PBL Netherlands Environmental Assessment Agency

GLOBIO MODEL DEVELOPMENT STRATEGY 2024-2027

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Summary

GLOBIO is a global biodiversity modelling framework designed to inform policy makers about responses of biodiversity and ecosystem services to potential future socio-economic development and policy pathways. The framework is developed and maintained by PBL Netherlands Environmental Assessment Agency. It consists of four components to quantify a set of complementary indicators of biodiversity and ecosystem services. GLOBIO and GLOBIO-Aquatic quantify impacts of human pressures on local biodiversity intactness in terrestrial and freshwater systems, respectively, using the mean species abundance (MSA) indicator. GLOBIO-Species quantifies the impacts of human pressures on the distribution and population size of individual (vertebrate) species and multi-species biodiversity indicators derived from those (e.g., Living Planet Index and Red List Index). The GLOBIO-ES model focuses on the quantification of ecosystem services (ES) - the contributions of ecosystems to human well-being – with a focus on regulating and maintenance services (e.g., pollination, climate regulation, soil retention).

This GLOBIO strategy document describes the **model development planned for 2024-2027**, providing a vision and general direction for the activities within the GLOBIO project. Based on a 'stock-take' of the current state of the model combined with an inventory of relevant policy developments, we identified two main needs for further model development:

1) To **broaden the indicator set** in the GLOBIO framework such that it is able to i) quantify progress towards recently agreed international nature/biodiversity policy targets (notably those of the Kunming-Montréal Global Biodiversity Framework), ii) capture the diverse relationships between nature and people and feedbacks from nature to society, iii) account for connections with other policy domains (e.g., climate change, food security), and iv) quantify the contributions of societal actors to biodiversity loss, conservation and restoration.
2) To **improve the representation of ecological responses** to (anthropogenic) environmental change, so as to allow for a credible assessment of the impacts of specific policy interventions on biodiversity and ecosystem services.

This strategy document provides an overview of the novel indicators to be developed and the model relationships to be added or refined, as well as initial ideas for the approach. It also provides a general direction for the implementation of this strategy. The specific activities will be prioritized, detailed and fine-tuned in annual and multi-year programmes and in line with internal or externally funded (future) projects.

1 Introduction

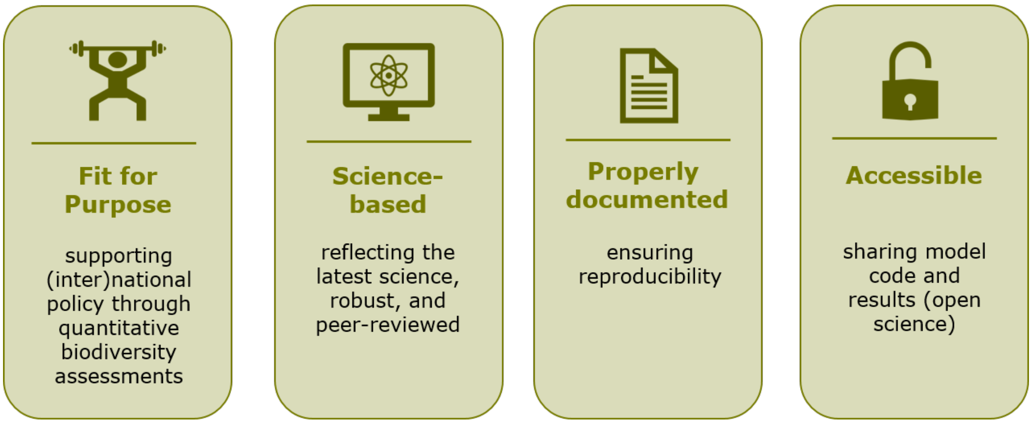
GLOBIO is a global biodiversity modelling framework designed to inform policy makers on responses of biodiversity and ecosystem services to potential future socio-economic development and policy pathways. The framework is developed and maintained by PBL Netherlands Environmental Assessment Agency. From 2002 onwards, the Dutch national government has been commissioning the development of GLOBIO in order to 1) strengthen the position of the Netherlands in negotiating international biodiversity targets by providing science-based information on the (possible future) global state of biodiversity; 2) quantify the impact of the Netherlands' economic development and policies on biodiversity globally; and 3) provide a relatively simple but credible tool for biodiversity assessments in data-poor, developing countries supported by development policies in the Netherlands. The development of GLOBIO has contributed to the position of the Netherlands in negotiation processes of the Convention on Biological Diversity (CBD) and the UN Convention on Combating Desertification (UNCCD).

