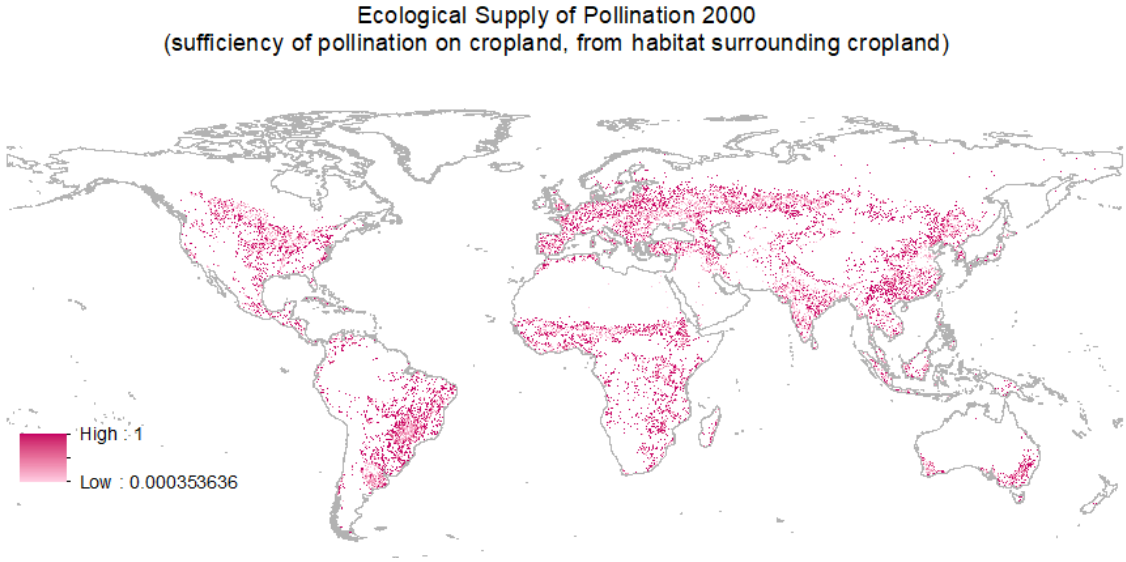
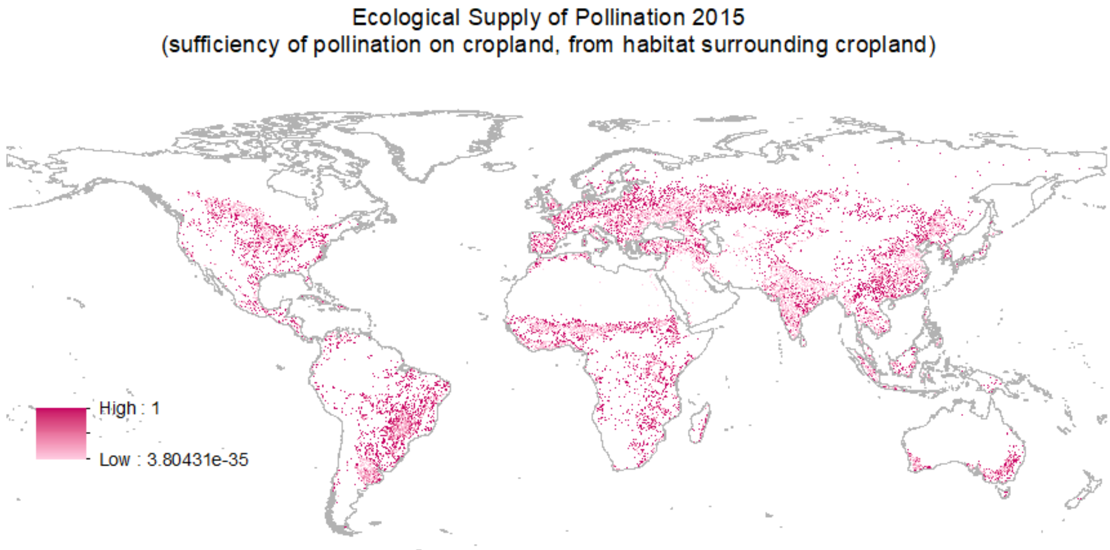


Figure S5. Maps on nature's contributions to people – pollination





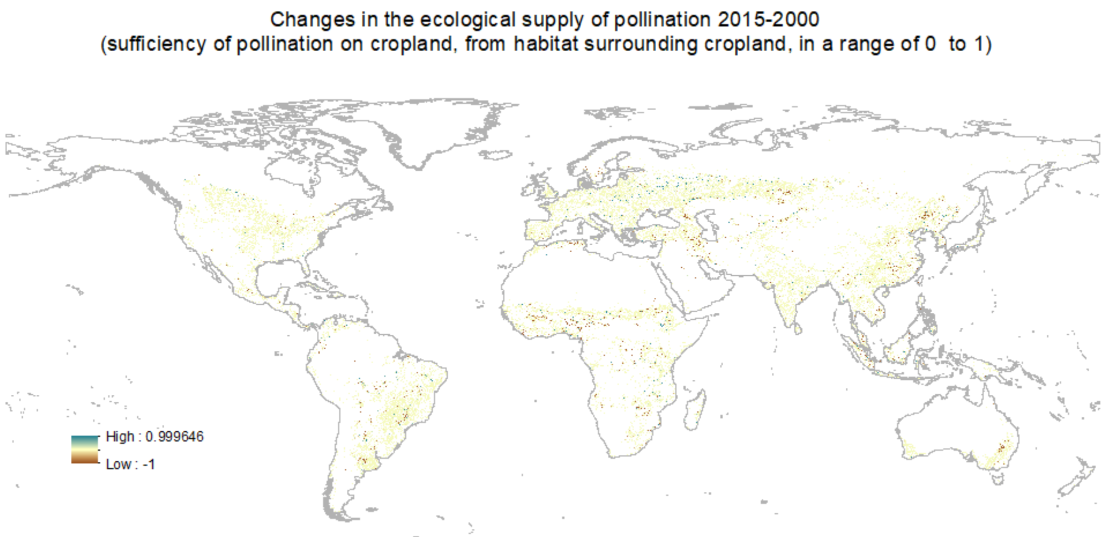
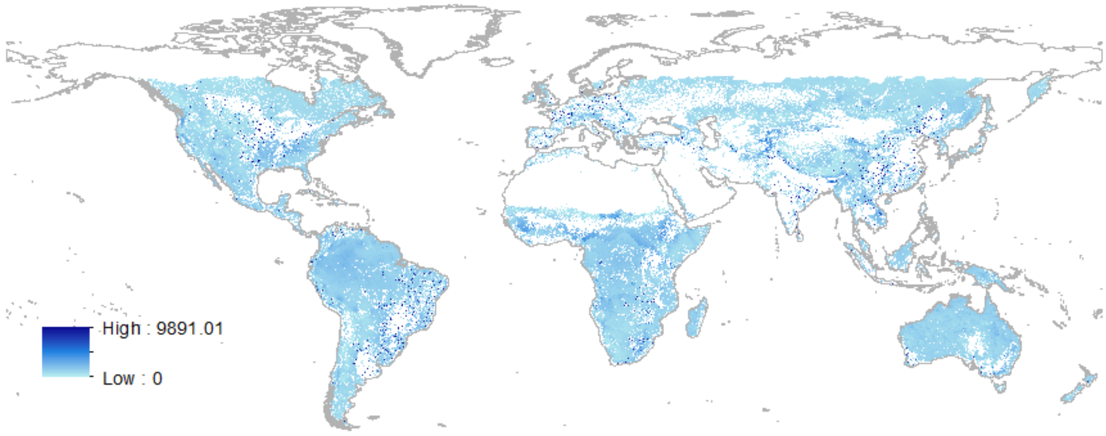
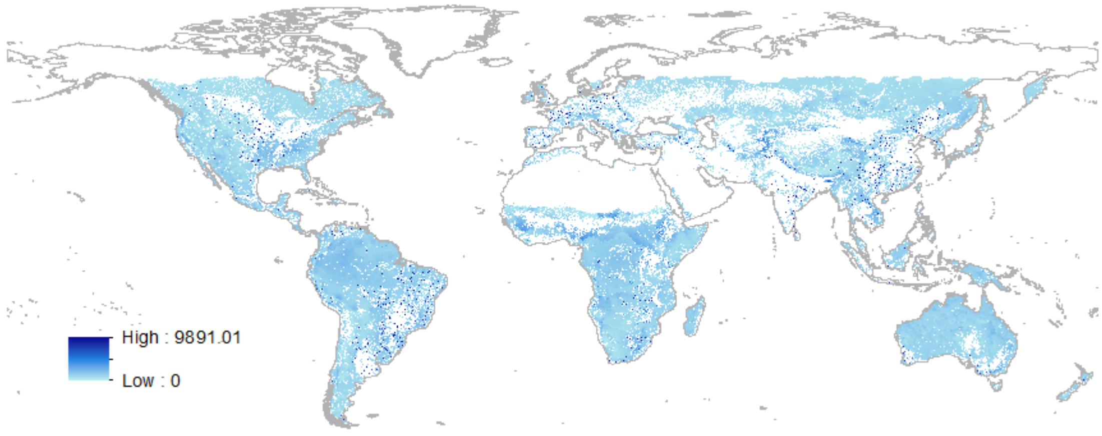


Figure S6. Maps on nature's contributions to people – nitrogen retention

Ecological Supply of Nitrogen Retention 2000 (modified load of nitrogen retention - nitrogen export) (kg)



Ecological Supply of Nitrogen Retention 2015 (modified load of nitrogen retention - nitrogen export) (kg)



Changes in the ecological supply of nitrogen retention 2015-1000
(modified load of nitrogen – nitrogen export, kg)

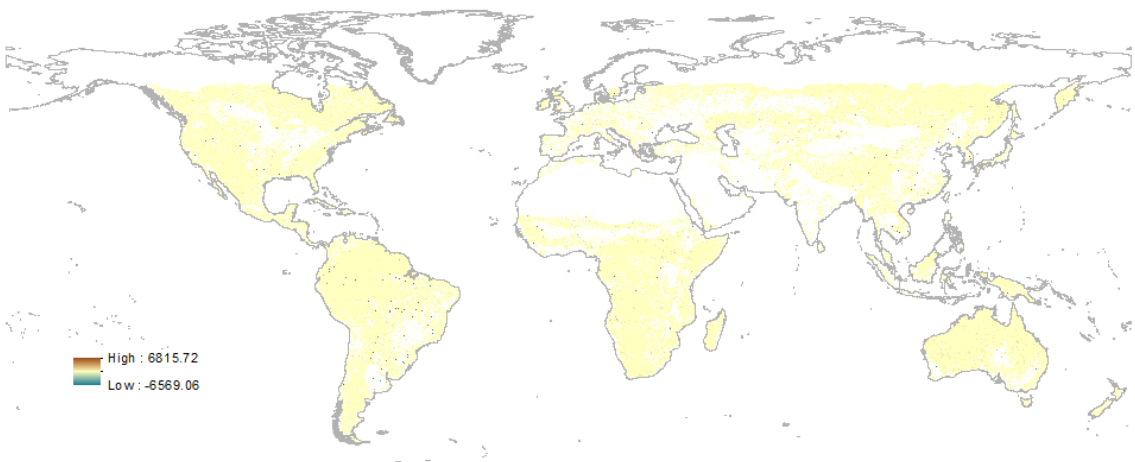
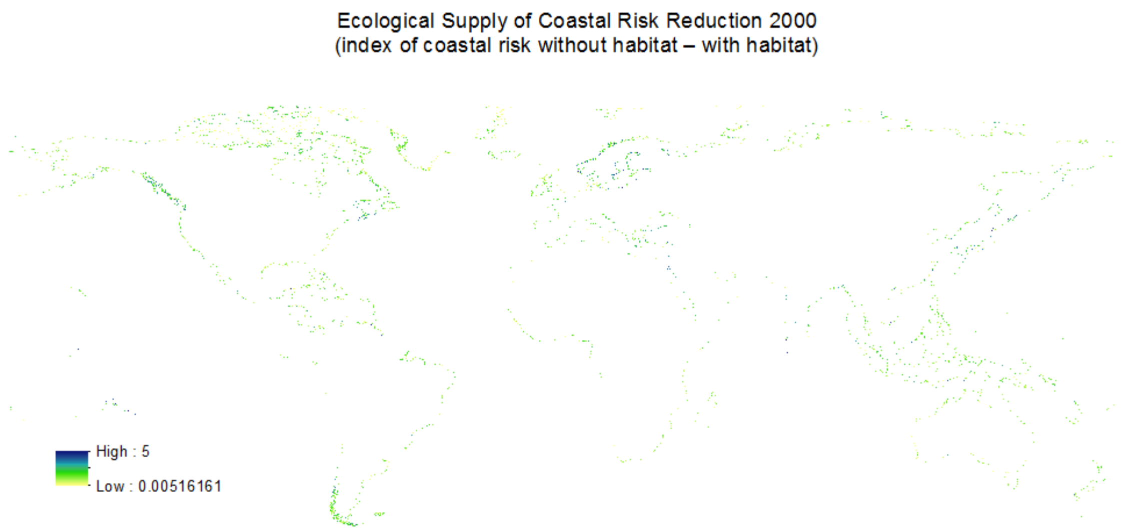
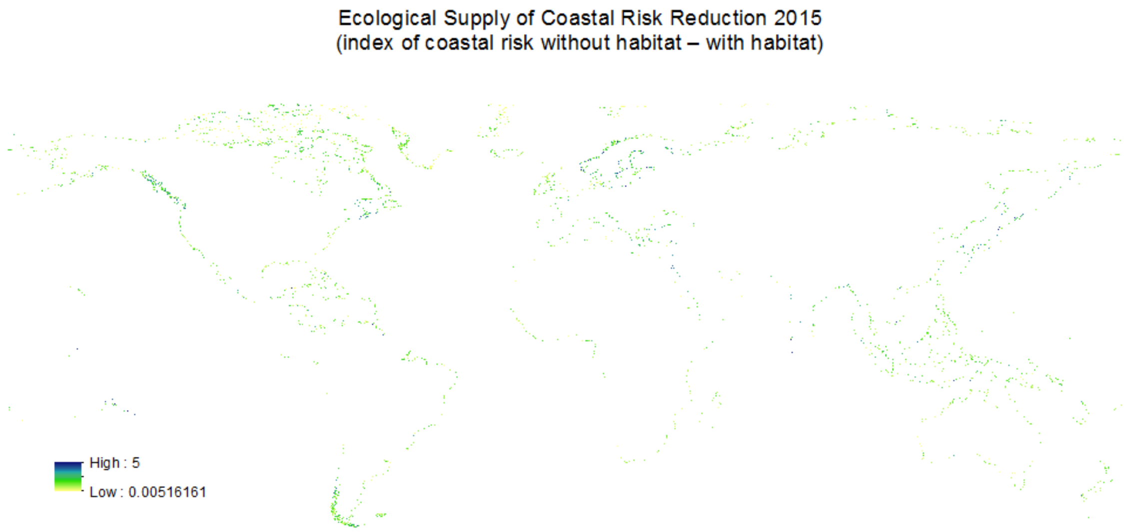
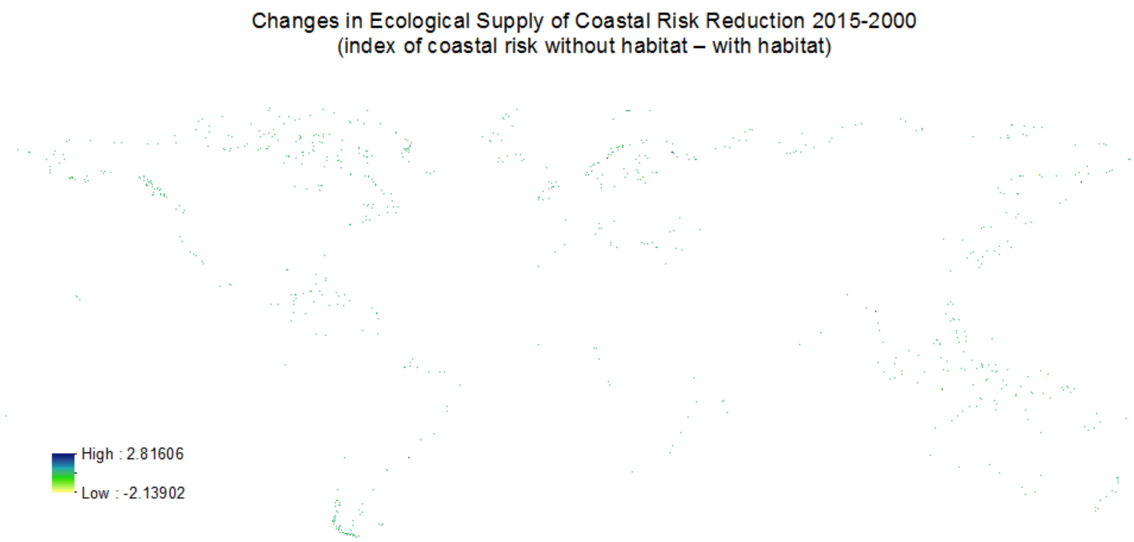


Figure S7. Maps on nature's contributions to people – coastal risk reduction







Tab S1. Descriptive information on essential variable datasets used in the analyses

INB	EBV CLASS	EBV	METRIC	TEMPORAL EXTENT	SPATIAL RESOLUTION	QUESTION	CBD RELE-VANCE	CBD POST-2020 GBF
NATURE (BES)	Species Population	Species distribution	**Area of suitable habitat by species**	2000, 2018	300 m	What is the spatio and temporal pattern in area of habitat-based species richness across Nature Future mapped protected areas (NN, NS, NC) and unprotected land (SQ)?	Goal A. **reduced threatened species**	Goal A. The **area, connectivity and integrity of natural ecosystems** increased by at least X% supporting **healthy and resilient populations of all species** while **reducing the number of species that are threatened** by X% and **maintaining genetic diversity.** 2030 Milestones: i) The area, connectivity and integrity of natural ecosystems increased by at least [5%] ii) The number of species that are threatened is reduced by [X%] and the abundance of species has increased on average by [X%]
NATURE (BES)	Ecosystem Structure	Ecosystem distribution	**Extent of 59 ecosystems**	2000, 2018	1-10km	What is the spatio and temporal pattern in natural and semi-natural ecosystem extent across Nature Future mapped protected areas (NN, NS, NC) and unprotected land (SQ)?	Goal A. **ecosystem area,** changes in natural ecosystems	
BENEFITS (NCP)	Ecosystem Services	Ecological supply	**Pollination** (sufficiency of pollination on cropland from surrounding pollinator habitat)	2000, 2015	300 m	What is the spatio and temporal pattern in the ecological supply of pollination for food and feed across Nature Future mapped protected areas (NN, NS, NC) and unprotected land (SQ)?	Goal B. sustainable **food** security	Goal B. Nature's contributions to people have been **valued, maintained or enhanced** through **conservation and sustainable use**, supporting the global development agenda for the **benefit of all people.** 2030 Milestones: (i) Nature contribute to the sustainable nutrition and **food** security, access to safe drinking **water** and resilience to **natural disasters** for at least [X] million people
BENEFITS (NCP)	Ecosystem Services	Ecological supply	**Nitrogen retention** (modified load of nitrogen – nitrogen export)	2000, 2015	300 m	What is the spatio and temporal pattern in the ecological supply of nitrogen retention for water regulation quality across Nature Future mapped protected areas (NN, NS, NC) and unprotected land (SQ)?	Goal B. access to safe **drinking water**	
BENEFITS (NCP)	Ecosystem Services	Ecological supply	**Coastal risk reduction** (index of coastal risk without habitat – with habitat)	2000, 2015	300 m	What is the spatio and temporal pattern in the ecological supply of coastal risk reduction for people's livelihood across Nature Future mapped protected areas (NN, NS, NC) and unprotected land (SQ)?	Goal B. resilience to **natural disasters**	

Tab S2. National distribution of land across Nature Futures protection regimes prior to 2000

			TOTAL		NN		NS		NC		SQ		NA	
REGION	**COUNTRY**	**ISO3**	**PIXELS**	**AREA**	**AREA**	**%**	**AREA**	**%**	**AREA**	**%**	**AREA**	**%**	**AREA**	**%**
AFRICA	Algeria	DZA	29,269,056	212.57	0.19	0.09	0.00	0.00	76.11	35.80	136.28	64.11	0.00	0.00
	Angola	AGO	14,292,945	103.81	5.73	5.52	1.22	1.17	3.76	3.62	93.10	89.68	0.00	0.00
	Benin	BEN	1,309,598	9.51	0.72	7.59	0.00	0.04	7.04	73.98	1.67	17.55	0.08	0.84
	Botswana	BWA	6,972,645	50.64	9.48	18.72	0.16	0.32	3.13	6.18	33.78	66.71	4.09	8.09
	Burkina Faso	BFA	3,128,768	22.72	0.41	1.81	2.13	9.38	20.18	88.82	0.00	0.00	0.00	0.00
	Burundi	BDI	301,835	2.19	0.11	4.80	0.00	0.02	0.07	3.12	2.00	91.25	0.02	0.81
	Cameroon	CMR	5,243,063	38.08	0.87	2.29	0.08	0.20	18.23	47.88	18.54	48.68	0.36	0.95
	C.A.R.	CAF	6,985,012	50.73	2.76	5.44	3.44	6.78	21.62	42.62	21.70	42.78	1.21	2.38
	Chad	TCD	14,750,886	107.13	0.34	0.32	9.58	8.94	93.62	87.39	3.58	3.35	0.00	0.00
	Congo	COG	3,826,095	27.79	0.62	2.24	0.33	1.19	4.03	14.52	21.21	76.31	1.60	5.74
	Cote d'Ivoire	CIV	3,630,539	26.37	1.70	6.46	0.04	0.16	8.94	33.89	12.64	47.95	3.04	11.54
	D.R. Congo	COD	26,160,222	189.99	9.25	4.87	5.26	2.77	41.67	21.93	132.78	69.89	1.03	0.54
	Djibouti	DJI	238,019	1.73	0.00	0.00	0.00	0.00	0.01	0.39	1.72	99.61	0.00	0.00
	Egypt	EGY	12,185,782	88.50	0.27	0.31	2.32	2.62	13.78	15.57	72.13	81.50	0.00	0.00
	E. Guinea	GNQ	279,445	2.03	0.16	7.98	0.00	0.00	0.00	0.04	1.87	91.98	0.00	0.00
	Eritrea	ERI	1,347,512	9.79	0.00	0.00	0.51	5.18	3.04	31.05	6.24	63.77	0.00	0.00
	Eswatini	SWZ	216,817	1.57	0.07	4.32	0.00	0.00	0.00	0.00	1.51	95.61	0.00	0.07
	Ethiopia	ETH	12,789,462	92.89	2.42	2.60	2.68	2.88	60.72	65.37	27.07	29.15	0.00	0.00
	Gabon	GAB	2,958,591	21.49	0.04	0.20	0.41	1.93	8.58	39.93	11.87	55.26	0.58	2.69
	Gambia	GMB	122,553	0.89	0.00	0.24	0.03	3.49	0.46	51.55	0.40	44.65	0.00	0.08
	Ghana	GHA	2,691,742	19.55	0.89	4.53	0.03	0.17	5.24	26.78	11.70	59.86	1.69	8.67
	Guinea	GIN	2,783,393	20.22	0.04	0.19	0.20	0.98	0.01	0.07	18.99	93.96	0.97	4.81
	Guinea-Bissau	GNB	385,428	2.80	0.00	0.00	0.00	0.00	0.00	0.07	2.44	87.27	0.35	12.65
	Kenya	KEN	6,541,823	47.51	2.65	5.58	0.44	0.93	30.01	63.17	13.67	28.77	0.73	1.55
	Lesotho	LSO	391,628	2.84	0.00	0.00	0.01	0.24	0.00	0.00	2.83	99.34	0.01	0.42
	Liberia	LBR	1,079,714	7.84	0.00	0.00	0.00	0.00	0.00	0.00	7.71	98.32	0.13	1.68
	Libya	LBY	20,189,773	146.63	0.00	0.00	0.00	0.00	15.51	10.57	131.13	89.43	0.00	0.00
	Madagascar	MDG	6,914,505	50.22	1.99	3.96	0.60	1.20	0.06	0.11	47.57	94.73	0.00	0.00
	Malawi	MWI	1,355,959	9.85	0.59	5.96	0.33	3.33	0.00	0.00	8.29	84.21	0.64	6.49
	Mali	MLI	14,672,140	106.56	0.00	0.00	3.84	3.60	74.29	69.71	28.44	26.69	0.00	0.00
	Morocco	MAR	5,410,952	39.30	0.27	0.69	0.00	0.00	15.54	39.53	22.91	58.30	0.58	1.47
	Mozambique	MOZ	9,112,153	66.18	3.43	5.18	1.56	2.36	0.00	0.00	50.23	75.90	10.97	16.57
	Namibia	NAM	9,939,834	72.19	8.13	11.26	0.00	0.00	12.47	17.28	50.06	69.34	1.53	2.12
	Niger	NER	13,876,121	100.78	1.29	1.28	6.19	6.14	70.85	70.31	22.45	22.27	0.00	0.00
	Nigeria	NGA	10,305,724	74.85	1.75	2.34	0.57	0.76	57.86	77.30	12.85	17.17	1.82	2.43
	Rwanda	RWA	282,933	2.05	0.10	4.79	0.09	4.38	0.11	5.53	1.75	85.21	0.00	0.08
	Senegal	SEN	2,268,568	16.48	0.72	4.39	1.04	6.31	11.75	71.29	2.56	15.51	0.41	2.49
	Sierra Leone	SLE	816,056	5.93	0.11	1.90	0.01	0.17	0.00	0.00	5.65	95.38	0.15	2.55
	Somalia	SOM	7,066,773	51.32	0.00	0.00	0.00	0.00	0.04	0.07	51.29	99.93	0.00	0.00
	South Africa	ZAF	15,394,095	111.80	0.01	0.01	0.00	0.00	1.16	1.03	103.91	92.94	6.73	6.02

			TOTAL		NN		NS		NC		SQ		NA	
REGION	**COUNTRY**	**ISO3**	**PIXELS**	**AREA**	**AREA**	**%**	**AREA**	**%**	**AREA**	**%**	**AREA**	**%**	**AREA**	**%**
	South Sudan	SSD	7,085,225	51.46	4.24	8.23	2.49	4.83	0.11	0.22	44.62	86.72	0.00	0.00
	Sudan	SDN	21,745,543	157.93	0.70	0.44	1.57	0.99	0.03	0.02	155.64	98.55	0.00	0.00
	Togo	TGO	644,732	4.68	0.29	6.12	0.07	1.44	1.54	32.87	2.65	56.55	0.14	3.02
	Tunisia	TUN	2,038,349	14.80	0.02	0.12	0.00	0.00	0.00	0.00	14.01	94.63	0.78	5.24
	Zambia	ZMB	8,632,956	62.70	5.29	8.44	14.19	22.64	0.01	0.02	38.45	61.33	4.75	7.57
	Zimbabwe	ZWE	4,617,197	33.53	2.35	7.00	1.64	4.88	0.36	1.07	27.83	83.00	1.36	4.04
	Regional		322,253,285	2,340	70.01	2.99	63.06	2.69	681.94	29.14	1479.72	63.22	45.75	1.95
AMERICAS	Argentina	ARG	38,194,101	277.39	4.96	1.79	6.70	2.42	59.49	21.45	205.42	74.05	0.82	0.30
	Belize	BLZ	253,916	1.84	0.17	9.42	0.42	22.52	0.58	31.61	0.67	36.44	0.00	0.01
	Bolivia	BOL	12,655,946	91.92	0.02	0.02	0.44	0.48	24.95	27.14	53.02	57.68	13.50	14.68
	Brazil	BRA	97,511,473	708.20	19.59	2.77	12.47	1.76	113.13	15.97	562.77	79.47	0.24	0.03
	Canada	CAN	227,939,728	1655.47	129.46	7.82	5.27	0.32	126.95	7.67	1392.2	84.09	1.62	0.10
	Chile	CHL	10,722,468	77.87	10.58	13.59	3.34	4.29	7.41	9.51	55.66	71.48	0.88	1.13
	Colombia	COL	12,748,927	92.59	9.99	10.79	0.53	0.58	23.96	25.88	58.09	62.74	0.01	0.01
	Costa Rica	CRI	575,985	4.18	0.50	11.85	0.43	10.34	0.38	9.11	2.83	67.76	0.04	0.92
	Cuba	CUB	1,259,159	9.14	0.00	0.00	0.00	0.00	0.00	0.00	8.80	96.19	0.35	3.81
	Dom. Republic	DOM	554,780	4.03	0.22	5.45	0.00	0.00	0.00	0.00	3.81	94.55	0.00	0.00
	Ecuador	ECU	2,835,945	20.60	0.00	0.00	0.00	0.00	6.26	30.40	12.48	60.58	1.86	9.01
	El Salvador	SLV	234,543	1.70	0.00	0.00	0.00	0.03	0.42	24.87	1.28	74.95	0.00	0.15
	Greenland	GRL	90,379,431	656.40	332.72	50.69	0.00	0.00	323.69	49.31	0.00	0.00	0.00	0.00
	Guatemala	GTM	1,264,989	9.19	0.39	4.29	0.09	0.96	5.20	56.61	1.92	20.93	1.58	17.21
	Guyana	GUY	2,341,173	17.00	0.01	0.03	0.35	2.08	2.67	15.71	13.97	82.18	0.00	0.00
	Haiti	HTI	295,944	2.15	0.03	1.28	0.00	0.00	0.03	1.25	2.10	97.48	0.00	0.00
	Honduras	HND	1,296,719	9.42	0.50	5.34	0.75	7.92	2.93	31.13	5.24	55.59	0.00	0.03
	Jamaica	JAM	127,356	0.92	0.00	0.00	0.10	11.20	0.05	5.17	0.76	81.63	0.02	2.00
	Mexico	MEX	23,792,447	172.80	1.72	1.00	4.96	2.87	25.49	14.75	138.56	80.18	2.07	1.20
	Nicaragua	NIC	1,468,798	10.67	0.36	3.34	0.48	4.51	3.10	29.06	4.79	44.90	1.94	18.20
	Panama	PAN	832,980	6.05	0.72	11.90	0.03	0.42	2.11	34.96	3.06	50.56	0.13	2.17
	Paraguay	PRY	4,857,642	35.28	1.13	3.21	0.14	0.39	4.07	11.53	29.90	84.76	0.04	0.11
	Peru	PER	14,677,846	106.60	3.19	2.99	2.46	2.31	31.25	29.32	68.15	63.93	1.55	1.46
	Puerto Rico	PRI	100,485	0.73	0.01	0.83	0.03	4.50	0.02	2.67	0.67	91.87	0.00	0.14
	Suriname	SUR	1,638,782	11.90	0.97	8.15	0.34	2.87	4.25	35.72	6.28	52.80	0.06	0.46
	Taiwan	TWN	419,330	3.05	0.35	11.52	0.01	0.26	0.51	16.61	2.18	71.60	0.00	0.00
	Tanzania	TZA	10,529,607	76.47	3.64	4.76	6.79	8.89	7.26	9.49	46.94	61.38	11.84	15.48
	Trinidad & Tobago	TTO	55,675	0.40	0.01	3.06	0.12	29.03	0.00	0.00	0.27	66.53	0.01	1.39
	Turkey	TUR	11,066,167	80.37	0.00	0.00	0.00	0.00	0.00	0.00	80.22	99.81	0.15	0.18
	Uganda	UGA	2,702,286	19.63	1.63	8.33	0.08	0.40	1.67	8.49	15.39	78.40	0.86	4.37
	Ukraine	UKR	10,141,680	73.66	1.03	1.40	1.08	1.46	0.43	0.58	70.86	96.20	0.26	0.35
	U.S.A.	USA	153,016,936	1111.32	76.52	6.89	63.16	5.68	100.04	9.00	871.10	78.38	0.50	0.04
	Uruguay	URY	2,341,384	17.00	0.00	0.00	0.00	0.00	0.00	0.00	15.83	93.07	1.18	6.92