GLOBIO is tightly connected to PBL's IMAGE model: a global integrated assessment model that simulates the environmental consequences of socio-economic development pathways and broad-scale policy measures (Stehfest et al., 2014; Van Vuuren, 2021). IMAGE projects the consequences of potential socio-economic development pathways for natural resources (energy, land, water), emissions of substances (greenhouse gasses, nutrients), and associated changes in the environment (e.g., climate change, eutrophication). The GLOBIO model then quantifies the responses of biodiversity and ecosystem services to these environmental changes. The IMAGE-GLOBIO framework is extensively used for (global) environmental assessments for policy support, for example the Global Biodiversity Outlooks of the CBD, the regional and global assessments of IPBES, the Global Environmental Outlooks of the UN Environment Programme (UNEP-GEO), and the UN Water Conference 2023. GLOBIO also supports Dutch national policy in its international context, for example by quantifying the biodiversity footprint of the Dutch economy (Wilting and van Oorschot, 2017). Further, GLOBIO is increasingly being adopted by external users (researchers, consultants), for example for evaluating biodiversity impacts of business and the financial sector.

PBL's GLOBIO project is in place to ensure that the GLOBIO modelling framework remains i) **fit for purpose** (i.e., for quantitative assessments supporting (inter)national biodiversity-relevant policy), ii) **science-based**, iii) **well-documented**, and iv) **accessible** to (internal and external) users (open science) (Figure 1.1). To accomplish this, the GLOBIO team revises and improves existing model components where needed, develops new model components in response to relevant developments in policy and science, and documents the improvements via model version control, manuals and technical descriptions, and the GLOBIO website. The model and its applications are also documented in scientific papers, not only as a means of dissemination but also to ensure transparency, scientific rigor and quality control (via the scientific peer-review process).

This GLOBIO strategy document describes the **model developments planned for 2024-2027**, providing a vision and direction for the research and development activities within the GLOBIO project. Hence, the focus of this document is on the first two overall goals of the project (Figure 1.1). The document first provides an overview of the current state of the GLOBIO modelling framework and of relevant policy developments, which both serve as a basis to identify priorities for model development (Chapter 2). These priorities are further elaborated in terms of proposed developments of the GLOBIO model components for biodiversity (Chapter 3) and ecosystem services (Chapter 4). The final chapter touches upon practical aspects related to organization and implementation as well as model quality aspects (Chapter 5).

Figure 1.1
Aims of the GLOBIO project.



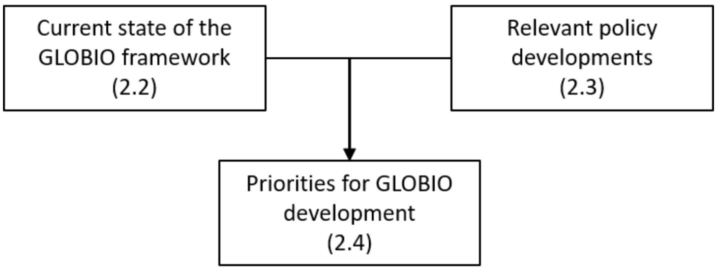
The GLOBIO project is in place to ensure that the GLOBIO model framework remains fit for purpose, science-based, properly documented and accessible.

2 Priorities for model development

2.1 Introduction

This chapter identifies priorities for further GLOBIO model development in view of two essential and complementary sets of considerations: the current state of the GLOBIO model as well as relevant recent policy developments. These form the basis for the direction of the model developments over 2024-2027 (Figure 2.1).

Figure 2.1
Identification of GLOBIO development priorities.



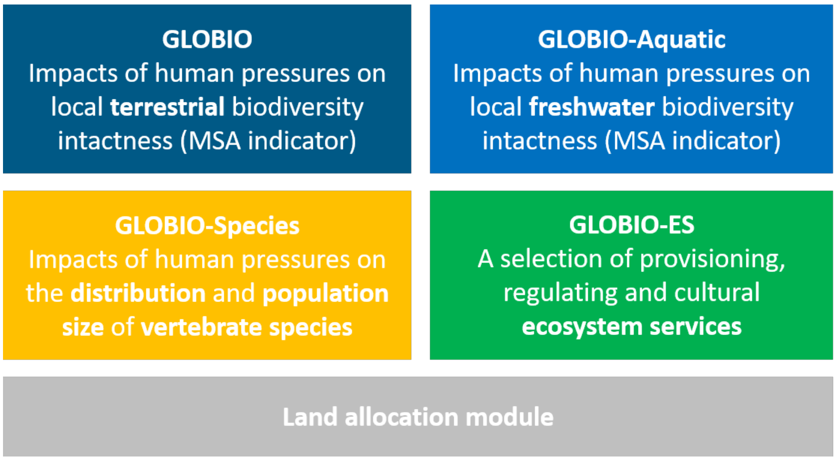
Identification of GLOBIO model developments priorities based on gaps in the current state of the model in combination with relevant policy developments. Numbers represent subsequent sections within this chapter.