REGION	COUNTRY	ISO3	TOTAL PIXELS	TOTAL AREA	NN AREA	NN %	NS AREA	NS %	NC AREA	NC %	SQ AREA	SQ %	NA AREA	NA %
	Venezuela	VEN	10,255,962	74.49	11.16	14.99	2.49	3.35	32.12	43.12	27.91	37.47	0.80	1.07
	Regional		749,090,590	5,440	611.58	11.24	113.06	2.08	910.42	16.73	3763.13	69.17	42.31	0.78
ASIA AND THE PACIFIC	Afghanistan	AFG	8,639,883	62.75	0.02	0.03	0.03	0.05	0.04	0.07	62.66	99.85	0.00	0.00
	Australia	AUS	95,449,680	693.23	27.22	3.93	1.80	0.26	350.46	50.55	311.75	44.97	2.00	0.29
	Bangladesh	BGD	1,632,414	11.86	0.15	1.26	0.05	0.39	1.09	9.17	10.27	86.66	0.30	2.52
	Bhutan	BTN	486,982	3.54	0.80	22.65	0.53	14.96	0.00	0.13	2.20	62.26	0.00	0.00
	Brunei Daruss.	BRN	64,303	0.47	0.10	20.65	0.00	0.00	0.01	2.14	0.35	75.34	0.01	1.87
	Cambodia	KHM	2,074,756	15.07	0.50	3.32	2.74	18.20	4.14	27.44	7.47	49.56	0.22	1.48
	China	CHN	130,855,286	950.37	0.15	0.02	0.39	0.04	384.39	40.45	563.05	59.25	2.39	0.25
	D.P.R. Korea	PRK	1,763,044	12.80	0.00	0.00	0.00	0.00	0.01	0.07	12.80	99.93	0.00	0.00
	Fiji	FJI	175,251	1.27	0.02	1.68	0.00	0.03	0.00	0.00	1.25	98.13	0.00	0.16
	Hong Kong	HKG	11,538	0.08	0.00	0.00	0.00	0.00	0.02	20.21	0.04	46.72	0.03	33.06
	India	IND	38,082,853	276.59	2.99	1.08	9.44	3.41	48.51	17.54	215.40	77.88	0.24	0.09
	Indonesia	IDN	19,999,717	145.25	12.56	8.65	2.39	1.64	61.55	42.37	68.32	47.03	0.44	0.30
	Iran	IRN	21,452,976	155.81	1.40	0.90	1.86	1.20	26.74	17.17	125.40	80.48	0.39	0.25
	Iraq	IRQ	5,919,773	42.99	0.00	0.00	0.00	0.00	0.00	0.01	42.99	99.99	0.00	0.00
	Japan	JPN	5,023,172	36.48	1.94	5.32	2.85	7.80	3.27	8.98	28.42	77.89	0.01	0.02
	Jordan	JOR	1,161,984	8.44	0.05	0.60	0.01	0.13	6.93	82.06	1.45	17.21	0.00	0.00
	Kuwait	KWT	209,964	1.52	0.03	2.11	0.02	1.32	0.00	0.00	1.47	96.57	0.00	0.00
	Laos	LAO	2,711,011	19.69	0.01	0.07	0.39	1.98	15.68	79.63	3.60	18.26	0.01	0.06
	Lebanon	LBN	135,045	0.98	0.00	0.00	0.00	0.01	0.00	0.01	0.96	97.40	0.03	2.57
	Malaysia	MYS	3,617,050	26.27	1.26	4.81	0.37	1.39	15.89	60.50	8.73	33.24	0.02	0.06
	Mongolia	MNG	25,448,691	184.83	22.60	12.23	2.24	1.21	0.04	0.02	159.68	86.40	0.26	0.14
	Myanmar	MMR	7,975,746	57.93	0.55	0.96	0.45	0.78	33.74	58.24	23.19	40.03	0.00	0.00
	Nepal	NPL	1,869,916	13.58	0.97	7.17	0.16	1.20	10.94	80.58	1.50	11.04	0.00	0.00
	New Zealand	NZL	3,933,414	28.57	7.14	25.00	0.22	0.79	3.11	10.88	18.09	63.34	0.00	0.00
	Oman	OMN	3,660,319	26.58	0.63	2.36	0.02	0.08	0.01	0.05	25.92	97.51	0.00	0.00
	Pakistan	PAK	11,263,667	81.80	0.93	1.13	2.86	3.50	56.21	68.72	18.34	22.41	3.47	4.24
	Palestine	PSE	77,692	0.56	0.00	0.43	0.03	4.56	0.00	0.14	0.50	88.61	0.04	6.26
	P.N. Guinea	PNG	4,996,604	36.29	0.00	0.00	0.00	0.01	0.00	0.00	35.17	96.93	1.11	3.06
	Philippines	PHL	2,966,713	21.55	0.20	0.94	1.34	6.22	3.34	15.50	16.63	77.16	0.04	0.18
	Qatar	QAT	138,100	1.00	0.00	0.00	0.00	0.01	0.00	0.00	0.89	88.37	0.12	11.62
	Rep. of Korea	KOR	1,304,096	9.47	0.39	4.17	0.27	2.84	0.16	1.70	8.54	90.18	0.10	1.11
	Saudi Arabia	SAU	23,443,049	170.26	1.70	1.00	6.58	3.87	0.09	0.05	161.89	95.08	0.00	0.00
	Singapore	SGP	7,590	0.06	0.00	5.96	0.00	0.00	0.00	0.00	0.05	94.04	0.00	0.00
	Solomon Isl.	SLB	199,283	1.45	0.00	0.00	0.00	0.00	0.00	0.00	1.45	99.99	0.00	0.01
	Sri Lanka	LKA	704,923	5.12	0.89	17.35	0.17	3.29	0.03	0.60	4.00	78.20	0.03	0.55
	Syria	SYR	2,522,931	18.32	0.00	0.00	0.00	0.00	0.01	0.03	18.32	99.97	0.00	0.00
	Thailand	THA	5,940,521	43.14	7.20	16.68	0.00	0.01	19.21	44.51	16.74	38.80	0.00	0.00
	U.A.E.	ARE	856,768	6.22	0.00	0.00	0.00	0.00	0.00	0.00	6.21	99.86	0.01	0.14
	Viet Nam	VNM	3,770,271	27.38	0.22	0.81	0.17	0.62	14.11	51.54	12.84	46.91	0.03	0.12

REGION	COUNTRY	ISO3	TOTAL PIXELS	TOTAL AREA	NN AREA	NN %	NS AREA	NS %	NC AREA	NC %	SQ AREA	SQ %	NA AREA	NA %
	Regional		440,546,976	3,200	92.62	2.89	37.38	1.17	1059.73	33.12	1998.53	62.46	11.3	0.35
EUROPE AND CENTRAL ASIA	Albania	ALB	424,018	3.08	0.08	2.75	0.06	1.85	0.03	0.98	2.90	94.08	0.01	0.33
	Armenia	ARM	433,000	3.14	0.21	6.54	0.07	2.10	0.00	0.00	2.54	80.66	0.34	10.69
	Austria	AUT	1,380,733	10.03	0.21	2.08	0.45	4.49	1.29	12.84	7.63	76.12	0.45	4.47
	Azerbaijan	AZE	1,246,970	9.06	0.14	1.55	0.37	4.05	0.00	0.05	8.54	94.24	0.01	0.10
	Belarus	BLR	3,865,282	28.07	0.72	2.57	1.33	4.75	0.00	0.01	26.00	92.61	0.02	0.06
	Belgium	BEL	536,910	3.90	0.00	0.06	0.25	6.29	0.20	5.11	3.02	77.34	0.44	11.20
	Bosnia Herzeg.	BIH	791,375	5.75	0.03	0.44	0.00	0.00	0.00	0.00	5.71	99.43	0.01	0.13
	Bulgaria	BGR	1,678,195	12.19	0.31	2.55	0.07	0.57	0.26	2.10	11.55	94.75	0.00	0.03
	Croatia	HRV	840,084	6.10	0.00	0.05	0.00	0.05	0.01	0.20	5.38	88.21	0.70	11.50
	Cyprus	CYP	74,916	0.54	0.01	2.45	0.00	0.00	0.00	0.00	0.52	95.45	0.01	2.10
	Czechia	CZE	1,353,964	9.83	0.16	1.65	0.16	1.62	1.33	13.48	8.13	82.71	0.05	0.54
	Denmark	DNK	772,765	5.61	0.00	0.07	0.50	8.92	0.06	1.04	2.95	52.59	2.10	37.38
	Estonia	EST	874,991	6.35	0.00	0.01	0.02	0.37	0.00	0.06	6.04	95.04	0.29	4.52
	Finland	FIN	8,581,762	62.33	6.38	10.23	0.23	0.37	19.71	31.62	35.43	56.85	0.58	0.93
	France	FRA	8,832,931	64.15	0.44	0.69	0.84	1.30	8.19	12.77	54.32	84.68	0.35	0.55
	Georgia	GEO	1,047,581	7.61	0.25	3.27	0.06	0.84	0.00	0.00	7.29	95.88	0.00	0.01
	Germany	DEU	6,298,545	45.74	0.21	0.46	1.75	3.83	9.38	20.50	33.22	72.62	1.18	2.58
	Greece	GRC	1,663,652	12.08	0.11	0.93	0.83	6.86	0.00	0.00	10.27	84.99	0.87	7.22
	Hungary	HUN	1,520,142	11.04	0.29	2.67	0.04	0.38	0.80	7.27	9.79	88.69	0.11	1.00
	Iceland	ISL	2,517,923	18.29	0.43	2.34	0.11	0.60	0.23	1.23	17.39	95.10	0.13	0.73
	Ireland	IRL	1,123,487	8.16	0.00	0.00	0.00	0.04	0.01	0.06	6.76	82.87	1.39	17.03
	Israel	ISR	288,971	2.10	0.00	0.00	0.28	13.47	0.04	1.71	1.73	82.52	0.05	2.30
	Italy	ITA	4,481,460	32.55	1.61	4.95	1.21	3.73	0.46	1.42	28.52	87.63	0.74	2.27
	Kazakhstan	KAZ	45,401,155	329.74	1.79	0.54	4.16	1.26	0.02	0.00	323.33	98.06	0.44	0.13
	Kyrgyzstan	KGZ	2,948,265	21.41	1.05	4.92	0.36	1.69	0.02	0.08	19.98	93.29	0.00	0.01
	Latvia	LVA	1,300,148	9.44	0.42	4.48	0.30	3.14	0.80	8.51	7.92	83.86	0.00	0.01
	Lithuania	LTU	1,266,410	9.20	0.23	2.55	0.30	3.27	0.70	7.60	7.72	83.94	0.24	2.64
	Luxembourg	LUX	44,370	0.32	0.08	26.22	0.00	0.09	0.00	0.20	0.20	61.62	0.04	11.87
	Moldova	MDA	554,319	4.03	0.00	0.07	0.00	0.01	0.00	0.00	4.02	99.85	0.00	0.07
	Montenegro	MNE	200,068	1.45	0.00	0.09	0.00	0.00	0.00	0.00	1.45	99.91	0.00	0.00
	Netherlands	NLD	673,158	4.89	0.07	1.36	0.04	0.82	0.00	0.05	4.64	94.93	0.14	2.83
	N. Macedonia	MKD	369,110	2.68	0.20	7.64	0.00	0.09	0.00	0.02	2.47	92.19	0.00	0.06
	Norway	NOR	8,088,179	58.74	2.29	3.90	0.14	0.23	30.66	52.20	25.62	43.61	0.03	0.06
	Poland	POL	5,642,619	40.98	0.28	0.68	0.32	0.79	3.42	8.34	27.87	68.02	9.09	22.18
	Portugal	PRT	1,292,866	9.39	0.09	0.99	0.08	0.89	0.60	6.37	8.13	86.63	0.48	5.12
	Romania	ROU	3,799,272	27.59	0.40	1.45	0.14	0.49	0.17	0.60	26.32	95.40	0.57	2.05
	Russia	RUS	400,184,426	2906.43	79.88	2.75	136.47	4.70	1492.2	51.34	1190.4	40.96	7.56	0.26
	Serbia	SRB	1,213,424	8.81	0.13	1.47	0.11	1.22	0.16	1.86	8.38	95.12	0.03	0.34
	Slovakia	SVK	826,046	6.00	0.18	3.08	0.02	0.28	0.41	6.86	4.90	81.65	0.49	8.13
	Slovenia	SVN	318,076	2.31	0.14	6.08	0.00	0.05	0.09	3.93	2.07	89.63	0.01	0.32

			TOTAL		NN		NS		NC		SQ		NA	
REGION	**COUNTRY**	**ISO3**	**PIXELS**	**AREA**	**AREA**	**%**	**AREA**	**%**	**AREA**	**%**	**AREA**	**%**	**AREA**	**%**
	Spain	ESP	7,235,709	52.55	0.95	1.81	0.39	0.75	3.39	6.45	44.16	84.04	3.65	6.95
	Sweden	SWE	10,708,114	77.77	1.54	1.98	0.10	0.12	46.22	59.43	29.52	37.96	0.40	0.51
	Switzerland	CHE	669,220	4.86	0.04	0.79	0.34	6.93	0.00	0.04	4.48	92.20	0.00	0.05
	Tajikistan	TJK	2,021,764	14.68	2.58	17.58	0.17	1.13	0.01	0.05	11.93	81.24	0.00	0.00
	Turkmenistan	TKM	6,793,825	49.34	0.98	1.99	0.55	1.12	0.01	0.02	47.78	96.83	0.02	0.04
	U.K.	GBR	4,413,266	32.05	0.23	0.72	3.66	11.43	3.82	11.93	23.18	72.32	1.15	3.59
	Uzbekistan	UZB	6,674,169	48.47	0.97	1.99	0.01	0.02	0.00	0.00	47.50	97.98	0.00	0.00
	Regional		563,267,635	4,091	106.11	2.59	156.29	3.82	1624.7	39.72	2169.6	53.04	34.17	0.84

Tab S3. Global and regional statistics across Nature Futures protection regimes in 2000 and 2015/2018