2.2 Current state of GLOBIO

2.2.1 Overview

The GLOBIO modelling framework consists of four model components to quantify a set of complementary indicators of biodiversity and ecosystem services (Figure 2.2). Three model components focus on biodiversity (GLOBIO, GLOBIO-Aquatic and GLOBIO-Species). GLOBIO and GLOBIO-Aquatic quantify impacts of human pressures on local biodiversity intactness in terrestrial and freshwater systems, respectively, using the mean species abundance (MSA) indicator (Alkemade et al., 2009; Janse et al., 2015; Schipper et al., 2020). GLOBIO-Species quantifies the impacts of human pressures on the distribution and population size of individual (vertebrate) species, building upon the InSiGHTS model (a global habitat availability model for terrestrial vertebrate species) (Baisero et al., 2020; Visconti et al., 2016). Changes in distribution and population size are then aggregated across species to quantify multi-species biodiversity indicators indicative of extinction risk (Red List Index; RLI) or population abundance trends (Living Planet Index; LPI), or to identify 'hotspots' of threats to vertebrate biodiversity (Barbarossa et al., 2021; Gallego-Zamorano et al., 2020; Kok et al., 2023). Together, the assemblage-level indicator of local biodiversity intactness (MSA) and the two multi-species indicators covering trends in population size and extinction risk (LPI and RLI) cover three complementary aspects of biodiversity change relevant to global biodiversity and sustainable development targets (Mace et al., 2018). A fourth model component, the GLOBIO-ES model, focuses on the quantification of ecosystem services (ES), i.e., the contributions of ecosystems to human well-being (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005). Ecosystem services are modelled for freshwater systems, terrestrial non-urban systems, and urban systems (Kok et al., 2023; Veerkamp et al., 2020; Veerkamp et al., submitted). While GLOBIO-ES covers all three main ES categories as recognized by the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2018), it focuses mostly on regulating and maintenance services. In addition to the biodiversity and ES model components, the framework includes a module to allocate coarse-grain land-use data to a higher spatial resolution (currently 10 arc-seconds globally, but down to higher spatial resolutions for smaller regions (Rashidi et al., 2023)), in order to allow for more fine-grained assessments (Figure 2.2). Below we describe the model components in more detail for biodiversity (2.2.2) and ecosystem services (2.2.3), respectively.

Figure 2.2
GLOBIO modelling framework.



The GLOBIO modelling framework consists of four main components designed to provide complementary indicators of biodiversity and ecosystem services, supplemented with a module that allocates coarse-grain land use data to a higher spatial resolution.

2.2.2 Biodiversity

The biodiversity indicators in the GLOBIO framework (MSA, RLI, LPI) are modelled as a function of multiple human pressures on or changes in the state of the environment (Janse et al., 2015; Kok et al., 2023; Schipper et al., 2020). This multi-pressure perspective is one of the key assets of GLOBIO, setting it apart from other global biodiversity models, which typically focus on climate change and/or land use (Kim et al., 2018). Currently, the GLOBIO framework includes seven pressure or state variables (Table 2.1): climate change, eutrophication, habitat loss or change due to land use, habitat fragmentation, disturbance by roads, hydrological alteration (due to climate change and/or human infrastructure, notably dams) and direct exploitation (hunting). Impacts of these pressures or changes in state on biodiversity are quantified based on correlative (meta-analytical) models that express a change in MSA (in GLOBIO and GLOBIO-Aquatic) or in the distribution or abundance of individual vertebrate species (in GLOBIO-Species) as a function of the pressure or state variable of concern. In GLOBIO, the impact of the different pressures is quantified for plants and vertebrates separately, and then combined into one overall MSA value. GLOBIO-Species covers two major vertebrate species groups: terrestrial mammals and freshwater fishes.

Over the past years, the GLOBIO model (i.e., the component for terrestrial MSA) underwent a major update. Compared to the preceding version (GLOBIO3), the current version (GLOBIO4) runs at a higher spatial resolution and is based on a larger empirical database (Schipper et al., 2020). In particular, extensive additional data collection was performed for quantifying the impacts of climate change (Nuñez et al., 2019), eutrophication (Midolo et al., 2019), direct exploitation (hunting) (Benítez-López et al., 2017) and disturbance by roads (De Jonge et al., 2022). Only for the impacts of land use and habitat fragmentation, which were quantified based on the PREDICTS database (Hudson et al., 2017), the number of observations underlying the pressure-impact relationships remained relatively small, pointing at the need for additional data collection (Table 2.1). The latter is relevant in particular in order to be able to differentiate between land management strategies and intensities and to assess the biodiversity response to restoration efforts.