		ALL		NN		NS		NC		SQ	
		2000	2018	2000	2018	2000	2018	2000	2018	2000	2018
AOHSR											
GLOBAL	median	48	48	49	49	46	46	48	48	46	46
	mean	56	55	59	59	56	56	55	55	52	52
	s.d.	34	34	37	37	35	35	34	34	31	31
	obs.	598	598	148	148	141	141	143	143	166	166
AFRICA	median	78	78	91	91	77	77	68	68	77	77
	mean	73	73	82	82	75	75	67	67	70	70
	s.d.	32	32	32	32	34	34	32	32	31	31
	obs.	170	170	42	42	39	39	42	42	47	47
AMERICAS	median	79	80	71	71	83	83	83	83	72	72
	mean	72	72	72	72	79	79	74	74	65	65
	s.d.	48	48	50	50	47	47	51	51	44	44
	obs.	105	105	27	27	23	23	27	27	28	28
ASIA & PACIFIC	median	33	33	33	33	34	33	34	34	32	32
	mean	41	41	45	44	40	40	42	42	37	37
	s.d.	27	27	32	31	29	29	26	26	22	22
	obs.	140	140	32	32	33	33	33	33	42	42
EUROPE & C. ASIA	median	45	45	46	46	42	42	45	45	44	44
	mean	41	41	41	41	40	40	42	42	42	42
	s.d.	14	14	15	15	13	13	15	15	12	12
	obs.	183	183	47	47	46	46	41	41	49	49

		ALL		NN		NS		NC		SQ	
		2000	2018	2000	2018	2000	2018	2000	2018	2000	2018
NATECO											
GLOBAL	median	54.28	53.69	60.89	61.07	55.57	55.41	52.61	50.84	47.56	47.46
	mean	53.20	52.84	59.50	59.33	55.60	55.42	51.95	51.24	46.76	46.38
	s.d.	20.57	20.43	19.59	19.35	19.37	19.36	21.73	21.61	19.50	19.23
	obs.	595	595	146	146	139	139	143	143	167	167
AFRICA	median	70.96	70.27	75.70	74.88	72.89	73.86	68.95	69.35	61.52	61.32
	mean	63.03	62.93	69.40	69.21	67.13	67.34	60.66	60.48	56.00	55.80
	s.d.	19.20	19.16	17.55	17.01	15.67	16.12	20.19	20.25	20.19	20.04
	obs.	169	169	42	42	39	39	41	41	47	47
AMERICAS	median	71.60	69.71	74.45	76.18	75.95	74.89	71.68	70.87	62.34	62.43
	mean	66.38	65.56	69.31	69.18	70.56	69.86	66.92	65.16	59.94	59.29
	s.d.	16.86	16.95	18.91	18.83	13.57	13.11	18.24	19.01	14.75	14.55
	obs.	105	105	26	26	23	23	27	27	29	29
ASIA & PACIFIC	median	54.75	52.69	63.30	61.53	55.75	55.99	56.53	52.81	43.28	43.03
	mean	48.93	48.06	58.05	57.34	51.86	50.98	46.86	45.59	41.72	41.04
	s.d.	21.44	21.09	20.52	20.37	20.65	20.35	22.37	22.02	19.65	19.05
	obs.	138	138	31	31	31	31	34	34	42	42
EUROPE & C. ASIA	median	40.48	40.57	49.35	49.44	41.15	41.38	38.94	38.28	37.15	37.33
	mean	39.77	39.82	46.19	46.37	40.85	41.07	37.61	37.52	34.40	34.28
	s.d.	12.13	12.21	11.85	11.88	10.36	10.64	13.32	13.21	10.01	9.94
	obs.	183	183	47	47	46	46	41	41	49	49

		ALL		NN		NS		NC		SQ	
		2000	**2015**	**2000**	**2015**	**2000**	**2015**	**2000**	**2015**	**2000**	**2015**
POLLECO											
GLOBAL	median	0.77	0.75	0.90	0.89	0.77	0.77	0.76	0.74	0.61	0.56
	mean	0.75	0.71	0.85	0.83	0.78	0.76	0.75	0.71	0.63	0.57
	s.d.	0.20	0.23	0.16	0.18	0.20	0.22	0.19	0.22	0.18	0.22
	obs.	577	577	139	139	137	137	137	137	164	164
AFRICA	median	0.80	0.77	0.89	0.88	0.92	0.91	0.73	0.69	0.65	0.59
	mean	0.77	0.72	0.86	0.82	0.83	0.81	0.73	0.67	0.66	0.59
	s.d.	0.19	0.23	0.16	0.19	0.21	0.23	0.19	0.24	0.17	0.20
	obs.	165	165	41	41	38	38	40	40	46	46
AMERICAS	median	0.86	0.84	0.98	0.98	0.93	0.95	0.83	0.81	0.76	0.74
	mean	0.84	0.82	0.95	0.94	0.87	0.85	0.83	0.80	0.74	0.72
	s.d.	0.14	0.16	0.06	0.08	0.13	0.16	0.12	0.14	0.13	0.15
	obs.	96	96	22	22	22	22	24	24	28	28
ASIA & PACIFIC	median	0.71	0.67	0.85	0.84	0.73	0.68	0.75	0.68	0.53	0.47
	mean	0.68	0.63	0.82	0.80	0.71	0.68	0.68	0.64	0.55	0.47
	s.d.	0.24	0.27	0.17	0.19	0.27	0.28	0.23	0.25	0.20	0.25
	obs.	138	138	31	31	32	32	33	33	42	42
EUROPE & C. ASIA	median	0.74	0.71	0.89	0.85	0.72	0.69	0.76	0.76	0.58	0.53
	mean	0.74	0.71	0.82	0.80	0.75	0.73	0.77	0.76	0.61	0.55
	s.d.	0.17	0.20	0.16	0.17	0.14	0.16	0.17	0.19	0.16	0.18
	obs.	178	178	45	45	45	45	40	40	48	48

		ALL		NN		NS		NC		SQ	
		2000	**2015**	**2000**	**2015**	**2000**	**2015**	**2000**	**2015**	**2000**	**2015**
NITREECO											
GLOBAL	median	52.70	52.12	49.67	49.37	50.64	50.40	53.95	52.98	60.16	59.78
	mean	66.26	66.05	54.59	54.59	66.94	67.14	67.92	67.52	74.55	73.96
	s.d.	53.45	52.84	29.55	29.60	52.93	54.90	66.40	64.02	56.66	55.42
	obs.	568	568	141	141	132	132	134	134	161	161
AFRICA	median	48.35	48.00	48.05	48.00	46.33	46.29	47.88	47.99	49.70	49.18
	mean	51.20	51.07	48.85	48.69	54.09	54.08	47.60	47.40	54.06	53.91
	s.d.	22.06	22.13	16.56	16.62	27.62	28.00	22.30	22.26	20.98	20.79
	obs.	167	167	41	41	38	38	41	41	47	47
AMERICAS	median	50.19	50.08	47.42	48.90	46.24	46.95	52.72	52.43	62.09	59.61
	mean	53.01	52.40	50.61	50.48	47.37	47.33	52.09	51.34	60.70	59.31
	s.d.	15.90	14.76	18.14	18.01	8.37	7.81	12.86	12.01	18.50	16.16
	obs.	102	102	26	26	23	23	25	25	28	28
ASIA & PACIFIC	median	60.06	59.23	50.66	50.26	60.96	60.87	64.38	60.33	68.87	69.36
	mean	85.38	85.76	58.80	58.95	88.36	89.16	86.39	87.47	102.47	102.20
	s.d.	76.65	77.09	45.12	45.64	83.17	84.78	70.97	74.14	90.76	88.88
	obs.	128	128	30	30	28	28	30	30	40	40
EUROPE & C. ASIA	median	61.82	62.37	52.23	53.30	63.92	63.22	62.95	63.35	74.34	72.64
	mean	74.57	74.06	59.44	59.54	74.83	74.95	85.67	84.12	79.63	78.81
	s.d.	61.98	59.80	30.75	30.36	53.44	57.46	100.16	92.55	48.40	46.79
	obs.	171	171	44	44	43	43	38	38	46	46

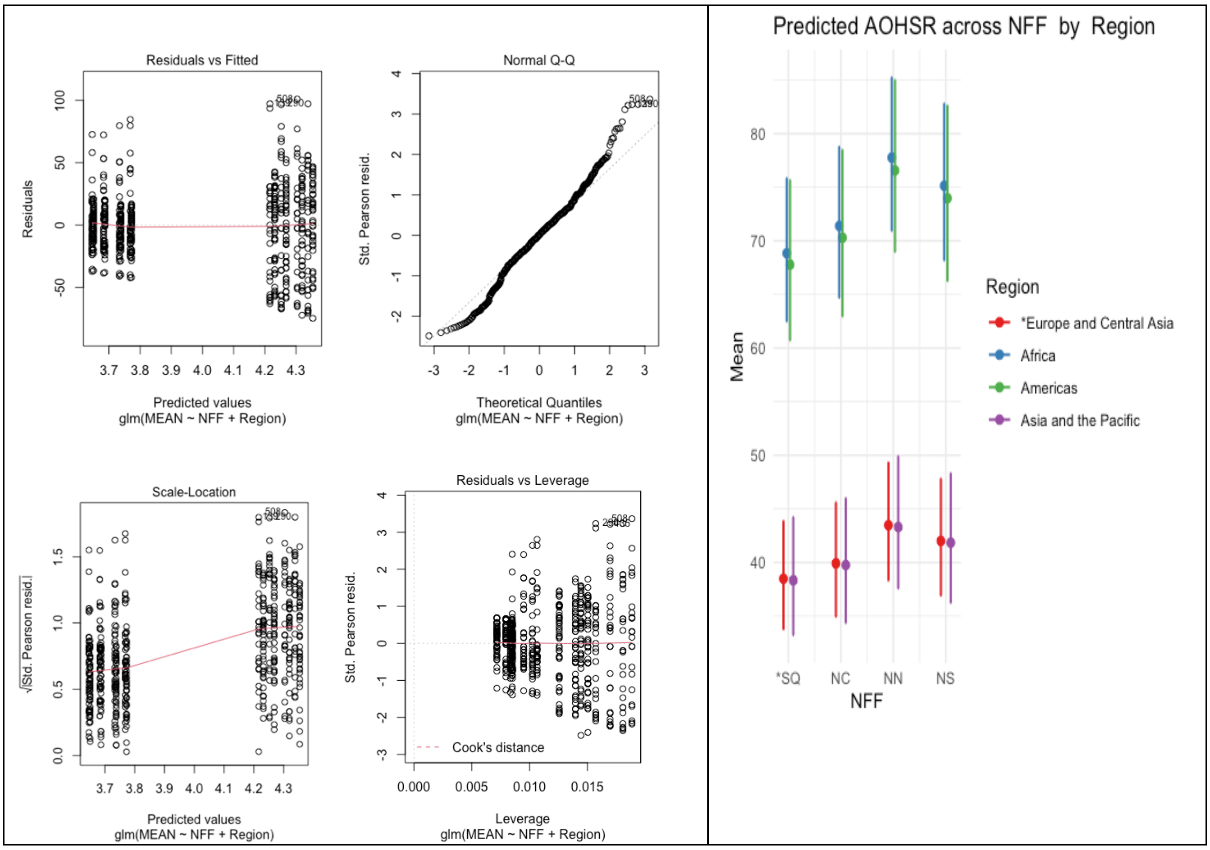
		ALL		NN		NS		NC		SQ	
		2000	**2015**	**2000**	**2015**	**2000**	**2015**	**2000**	**2015**	**2000**	**2015**
COASTECO											
GLOBAL	median	0.98	1.00	1.12	1.12	0.97	0.97	0.98	0.98	0.97	0.98
	mean	1.081	1.09	1.17	1.18	1.05	1.06	1.13	1.14	1.02	1.02
	s.d.	0.44	0.43	0.50	0.49	0.40	0.40	0.54	0.54	0.33	0.33
	obs.	348	348	73	73	76	76	74	74	125	125
AFRICA	median	0.87	0.88	0.92	0.92	0.76	0.77	0.98	0.95	0.89	0.89
	mean	0.96	0.96	1.06	1.07	0.79	0.80	1.10	1.11	0.91	0.91
	s.d.	0.44	0.45	0.65	0.66	0.32	0.32	0.58	0.58	0.27	0.28
	obs.	68	68	13	13	10	10	13	13	32	32
AMERICAS	median	1.08	1.08	1.12	1.12	1.08	1.09	1.07	1.07	1.08	1.08
	mean	1.08	1.08	1.09	1.09	1.05	1.06	1.08	1.08	1.08	1.09
	s.d.	0.26	0.26	0.27	0.27	0.23	0.23	0.32	0.32	0.23	0.23
	obs.	86	86	18	18	20	20	22	22	26	26
ASIA & THE PACIFIC	median	0.96	0.97	1.08	1.08	0.97	0.97	0.96	0.96	0.95	0.95
	mean	1.06	1.07	1.12	1.12	1.01	1.02	1.18	1.19	1.00	1.01
	s.d.	0.40	0.40	0.26	0.26	0.37	0.38	0.58	0.58	0.36	0.37
	obs.	95	95	20	20	20	20	19	19	36	36
EUROPE & C. ASIA	median	1.04	1.04	1.26	1.26	0.98	0.99	0.93	0.93	1.05	1.05
	mean	1.20	1.20	1.37	1.36	1.18	1.19	1.17	1.17	1.11	1.10
	s.d.	0.55	0.54	0.65	0.63	0.50	0.49	0.69	0.69	0.38	0.37
	obs.	99	99	22	22	26	26	20	20	31	31

Models S1. Generalized Linear Model on EBV Status in 2000

EBVt₀ ~ NFF + Region (reference group: NFF - SQ, Region – Europe & C. Asia)

Area or Habitat based Species Richness

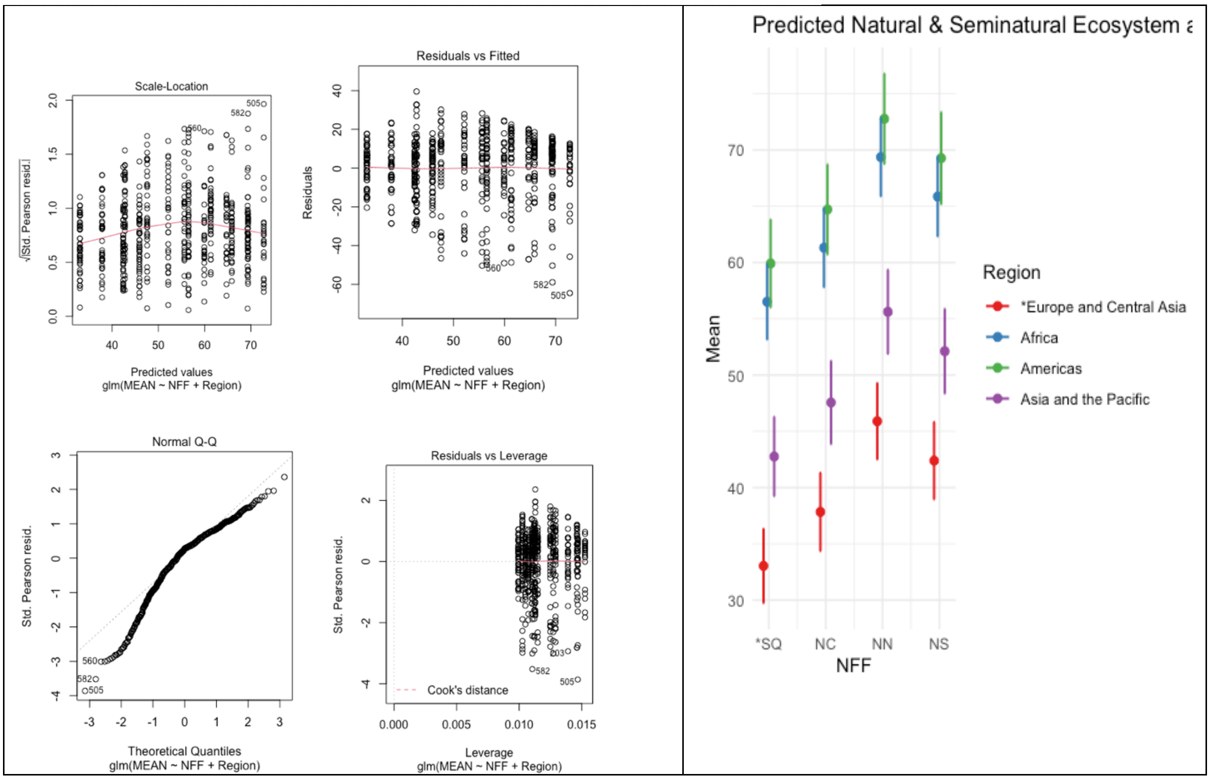
```
> glm_aohsr <- glm(MEAN ~ NFF +  Region, data = AOHSR_00, family = gaussian(link="log"))
> summary(glm_aohsr)

Call:
glm(formula = MEAN ~ NFF + Region, family = gaussian(link = "log"),
    data = AOHSR_00)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-74.775  -16.910    0.548   16.747  101.070

Coefficients:
                            Estimate Std. Error t value Pr(>|t|)
(Intercept)                 3.650383   0.066673  54.750  < 2e-16 ***
NFFNC                       0.036356   0.062201   0.584   0.5591
NFFNN                       0.121890   0.059419   2.051   0.0407 *
NFFNS                       0.087506   0.061534   1.422   0.1555
RegionAfrica                0.581448   0.063196   9.201  < 2e-16 ***
RegionAmericas              0.565925   0.068330   8.282  8.1e-16 ***
RegionAsia and the Pacific -0.003974   0.083379  -0.048   0.9620
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for gaussian family taken to be 918.6133)

    Null deviance: 697489  on 597  degrees of freedom
Residual deviance: 542899  on 591  degrees of freedom
AIC: 5786.1

Number of Fisher Scoring iterations: 6
```



```
> anova(glm_aohsr,test="F")
Analysis of Deviance Table

Model: gaussian, link: log

Response: MEAN

Terms added sequentially (first to last)


       Df Deviance Resid. Df Resid. Dev       F Pr(>F)
NULL                     597     697489
NFF     3     3514       594     693975  1.2751  0.282
Region  3   151076       591     542899 54.8201 <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
> anova(glm_aohsr,test="Chi")
Analysis of Deviance Table

Model: gaussian, link: log

Response: MEAN

Terms added sequentially (first to last)


       Df Deviance Resid. Df Resid. Dev Pr(>Chi)
NULL                     597     697489
NFF     3     3514       594     693975    0.281
Region  3   151076       591     542899   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> post.hoc_aohsr_nff <- glht(glm_aohsr, linfct = mcp(NFF = 'Tukey'))
> summary(post.hoc_aohsr_nff)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: glm(formula = MEAN ~ NFF + Region, family = gaussian(link = "log"),
    data = AOHSR_00)

Linear Hypotheses:
               Estimate Std. Error z value Pr(>|z|)
NC - *SQ == 0  0.03636    0.06220   0.584    0.937
NN - *SQ == 0  0.12189    0.05942   2.051    0.169
NS - *SQ == 0  0.08751    0.06153   1.422    0.485
NN - NC == 0   0.08553    0.06012   1.423    0.485
NS - NC == 0   0.05115    0.06224   0.822    0.844
NS - NN == 0  -0.03438    0.05944  -0.579    0.939
(Adjusted p values reported -- single-step method)
> post.hoc_aohsr_reg <- glht(glm_aohsr, linfct = mcp(Region = 'Tukey'))
> summary(post.hoc_aohsr_reg)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: glm(formula = MEAN ~ NFF + Region, family = gaussian(link = "log"),
    data = AOHSR_00)

Linear Hypotheses:
                                                     Estimate Std. Error z value Pr(>|z|)
Africa - *Europe and Central Asia == 0               0.581448   0.063196   9.201   <1e-05 ***
Americas - *Europe and Central Asia == 0             0.565925   0.068330   8.282   <1e-05 ***
Asia and the Pacific - *Europe and Central Asia == 0 -0.003974   0.083379  -0.048     1.00
Americas - Africa == 0                              -0.015522   0.051873  -0.299     0.99
Asia and the Pacific - Africa == 0                  -0.585422   0.070536  -8.300   <1e-05 ***
Asia and the Pacific - Americas == 0                -0.569900   0.075177  -7.581   <1e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)
```

Natural and Seminatural Ecosystem Extent

```
> summary(glm.nateco)

Call:
glm(formula = MEAN ~ NFF + Region, family = gaussian(link = "identity"),
    data = NATECO_00)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-64.548   -7.435    4.619   11.575   39.539

Coefficients:
                          Estimate Std. Error t value Pr(>|t|)
(Intercept)                 33.039      1.679  19.682  < 2e-16 ***
NFFNC                        4.799      1.919   2.501   0.0127 *
NFFNN                       12.858      1.909   6.735 3.91e-11 ***
NFFNS                        9.357      1.935   4.837 1.69e-06 ***
RegionAfrica                23.471      1.797  13.061  < 2e-16 ***
RegionAmericas              26.874      2.063  13.028  < 2e-16 ***
RegionAsia and the Pacific   9.721      1.900   5.115 4.24e-07 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for gaussian family taken to be 283.5877)

    Null deviance: 251329  on 594  degrees of freedom
Residual deviance: 166750  on 588  degrees of freedom
AIC: 5057.8

Number of Fisher Scoring iterations: 2
```



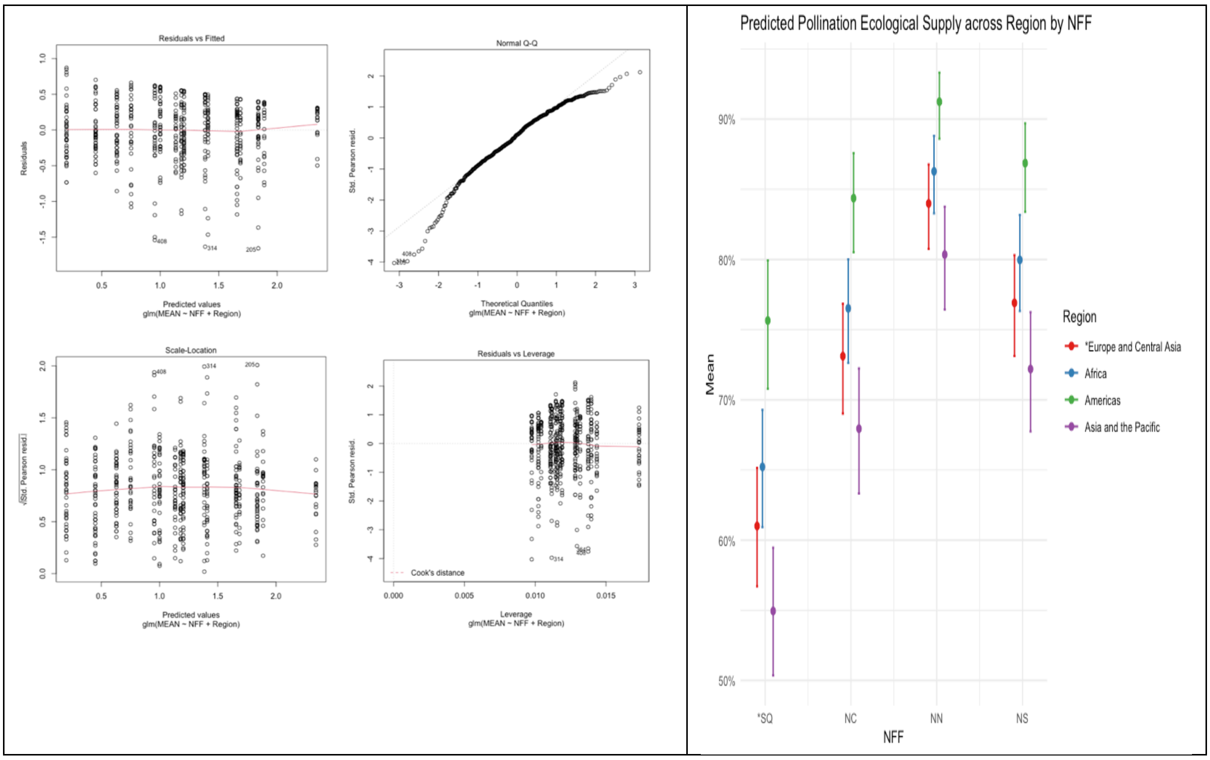
```
> anova(glm.nateco,test="F")
Analysis of Deviance Table

Model: gaussian, link: identity

Response: MEAN

Terms added sequentially (first to last)


       Df Deviance Resid. Df Resid. Dev      F    Pr(>F)
NULL                     594     251329
NFF     3    13747       591     237581 16.159 4.185e-10 ***
Region  3    70832       588     166750 83.257 < 2.2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
> anova(glm.nateco,test="Chi")
Analysis of Deviance Table

Model: gaussian, link: identity

Response: MEAN

Terms added sequentially (first to last)


       Df Deviance Resid. Df Resid. Dev  Pr(>Chi)
NULL                     594     251329
NFF     3    13747       591     237581 1.686e-10 ***
Region  3    70832       588     166750 < 2.2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
> post.hoc_nateco_reg <- glht(glm.nateco, linfct = mcp(Region = 'Tukey'))
> summary(post.hoc_nateco_reg)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: glm(formula = MEAN ~ NFF + Region, family = gaussian(link = "identity"),
    data = NATECO_00)

Linear Hypotheses:
                                                 Estimate Std. Error z value Pr(>|z|)
Africa - *Europe and Central Asia == 0             23.471      1.797  13.061   <1e-04 ***
Americas - *Europe and Central Asia == 0           26.874      2.063  13.028   <1e-04 ***
Asia and the Pacific - *Europe and Central Asia == 0  9.721    1.900   5.115   <1e-04 ***
Americas - Africa == 0                              3.403      2.093   1.626    0.362
Asia and the Pacific - Africa == 0                -13.750      1.933  -7.114   <1e-04 ***
Asia and the Pacific - Americas == 0              -17.153      2.181  -7.863   <1e-04 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)
```

```
> post.hoc_nateco_nff <- glht(glm.nateco, linfct = mcp(NFF = 'Tukey'))
> summary(post.hoc_nateco_nff)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: glm(formula = MEAN ~ NFF + Region, family = gaussian(link = "identity"),
    data = NATECO_00)

Linear Hypotheses:
              Estimate Std. Error z value Pr(>|z|)
NC - *SQ == 0    4.799      1.919   2.501   0.0594 .
NN - *SQ == 0   12.858      1.909   6.735   <0.001 ***
NS - *SQ == 0    9.357      1.935   4.837   <0.001 ***
NN - NC == 0     8.059      1.982   4.066   <0.001 ***
NS - NC == 0     4.558      2.007   2.271   0.1049
NS - NN == 0    -3.501      1.996  -1.754   0.2955
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Adjusted p values reported -- single-step method)
```

Ecological Supply of Pollination

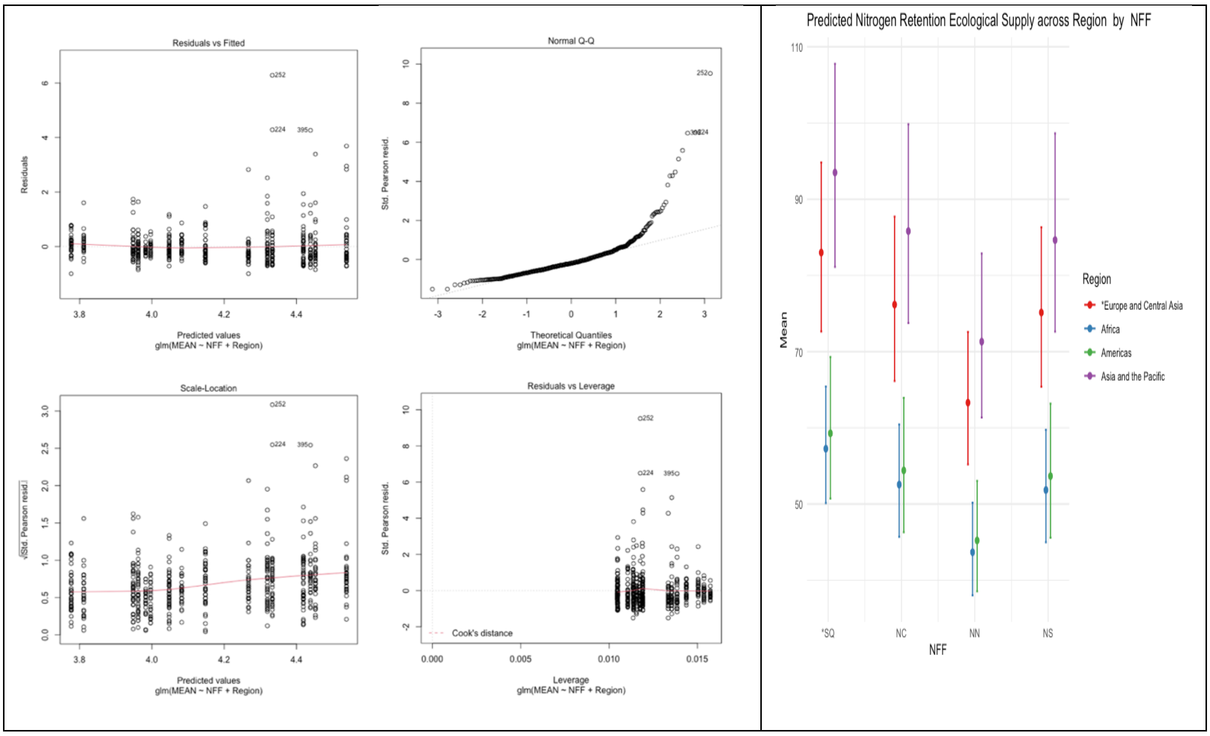
```
> glm.poll <- glm(MEAN ~ NFF + Region , data = POLLECO_00, family=quasibinomial(link="logit"))
> summary(glm.poll)

Call:
glm(formula = MEAN ~ NFF + Region, family = quasibinomial(link = "logit"),
    data = POLLECO_00)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.4913  -0.2308   0.0435   0.3386   1.0161

Coefficients:
                          Estimate Std. Error t value Pr(>|t|)
(Intercept)                0.44768    0.09067   4.938 1.04e-06 ***
NFFNC                      0.55249    0.10623   5.201 2.77e-07 ***
NFFNN                      1.20963    0.11963  10.112  < 2e-16 ***
NFFNS                      0.75542    0.10955   6.896 1.43e-11 ***
RegionAfrica               0.18110    0.10540   1.718   0.0863 .
RegionAmericas             0.68575    0.13685   5.011 7.24e-07 ***
RegionAsia and the Pacific -0.24898   0.10504  -2.370   0.0181 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for quasibinomial family taken to be 0.1706944)

    Null deviance: 132.89  on 576  degrees of freedom
Residual deviance: 103.80  on 570  degrees of freedom
AIC: NA

Number of Fisher Scoring iterations: 4
```



```
> anova(glm.nateco,test="F")
Analysis of Deviance Table

Model: quasipoisson, link: log

Response: MEAN

Terms added sequentially (first to last)


       Df Deviance Resid. Df Resid. Dev      F    Pr(>F)
NULL                     594     5374.1
NFF     3   259.76       591     5114.4 16.192 3.999e-10 ***
Region  3  1350.11       588     3764.2 84.158 < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> anova(glm.nateco,test="Chi")
Analysis of Deviance Table

Model: quasipoisson, link: log

Response: MEAN

Terms added sequentially (first to last)


       Df Deviance Resid. Df Resid. Dev  Pr(>Chi)
NULL                     594     5374.1
NFF     3   259.76       591     5114.4 1.605e-10 ***
Region  3  1350.11       588     3764.2 < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> post.hoc_polleco_nff <- glht(glm.poll, linfct = mcp(NFF = 'Tukey'))
> summary(post.hoc_polleco_nff)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: glm(formula = MEAN ~ NFF + Region, family = quasibinomial(link = "logit"),
    data = POLLECO_00)

Linear Hypotheses:
              Estimate Std. Error z value Pr(>|z|)
NC - *SQ == 0   0.5525     0.1062   5.201  < 0.001 ***
NN - *SQ == 0   1.2096     0.1196  10.112  < 0.001 ***
NS - *SQ == 0   0.7554     0.1096   6.896  < 0.001 ***
NN - NC == 0    0.6571     0.1283   5.123  < 0.001 ***
NS - NC == 0    0.2029     0.1189   1.706  0.31847
NS - NN == 0   -0.4542     0.1309  -3.469  0.00268 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- single-step method)

> post.hoc_polleco_reg <- glht(glm.poll, linfct = mcp(Region = 'Tukey'))
> summary(post.hoc_polleco_reg)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: glm(formula = MEAN ~ NFF + Region, family = quasibinomial(link = "logit"),
    data = POLLECO_00)

Linear Hypotheses:
                                                   Estimate Std. Error z value Pr(>|z|)
Africa - *Europe and Central Asia == 0               0.1811     0.1054   1.718  0.30998
Americas - *Europe and Central Asia == 0             0.6858     0.1368   5.011  < 0.001 ***
Asia and the Pacific - *Europe and Central Asia == 0 -0.2490     0.1050  -2.370  0.08116 .
Americas - Africa == 0                               0.5047     0.1398   3.609  0.00172 **
Asia and the Pacific - Africa == 0                  -0.4301     0.1090  -3.945  < 0.001 ***
Asia and the Pacific - Americas == 0                -0.9347     0.1396  -6.697  < 0.001 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- single-step method)
```