For GLOBIO-Aquatic and GLOBIO-Species, updates of the pressure-impact relationships remain to be done or finalized. GLOBIO-Aquatic was first established and published in 2015 (Janse et al., 2015) and underwent only minor updates since (Janse et al., 2023). Hence, the need remains for a thorough and systematic update of the model relationships through the collection of additional empirical data combined with a consistent meta-regression modelling approach, similar to the update done for GLOBIO. GLOBIO-Species was established more recently (Barbarossa et al., 2021; Barbarossa et al., 2020; Kok et al., 2023), and first scenario runs revealed the need for improvements of the first version. In particular, the climate change impact modules need to be refined in order to account for species' dispersal. Further, for terrestrial species, the land use module needs to be improved such that it can account for differences in responses of species to different land management practices and use intensity. For freshwater fishes, the impact modules for climate change and hydrological alteration on the one hand and habitat fragmentation on the other need to be harmonized and integrated, as they are currently based on different indicators (distribution and connectivity, respectively) (Barbarossa et al., 2021; Barbarossa et al., 2020).

Table 2.1
Pressure-impact relationships in GLOBIO.

Pressure/State	**GLOBIO**	**GLOBIO-Aquatic**	**GLOBIO-Species** Mammals	**GLOBIO-Species** Freshwater fishes
Climate change	+/-	+/-	+/-	+/-
Eutrophication	+	+/-	NA	-
Land use	+/-	+/- [a]	+/-	NA
Habitat fragmentation	+/-	-	+	+/-
Road disturbance	+	NA	+	NA
Hydrological alteration	NA	+/-	NA	+/-
Direct exploitation	+	-	+	-
Mining	+/-	-	-	-
Invasive species	-	-	-	-
Pollution	-	-	-	-

Coverage of pressures by GLOBIO, GLOBIO-Aquatic and GLOBIO-Species. Pressure-impact relationships are classified as relatively well-defined (+), in need of (further) improvement (+/-), not yet included (-) or not applicable (NA).
a) In GLOBIO-Aquatic, land use in the upstream catchment is used as a proxy of eutrophication.

2.2.3 Ecosystem services

GLOBIO-ES includes a number of ecosystem services (ES) for terrestrial, freshwater and urban ecosystems (Table 2.2, 2.3, 2.4). For terrestrial and freshwater ES, two components are modelled: i) the production function component, which informs on the potential of the ecosystem to provide a service, and ii) the service component, which accounts for the demand for, or actual use of, a certain ES. For urban ES, three components are modelled: the ES supply (i.e. capacity or potential of an ecosystem to provide a service, similar to 'function'), the societal demand (i.e. society's needs or desire for ES), and the benefit (i.e., the actual use of a service, where supply meets demand).

For some of the terrestrial and freshwater ecosystem services, GLOBIO-ES is tightly linked to or building on outputs of IMAGE and models integrated in or connected to the IMAGE framework, such as the Global Nutrient Model (GNM), PCR-GLOBWB and LPJmL (Beusen et al., 2015; Schaphoff et al., 2018; Stehfest et al., 2014; Sutanudjaja et al., 2018). For example, the crop and grass provision production functions and the carbon sequestration function of terrestrial ecosystems are directly obtained from IMAGE. Similarly, nutrient removal is directly obtained from GNM and water provision directly from LPJmL (Table 2.2, 2.3). Other ES, such as pollination, pest control and the urban ES, are relatively independent of IMAGE. These different levels of dependency come with trade-offs. A strong linkage with or dependence on IMAGE or other models ensures consistency in scenario analyses, yet it also makes the modelling workflow more complex, requiring additional modelling capacity. The stand-alone modules within GLOBIO-ES allow for more flexibility in input data sources and resolution, yet make coupled IMAGE-GLOBIO scenario runs more challenging. Ideally, the GLOBIO-ES models are soft-coupled to IMAGE, facilitating streamlined joint scenario analyses, while also facilitating stand-alone applications.