Ecological Supply of Nitrogen Retention

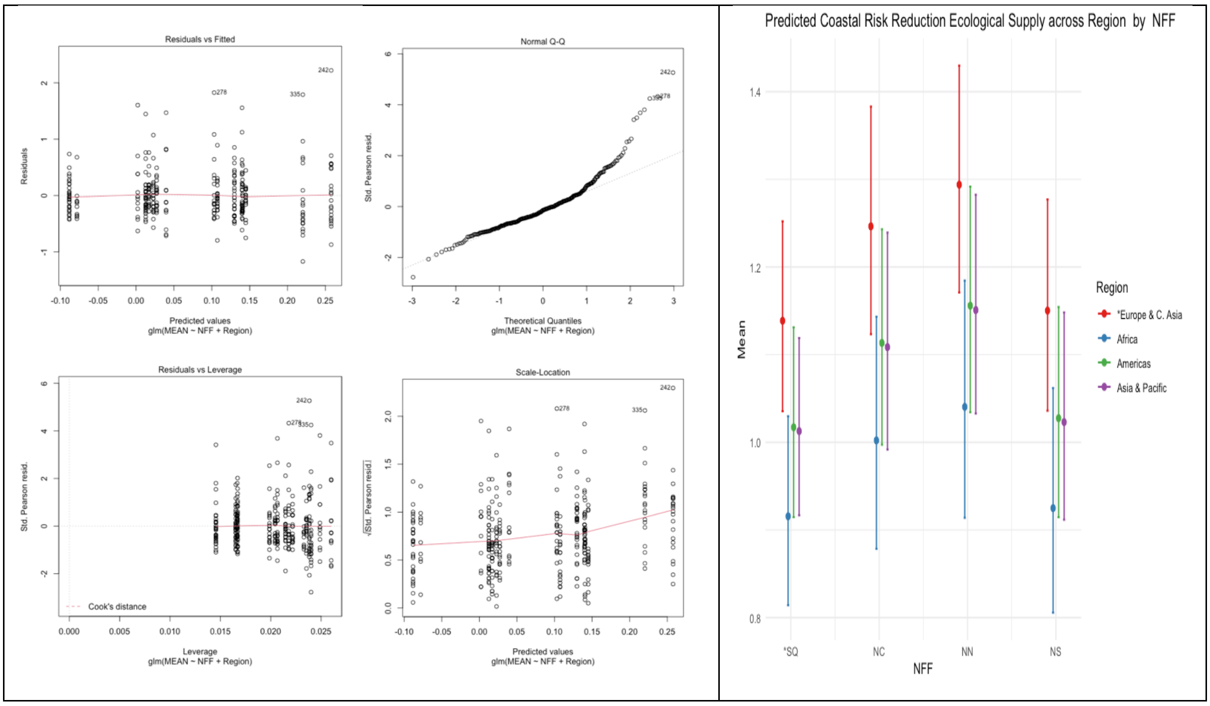
```
> glm.nitre <- glm(MEAN ~ NFF + Region , family = Gamma(link = "log"), data = NITREECO_00)
> summary(glm.nitre)

Call:
glm(formula = MEAN ~ NFF + Region, family = Gamma(link = "log"),
    data = NITREECO_00)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-3.6577  -0.4011  -0.1330   0.1464   2.9313

Coefficients:
                           Estimate Std. Error t value Pr(>|t|)
(Intercept)                 4.41884    0.06798  65.000  < 2e-16 ***
NFFNC                      -0.08580    0.07764  -1.105 0.269549
NFFNN                      -0.27090    0.07660  -3.537 0.000439 ***
NFFNS                      -0.09955    0.07799  -1.276 0.202312
RegionAfrica               -0.37113    0.07224  -5.137 3.85e-07 ***
RegionAmericas             -0.33648    0.08306  -4.051 5.82e-05 ***
RegionAsia and the Pacific  0.11917    0.07765   1.535 0.125408
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for Gamma family taken to be 0.4405529)

    Null deviance: 214.90  on 567  degrees of freedom
Residual deviance: 182.99  on 561  degrees of freedom
AIC: 5564

Number of Fisher Scoring iterations: 5
```



```
> anova(glm.nitre,test="Chi")
Analysis of Deviance Table

Model: Gamma, link: log

Response: MEAN

Terms added sequentially (first to last)


       Df Deviance Resid. Df Resid. Dev  Pr(>Chi)
NULL                     567     214.90
NFF     3   7.3854       564     207.51 0.0007903 ***
Region  3  24.5205       561     182.99 4.968e-12 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> anova(glm.nitre,test="F")
Analysis of Deviance Table

Model: Gamma, link: log

Response: MEAN

Terms added sequentially (first to last)


       Df Deviance Resid. Df Resid. Dev      F    Pr(>F)
NULL                     567     214.90
NFF     3   7.3854       564     207.51  5.588 0.0008815 ***
Region  3  24.5205       561     182.99 18.553 1.733e-11 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> post.hoc_nitreeco_nff <- glht(glm.nitre, linfct = mcp(NFF = 'Tukey'))
> summary(post.hoc_nitreeco_nff)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: glm(formula = MEAN ~ NFF + Region, family = Gamma(link = "log"),
    data = NITREECO_00)

Linear Hypotheses:
              Estimate Std. Error z value Pr(>|z|)
NC - *SQ == 0 -0.08580    0.07764  -1.105  0.68617
NN - *SQ == 0 -0.27090    0.07660  -3.537  0.00217 **
NS - *SQ == 0 -0.09955    0.07799  -1.276  0.57778
NN - NC == 0  -0.18510    0.08010  -2.311  0.09522 .
NS - NC == 0  -0.01375    0.08144  -0.169  0.99829
NS - NN == 0   0.17134    0.08039   2.131  0.14303
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- single-step method)

> post.hoc_nitreeco_reg <- glht(glm.nitre, linfct = mcp(Region = 'Tukey'))
> summary(post.hoc_nitreeco_reg)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: glm(formula = MEAN ~ NFF + Region, family = Gamma(link = "log"),
    data = NITREECO_00)

Linear Hypotheses:
                                                     Estimate Std. Error z value Pr(>|z|)
Africa - *Europe and Central Asia == 0               -0.37113    0.07224  -5.137  < 1e-04 ***
Americas - *Europe and Central Asia == 0             -0.33648    0.08306  -4.051 0.000294 ***
Asia and the Pacific - *Europe and Central Asia == 0  0.11917    0.07765   1.535 0.415242
Americas - Africa == 0                                0.03465    0.08341   0.415 0.975728
Asia and the Pacific - Africa == 0                    0.49030    0.07800   6.286  < 1e-04 ***
Asia and the Pacific - Americas == 0                  0.45565    0.08813   5.170  < 1e-04 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- single-step method)
```

Ecological Supply of Coastal Risk Reduction

```
> glm.coast <- glm(MEAN ~ NFF +  Region , data = COASTECO_00,  family = gaussian(link="log"))
> summary(glm.coast)

Call:
glm(formula = MEAN ~ NFF + Region, family = gaussian(link = "log"),
    data = COASTECO_00)

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-1.17054  -0.26269  -0.06015   0.14862   2.22059

Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)           0.12983    0.04846   2.679 0.007743 **
NFFNC                 0.09039    0.05784   1.563 0.119013
NFFNN                 0.12783    0.05665   2.257 0.024668 *
NFFNS                 0.01012    0.05990   0.169 0.865867
RegionAfrica         -0.21804    0.06520  -3.344 0.000917 ***
RegionAmericas       -0.11283    0.05588  -2.019 0.044248 *
RegionAsia & Pacific -0.11714    0.05460  -2.145 0.032635 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for gaussian family taken to be 0.1822555)

    Null deviance: 65.782  on 347  degrees of freedom
Residual deviance: 62.148  on 341  degrees of freedom
AIC: 404.09

Number of Fisher Scoring iterations: 5
```



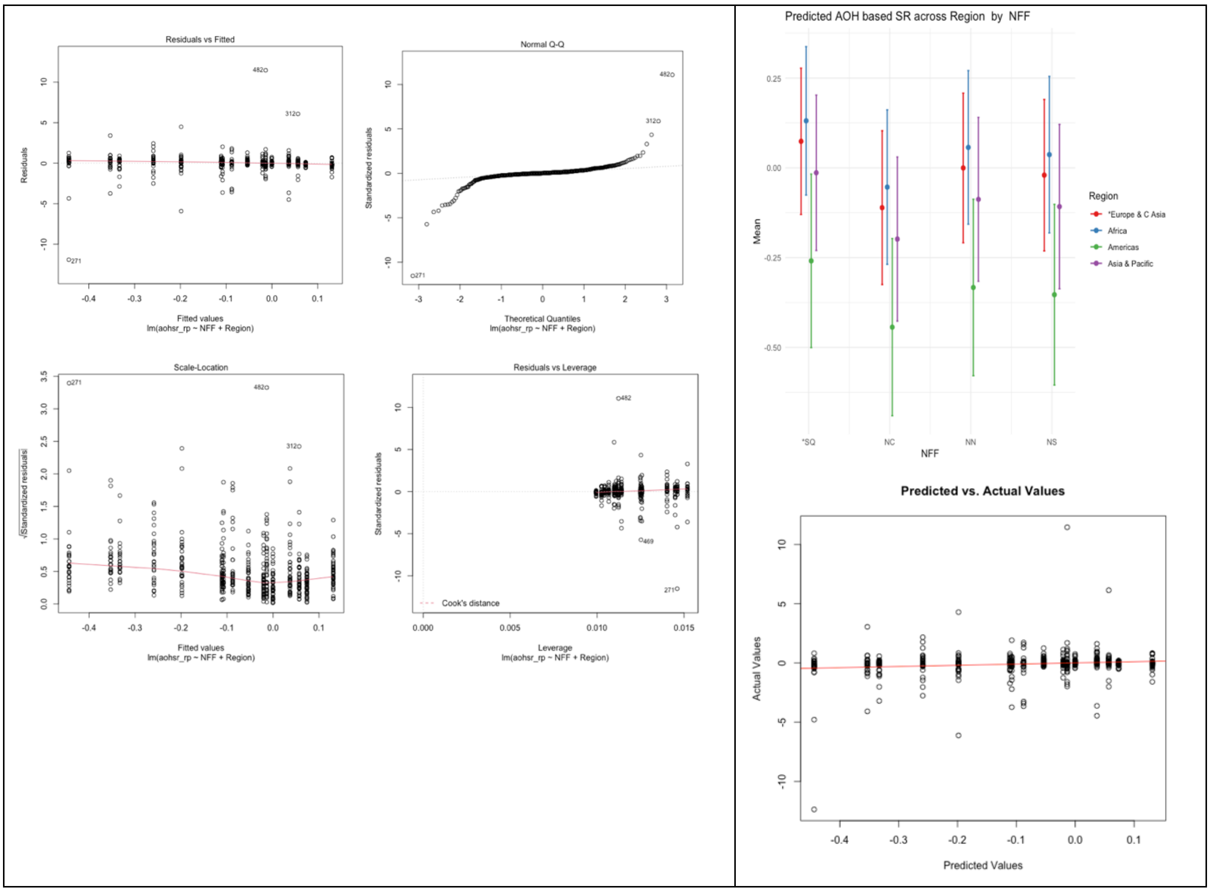
```
> dropterm(glm.coast, test = "F")
Single term deletions

Model:
MEAN ~ NFF + Region
       Df Deviance    AIC F value    Pr(F)
<none>      62.148 404.09
NFF     3   63.342 404.71  2.1847 0.089605 .
Region  3   64.445 410.72  4.2020 0.006141 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> dropterm(glm.coast, test = "Chi")
Single term deletions

Model:
MEAN ~ NFF + Region
       Df Deviance    AIC scaled dev.  Pr(Chi)
<none>      62.148 404.09
NFF     3   63.342 404.71      6.6252 0.084852 .
Region  3   64.445 410.72     12.6328 0.005502 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> post.hoc_coasteco_nff <- glht(glm.coast, linfct = mcp(NFF = 'Tukey'))
> summary(post.hoc_coasteco_nff)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: glm(formula = MEAN ~ NFF + Region, family = gaussian(link = "log"),
    data = COASTECO_00)

Linear Hypotheses:
              Estimate Std. Error z value Pr(>|z|)
NC - *SQ == 0  0.09039    0.05784   1.563    0.399
NN - *SQ == 0  0.12783    0.05665   2.257    0.108
NS - *SQ == 0  0.01012    0.05990   0.169    0.998
NN - NC == 0   0.03744    0.06105   0.613    0.928
NS - NC == 0  -0.08027    0.06389  -1.256    0.590
NS - NN == 0  -0.11771    0.06283  -1.873    0.239
(Adjusted p values reported -- single-step method)

> post.hoc_coasteco_reg <- glht(glm.coast, linfct = mcp(Region = 'Tukey'))
> summary(post.hoc_coasteco_reg)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: glm(formula = MEAN ~ NFF + Region, family = gaussian(link = "log"),
    data = COASTECO_00)

Linear Hypotheses:
                                         Estimate Std. Error z value Pr(>|z|)
Africa - *Europe & C. Asia == 0         -0.218036   0.065201  -3.344  0.00473 **
Americas - *Europe & C. Asia == 0       -0.112833   0.055880  -2.019  0.17895
Asia & Pacific - *Europe & C. Asia == 0 -0.117142   0.054604  -2.145  0.13748
Americas - Africa == 0                   0.105203   0.069335   1.517  0.42434
Asia & Pacific - Africa == 0             0.100895   0.068018   1.483  0.44487
Asia & Pacific - Americas == 0          -0.004308   0.059512  -0.072  0.99986
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- single-step method)
```

Models S2. Linear Model on EBV's Relative Change 2018-2000 (%)

$EBVt_1$ -t_0 (%) ~ NFF + Region (reference group: NFF – SQ, Region – Europe & C. Asia)

Area or Habitat based Species Richness

```
> lm.AOHSR_rp <- lm(aohsr_rp ~ NFF + Region, data = AOHSR_rp)
> summary(lm.AOHSR_rp)

Call:
lm(formula = aohsr_rp ~ NFF + Region, data = AOHSR_rp)

Residuals:
     Min       1Q   Median       3Q      Max 
-11.9191  -0.1426   0.0252   0.2083  11.4658 

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)   
(Intercept)          0.07372    0.10385   0.710  0.47808   
NFFNC               -0.18460    0.11886  -1.553  0.12094   
NFFNN               -0.07403    0.11780  -0.628  0.52998   
NFFNS               -0.09415    0.11931  -0.789  0.43037   
RegionAfrica         0.05726    0.11098   0.516  0.60607   
RegionAmericas      -0.33274    0.12757  -2.608  0.00933 **
RegionAsia & Pacific -0.08743    0.11700  -0.747  0.45521   
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.041 on 591 degrees of freedom
Multiple R-squared:  0.02087,	Adjusted R-squared:  0.01093 
F-statistic: 2.099 on 6 and 591 DF,  p-value: 0.05159
```

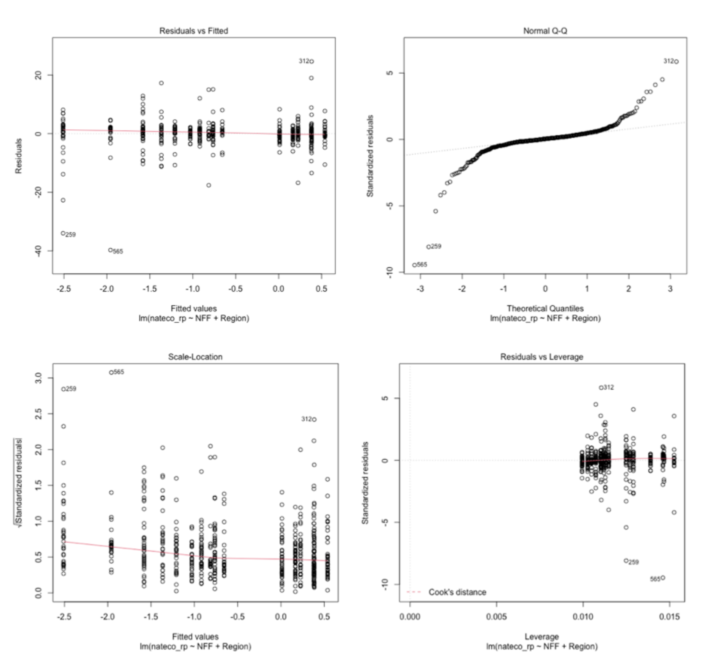


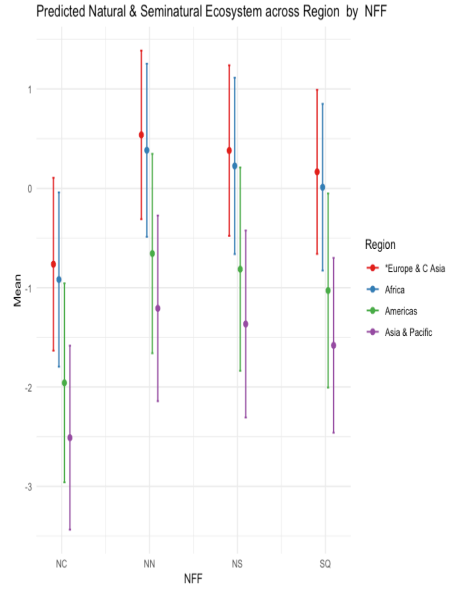
```
> dropterm(lm.AOHSR_rp, test="F")
Single term deletions

Model:
aohsr_rp ~ NFF + Region
       Df Sum of Sq    RSS    AIC F Value    Pr(F)
<none>              641.01 55.530
NFF     3    2.6461 643.65 51.994  0.8132 0.48684
Region  3   10.9042 651.91 59.617  3.3512 0.01876 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> dropterm(lm.AOHSR_rp, test="Chi")
Single term deletions

Model:
aohsr_rp ~ NFF + Region
       Df Sum of Sq    RSS    AIC   Pr(Chi)
<none>              641.01 55.530
NFF     3    2.6461 643.65 51.994 < 2.2e-16 ***
Region  3   10.9042 651.91 59.617 < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

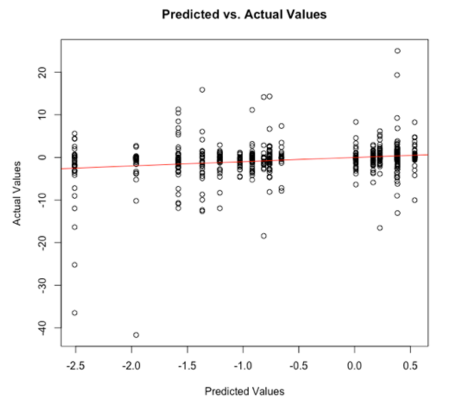
```
> post.hoc_aohsr_rp_nff <- glht(lm.AOHSR_rp, linfct = mcp(NFF = 'Tukey'))
> summary(post.hoc_aohsr_rp_nff)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lm(formula = aohsr_rp ~ NFF + Region, data = AOHSR_rp)

Linear Hypotheses:
              Estimate Std. Error t value Pr(>|t|)
NC - *SQ == 0 -0.18460    0.11886  -1.553    0.406
NN - *SQ == 0 -0.07403    0.11780  -0.628    0.923
NS - *SQ == 0 -0.09415    0.11931  -0.789    0.859
NN - NC == 0   0.11057    0.12215   0.905    0.802
NS - NC == 0   0.09045    0.12367   0.731    0.884
NS - NN == 0  -0.02012    0.12259  -0.164    0.998
(Adjusted p values reported -- single-step method)

> post.hoc_aohsr_rp_reg <- glht(lm.AOHSR_rp, linfct = mcp(Region = 'Tukey'))
> summary(post.hoc_aohsr_rp_reg)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lm(formula = aohsr_rp ~ NFF + Region, data = AOHSR_rp)

Linear Hypotheses:
                                    Estimate Std. Error t value Pr(>|t|)
Africa - *Europe & C Asia == 0        0.05726    0.11098   0.516   0.9550
Americas - *Europe & C Asia == 0     -0.33274    0.12757  -2.608   0.0455 *
Asia & Pacific - *Europe & C Asia == 0 -0.08743    0.11700  -0.747   0.8773
Americas - Africa == 0               -0.39000    0.12928  -3.017   0.0138 *
Asia & Pacific - Africa == 0         -0.14469    0.11889  -1.217   0.6150
Asia & Pacific - Americas == 0        0.24531    0.13452   1.824   0.2620
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- single-step method)
```

Natural and Seminatural Ecosystem Extent

```
> lm.NATECO_rp <- lm(nateco_rp ~ NFF + Region, data =NATECO_rp)
> summary(lm.NATECO_rp)

Call:
lm(formula = nateco_rp ~ NFF + Region, data = NATECO_rp)

Residuals:
    Min      1Q  Median      3Q     Max 
-39.708  -0.824   0.194   1.256  24.617 

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)    
(Intercept)           0.1656     0.4214   0.393 0.694444    
NFFNC                -0.9295     0.4818  -1.929 0.054175 .  
NFFNN                 0.3725     0.4793   0.777 0.437385    
NFFNS                 0.2148     0.4857   0.442 0.658414    
RegionAfrica         -0.1547     0.4512  -0.343 0.731740    
RegionAmericas       -1.1946     0.5179  -2.307 0.021420 *  
RegionAsia & Pacific -1.7465     0.4771  -3.661 0.000274 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 4.228 on 588 degrees of freedom
Multiple R-squared:  0.04315,	Adjusted R-squared:  0.03338 
F-statistic: 4.419 on 6 and 588 DF,  p-value: 0.0002206
```







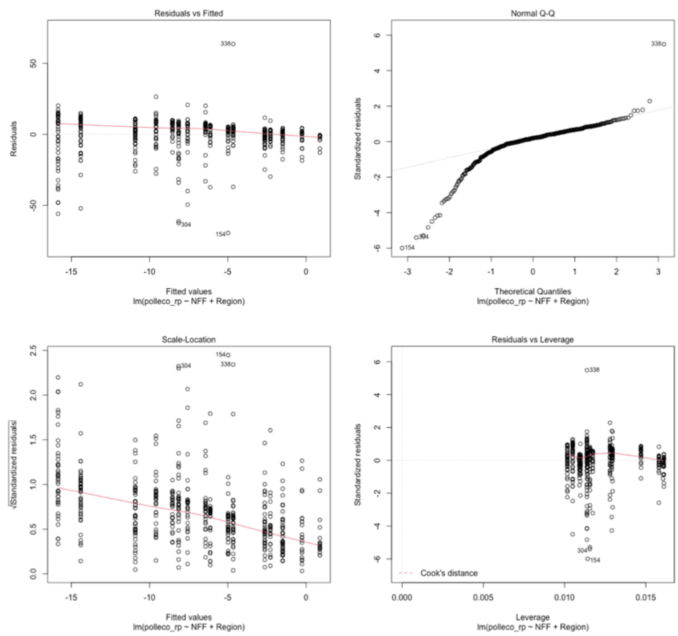
```
> dropterm(lm.NATECO_rp, test="F")
Single term deletions

Model:
nateco_rp ~ NFF + Region
       Df Sum of Sq   RSS    AIC F Value     Pr(F)
<none>              10510 1722.6
NFF     3    146.07 10656 1724.8   2.724 0.0435469 *
Region  3    315.25 10825 1734.2   5.879 0.0005869 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> dropterm(lm.NATECO_rp, test="Chi")
Single term deletions

Model:
nateco_rp ~ NFF + Region
       Df Sum of Sq   RSS    AIC   Pr(Chi)
<none>              10510 1722.6
NFF     3    146.07 10656 1724.8 < 2.2e-16 ***
Region  3    315.25 10825 1734.2 < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

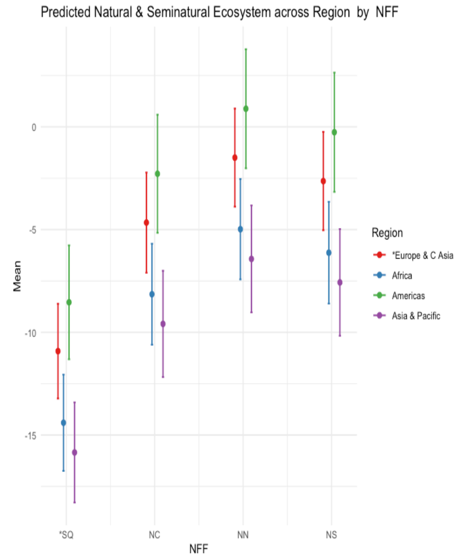
```
> post.hoc_nateco_rp_reg <- glht(lm.NATECO_rp, linfct = mcp(Region = 'Tukey'))
> summary(post.hoc_nateco_rp_reg)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lm(formula = nateco_rp ~ NFF + Region, data = NATECO_rp)

Linear Hypotheses:
                                      Estimate Std. Error t value Pr(>|t|)
Africa - *Europe & C Asia == 0         -0.1547     0.4512  -0.343  0.98604
Americas - *Europe & C Asia == 0       -1.1946     0.5179  -2.307  0.09722 .
Asia & Pacific - *Europe & C Asia == 0 -1.7465     0.4771  -3.661  0.00149 **
Americas - Africa == 0                 -1.0398     0.5254  -1.979  0.19593
Asia & Pacific - Africa == 0           -1.5917     0.4852  -3.280  0.00603 **
Asia & Pacific - Americas == 0         -0.5519     0.5477  -1.008  0.74394
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- single-step method)
```

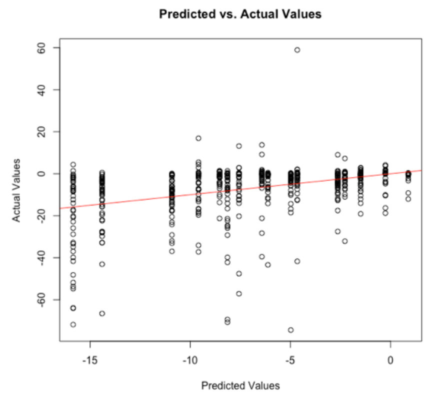
```
> post.hoc_nateco_rp_nff <- glht(lm.NATECO_rp, linfct = mcp(NFF = 'Tukey'))
> summary(post.hoc_nateco_rp_nff)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lm(formula = nateco_rp ~ NFF + Region, data = NATECO_rp)

Linear Hypotheses:
              Estimate Std. Error t value Pr(>|t|)
NC - *SQ == 0  -0.9295     0.4818  -1.929   0.2167
NN - *SQ == 0   0.3725     0.4793   0.777   0.8647
NS - *SQ == 0   0.2148     0.4857   0.442   0.9711
NN - NC == 0    1.3020     0.4976   2.616   0.0447 *
NS - NC == 0    1.1443     0.5039   2.271   0.1059
NS - NN == 0   -0.1577     0.5011  -0.315   0.9892
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- single-step method)
```

Ecological Supply of Pollination

```
> lm.POLLECO_rp <- lm(polleco_rp ~ NFF + Region, data = POLLECO_rp)
> summary(lm.POLLECO_rp)

Call:
lm(formula = polleco_rp ~ NFF + Region, data = POLLECO_rp)

Residuals:
    Min      1Q  Median      3Q     Max 
-69.464  -2.282   2.281   6.124  63.602 

Coefficients:
                     Estimate Std. Error t value Pr(>|t|)    
(Intercept)           -10.916      1.176  -9.281  < 2e-16 ***
NFFNC                   6.258      1.350   4.635 4.43e-06 ***
NFFNN                   9.421      1.346   7.002 7.13e-12 ***
NFFNS                   8.278      1.351   6.129 1.65e-09 ***
RegionAfrica           -3.486      1.261  -2.765 0.005882 ** 
RegionAmericas          2.378      1.478   1.609 0.108155    
RegionAsia & Pacific   -4.931      1.324  -3.725 0.000215 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 11.66 on 570 degrees of freedom
Multiple R-squared:  0.1383,	Adjusted R-squared:  0.1292 
F-statistic: 15.24 on 6 and 570 DF,  p-value: 3.138e-16
```



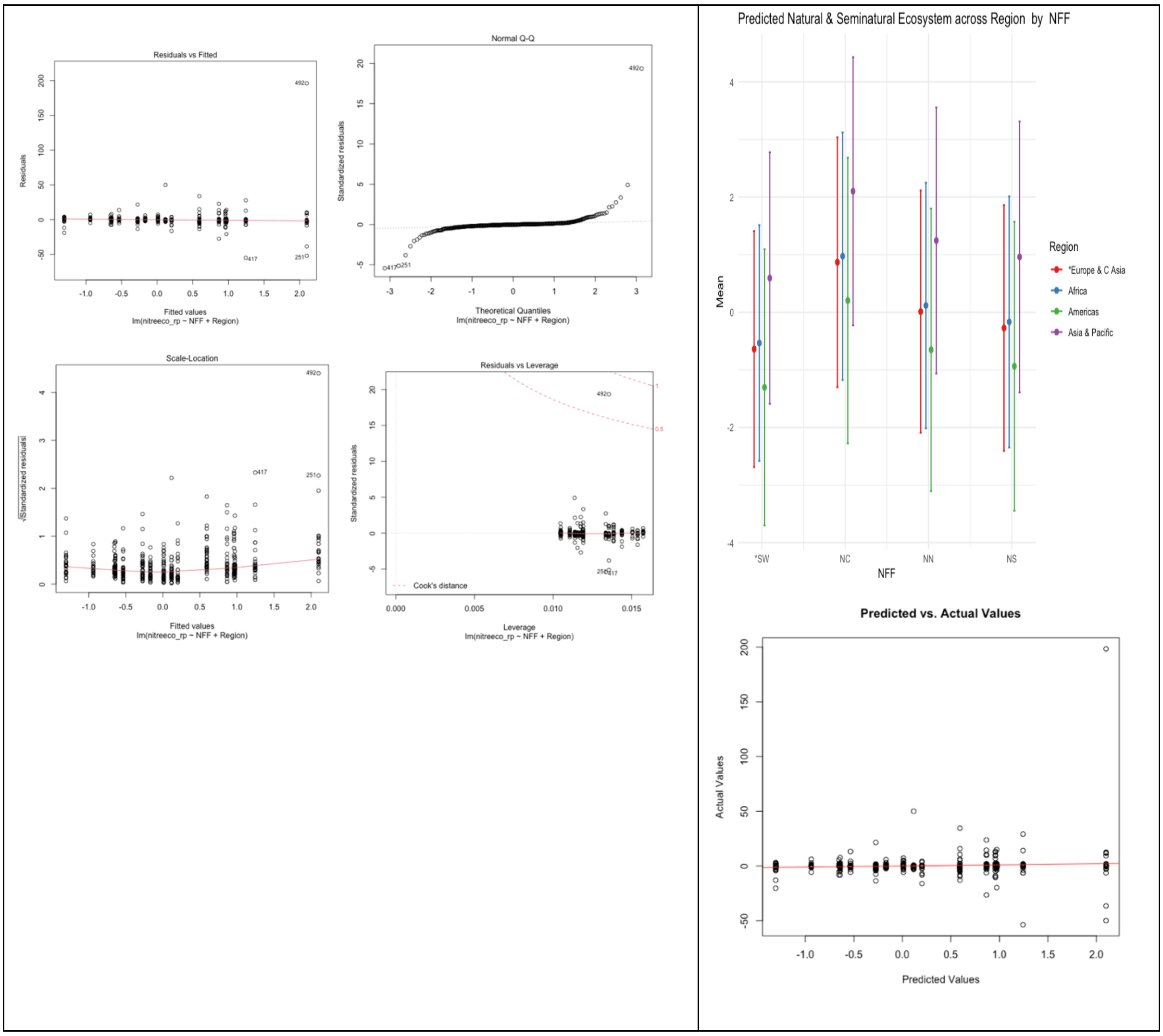




```
> dropterm(lm.POLLECO_rp, test="F")
Single term deletions

Model:
polleco_rp ~ NFF + Region
       Df Sum of Sq   RSS    AIC F Value     Pr(F)
<none>              77545 2841.7
NFF     3    8195.5 85740 2893.7  20.081 2.200e-12 ***
Region  3    4073.1 81618 2865.3   9.980 2.027e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> dropterm(lm.POLLECO_rp, test="Chi")
Single term deletions

Model:
polleco_rp ~ NFF + Region
       Df Sum of Sq   RSS    AIC  Pr(Chi)
<none>              77545 2841.7
NFF     3    8195.5 85740 2893.7 < 2.2e-16 ***
Region  3    4073.1 81618 2865.3 < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> post.hoc_polleco_rp_nff <- glht(lm.POLLECO_rp, linfct = mcp(NFF = 'Tukey'))
> summary(post.hoc_polleco_rp_nff)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lm(formula = polleco_rp ~ NFF + Region, data = POLLECO_rp)

Linear Hypotheses:
              Estimate Std. Error t value Pr(>|t|)
NC - *SQ == 0    6.258      1.350   4.635   <0.001 ***
NN - *SQ == 0    9.421      1.346   7.002   <0.001 ***
NS - *SQ == 0    8.278      1.351   6.129   <0.001 ***
NN - NC == 0     3.164      1.405   2.252    0.111
NS - NC == 0     2.020      1.410   1.433    0.479
NS - NN == 0    -1.143      1.404  -0.814    0.848
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- single-step method)

> post.hoc_polleco_reg <- glht(lm.POLLECO_rp, linfct = mcp(Region = 'Tukey'))
> summary(post.hoc_polleco_reg)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lm(formula = polleco_rp ~ NFF + Region, data = POLLECO_rp)

Linear Hypotheses:
                                      Estimate Std. Error t value Pr(>|t|)
Africa - *Europe & C Asia == 0          -3.486      1.261  -2.765  0.02962 *
Americas - *Europe & C Asia == 0         2.378      1.478   1.609  0.37262
Asia & Pacific - *Europe & C Asia == 0  -4.931      1.324  -3.725  0.00115 **
Americas - Africa == 0                   5.863      1.497   3.916  < 0.001 ***
Asia & Pacific - Africa == 0            -1.445      1.346  -1.074  0.70419
Asia & Pacific - Americas == 0          -7.309      1.550  -4.715  < 0.001 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- single-step method)
```

Ecological Supply of Nitrogen Retention

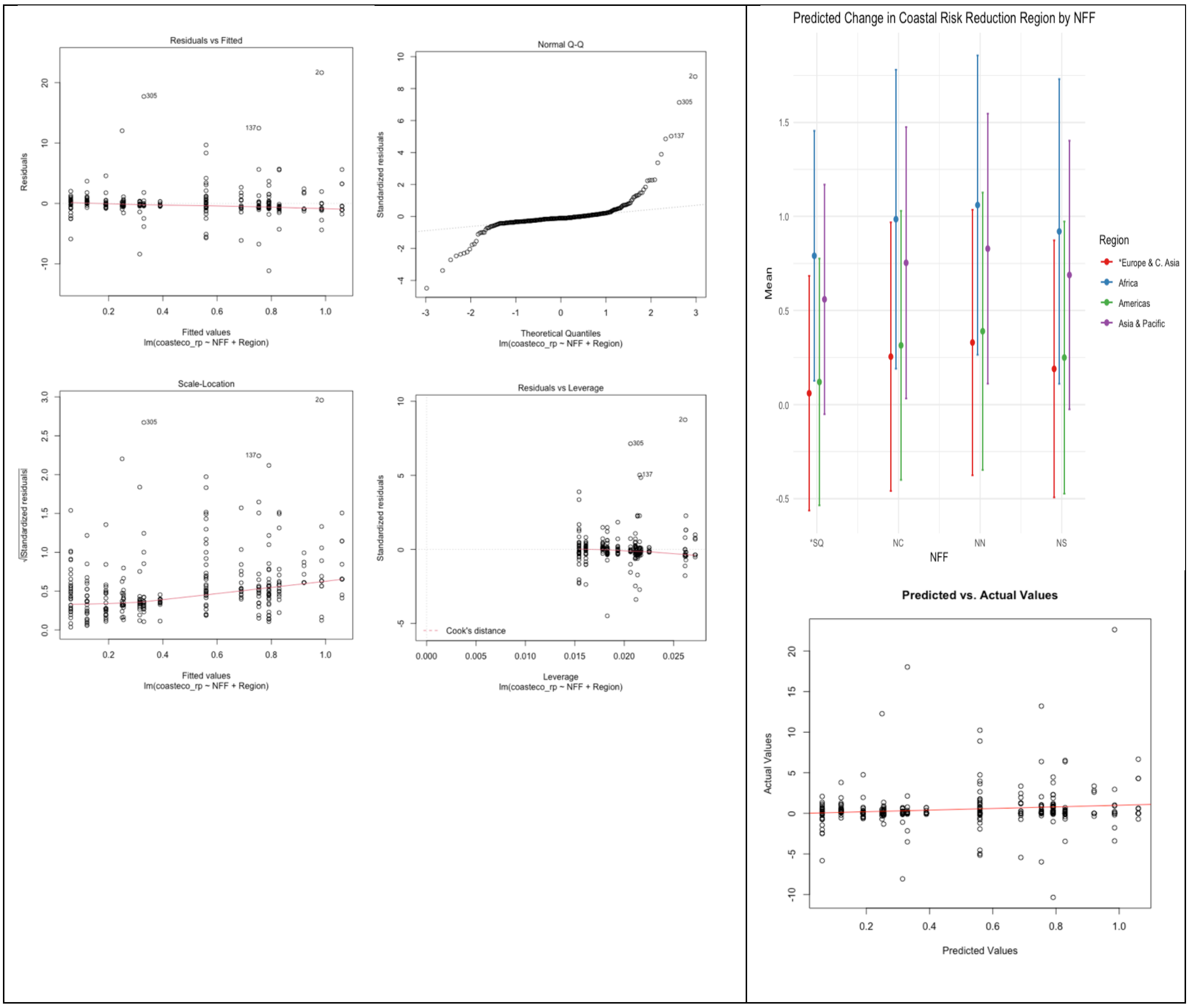
```
> lm.NITREECO_rp <- lm(nitreeco_rp ~ NFF + Region, data = NITREECO_rp)
> summary(lm.NITREECO_rp)

Call:
lm(formula = nitreeco_rp ~ NFF + Region, data = NITREECO_rp)

Residuals:
    Min      1Q  Median      3Q     Max
-54.981  -1.282  -0.153   0.643 196.193

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)         -0.6410     1.0452  -0.613    0.540
NFFNC                1.5076     1.1937   1.263    0.207
NFFNN                0.6518     1.1777   0.553    0.580
NFFNS                0.3669     1.1991   0.306    0.760
RegionAfrica         0.1056     1.1107   0.095    0.924
RegionAmericas      -0.6645     1.2771  -0.520    0.603
RegionAsia & Pacific 1.2337     1.1938   1.033    0.302

Residual standard error: 10.21 on 561 degrees of freedom
Multiple R-squared:  0.006635,	Adjusted R-squared:  -0.003989
F-statistic: 0.6245 on 6 and 561 DF,  p-value: 0.7107
```



```
> dropterm(lm.NITREECO_rp, test="F")
Single term deletions

Model:
nitreeco_rp ~ NFF + Region
       Df Sum of Sq   RSS    AIC F Value  Pr(F)
<none>              58425 2645.8
NFF     3    175.79 58601 2641.5 0.56265 0.6398
Region  3    221.02 58646 2641.9 0.70741 0.5479
> dropterm(lm.NITREECO_rp, test="Chi")
Single term deletions

Model:
nitreeco_rp ~ NFF + Region
       Df Sum of Sq   RSS    AIC   Pr(Chi)
<none>              58425 2645.8
NFF     3    175.79 58601 2641.5 < 2.2e-16 ***
Region  3    221.02 58646 2641.9 < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> post.hoc_nitreeco_rp_nff <- glht(lm.NITREECO_rp, linfct = mcp(NFF = 'Tukey'))
> summary(post.hoc_nitreeco_rp_nff)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lm(formula = nitreeco_rp ~ NFF + Region, data = NITREECO_rp)

Linear Hypotheses:
               Estimate Std. Error t value Pr(>|t|)
NC - *SW == 0    1.5076     1.1937   1.263    0.587
NN - *SW == 0    0.6518     1.1777   0.553    0.946
NS - *SW == 0    0.3669     1.1991   0.306    0.990
NN - NC == 0    -0.8557     1.2315  -0.695    0.899
NS - NC == 0    -1.1407     1.2521  -0.911    0.799
NS - NN == 0    -0.2850     1.2360  -0.231    0.996
(Adjusted p values reported -- single-step method)

> post.hoc_nitreeco_rp_reg <- glht(lm.NITREECO_rp, linfct = mcp(Region = 'Tukey'))
> summary(post.hoc_nitreeco_rp_reg)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lm(formula = nitreeco_rp ~ NFF + Region, data = NITREECO_rp)

Linear Hypotheses:
                                     Estimate Std. Error t value Pr(>|t|)
Africa - *Europe & C Asia == 0         0.1056     1.1107   0.095    1.000
Americas - *Europe & C Asia == 0      -0.6645     1.2771  -0.520    0.954
Asia & Pacific - *Europe & C Asia == 0  1.2337     1.1938   1.033    0.729
Americas - Africa == 0                -0.7702     1.2825  -0.601    0.932
Asia & Pacific - Africa == 0           1.1280     1.1992   0.941    0.782
Asia & Pacific - Americas == 0         1.8982     1.3550   1.401    0.498
(Adjusted p values reported -- single-step method)
```

Ecological Supply of Coastal Risk Reduction

```
> lm.COASTECO_rp <- lm(coasteco_rp ~ NFF + Region, data = COASTECO_rp)
> summary(lm.COASTECO_rp)

Call:
lm(formula = coasteco_rp ~ NFF + Region, data = COASTECO_rp)

Residuals:
     Min       1Q   Median       3Q      Max 
-11.1450  -0.6846  -0.2548   0.2047  21.6436 

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)  
(Intercept)         0.06044    0.31819   0.190   0.8495  
NFFNC               0.19437    0.36938   0.526   0.5991  
NFFNN               0.26946    0.37039   0.728   0.4674  
NFFNS               0.12951    0.36771   0.352   0.7249  
RegionAfrica        0.73047    0.39790   1.836   0.0673 .
RegionAmericas      0.05989    0.36992   0.162   0.8715  
RegionAsia & Pacific 0.49890   0.36061   1.383   0.1674  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2.506 on 341 degrees of freedom
Multiple R-squared:  0.01472,	Adjusted R-squared:  -0.002613 
F-statistic: 0.8493 on 6 and 341 DF,  p-value: 0.5326
```



```
> dropterm(lm.COASTECO_rp, test="Chi")
Single term deletions

Model:
coasteco_rp ~ NFF + Region
       Df Sum of Sq    RSS    AIC   Pr(Chi)
<none>              2142.1 646.43
NFF     3    3.7961 2145.9 641.05 < 2.2e-16 ***
Region  3   29.6747 2171.8 645.22 < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> dropterm(lm.COASTECO_rp, test="F")
Single term deletions

Model:
coasteco_rp ~ NFF + Region
       Df Sum of Sq    RSS    AIC F Value  Pr(F)
<none>              2142.1 646.43
NFF     3    3.7961 2145.9 641.05 0.20144 0.8954
Region  3   29.6747 2171.8 645.22 1.57464 0.1953
```

```
> post.hoc_COASTECO_rp_nff <- glht(lm.COASTECO_rp, linfct = mcp(NFF = 'Tukey'))
> summary(post.hoc_COASTECO_rp_nff)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lm(formula = coasteco_rp ~ NFF + Region, data = COASTECO_rp)

Linear Hypotheses:
              Estimate Std. Error t value Pr(>|t|)
NC - *SQ == 0  0.19437    0.36938   0.526    0.952
NN - *SQ == 0  0.26946    0.37039   0.728    0.886
NS - *SQ == 0  0.12951    0.36771   0.352    0.985
NN - NC == 0   0.07509    0.41378   0.181    0.998
NS - NC == 0  -0.06486    0.41005  -0.158    0.999
NS - NN == 0  -0.13995    0.41115  -0.340    0.986
(Adjusted p values reported -- single-step method)
```

```
> post.hoc_COASTECO_rp_reg <- glht(lm.COASTECO_rp, linfct = mcp(Region = 'Tukey'))
> summary(post.hoc_COASTECO_rp_reg)

         Simultaneous Tests for General Linear Hypotheses

Multiple Comparisons of Means: Tukey Contrasts


Fit: lm(formula = coasteco_rp ~ NFF + Region, data = COASTECO_rp)

Linear Hypotheses:
                                       Estimate Std. Error t value Pr(>|t|)
Africa - *Europe & C. Asia == 0         0.73047    0.39790   1.836    0.258
Americas - *Europe & C. Asia == 0       0.05989    0.36992   0.162    0.998
Asia & Pacific - *Europe & C. Asia == 0 0.49890    0.36061   1.383    0.510
Americas - Africa == 0                 -0.67058    0.40973  -1.637    0.359
Asia & Pacific - Africa == 0           -0.23157    0.39914  -0.580    0.938
Asia & Pacific - Americas == 0          0.43901    0.37387   1.174    0.643
(Adjusted p values reported -- single-step method)
```