Overall, the provisioning and regulating and maintenance services are better represented than cultural services, pointing at a need for further development of the cultural ES components, particularly in view of the increasing attention for the relational values of nature (Pascual et al., 2017). Nevertheless, gaps remain also in the provisioning and regulating services. For example, flood protection is currently considered only in urban systems, while air quality regulation is completely missing (Table 2.3). In addition to gaps in the representation of ES, we also note that the majority of the modules is based on relatively limited or old empirical data. For instance, the relationship between crop yield and pollinator abundance, which is the core of the pollination model, is based on data from a single study (Morandin and Winston, 2006). Finally, we note that IMAGE-GLOBIO scenarios typically consider impacts on biodiversity and changes in ecosystem services as final output indicators, without considering possible societal consequences of biodiversity and ES loss (feedbacks). For example, a reduction in pollination service has consequences for agricultural yield and therefore the prices of agricultural products and land demand, yet these consequences are not (yet) considered within the representation of the agricultural sector within the IMAGE model.

Table 2.2
Overview of provisioning ecosystem service output indicators from GLOBIO-ES and connected models. T = terrestrial, F = freshwater.

Ecosystem service	System	Component	Indicator	Unit	Model
Crop provision	T	Function	Potential crop yield	Mg; kcal	IMAGE
Crop provision	T	Service	Actual crop yield	Mg; kcal	IMAGE
Grass provision	T	Function	Potential grass yield	Mg	IMAGE
Grass provision	T	Service	Actual grass yield	Mg	IMAGE
Wild food provision[a]	T	Function	Available wild food	kg; kcal	GLOBIO-ES
Wild food provision[a]	T	Service	Accessible wild food	kg; kcal	GLOBIO-ES
Water provision	F	Function	Available water	m^3/month	LPJ-mL
Water provision	F	Service	Relief from water stress	%	LPJmL, GLOBIO-Aquatic

a) Wild food provision can also be considered as a cultural ES.

Table 2.3
Overview of regulating and maintenance ecosystem service output indicators from GLOBIO-ES and connected models. T = terrestrial, F = freshwater, U = urban.

Ecosystem service	System	Component	Indicator	Unit	Model
Pest control	T	Function	Natural habitat surrounding cropland	%	GLOBIO-ES

Ecosystem service	System	Component	Indicator	Unit	Model
		Service	Cropland area protected from pests	%	GLOBIO-ES
Pollination	T	Function	Natural habitat surrounding cropland	%	GLOBIO-ES
		Service	Pollinator-dependent part of the crop yield	%	GLOBIO-ES
Soil retention	T	Function	Erosion reduction by natural habitat	%	IMAGE
		Service	Cultivated land protected from erosion	%	GLOBIO-ES
Global climate regulation	T	Function	Carbon sequestration	tons C/km²/year	IMAGE
		Service	Anthropogenic CO_2 emissions captured by ecosystems	%	GLOBIO-ES
	F	Function	Macrophyte net productivity	kg/year	GLOBO-Aquatic
	U	Supply	Carbon sequestration by (urban) trees	tons C/year	GLOBIO-ES
		Demand	Anthropogenic CO_2 emissions (from the city)	tons C/year	-
		Benefit	Climate change mitigation	%	GLOBIO-ES
Water purification	F	Function	Annual N and P retention	%	GNM
		Service	Water bodies meeting N and P standards	%	GLOBIO-Aquatic
		Service	Proportion of healthy lakes (cyanobacteria < WHO standards)	%	GLOBIO-Aquatic, PCLake[+]
Flood protection	U	Supply	Runoff retained by vegetation	mm	InVEST[a]
		Demand	Rainfall	mm	-
		Benefit	Flood risk reduction	%	GLOBIO-ES
Local temperature regulation	U	Supply	Heat mitigation by vegetation	°C	InVEST[a] + GLOBIO-ES
		Demand	Temperature above threshold	°C	GLOBIO-ES
		Benefit	Heat stress reduction	%	GLOBIO-ES

a) InVEST is an open-source ES modelling suite; where useful components from InVEST have been integrated in GLOBIO-ES.

Table 2.4
Overview of cultural ecosystem service output indicators from GLOBIO-ES and connected models. T = terrestrial, F = freshwater, U = urban.

Ecosystem service	System	Component	Indicator	Unit	Model
Nature-based recreation	F	Service	Proportion of healthy lakes (cyanobacteria < WHO standards)	%	GLOBIO-Aquatic, PCLake+
Interaction with nature	U	Supply	Presence of (large) urban green space	0/1	GLOBIO-ES
		Demand	Proximity of (large) urban green space	m	GLOBIO-ES
		Benefit	Population living within proximity of (large) urban green space	%	GLOBIO-ES

2.3 Relevant policy developments

Nature and biodiversity are gaining attention within global, European and national policies. It is increasingly recognized that anthropogenic threats to biodiversity have intensified over the past decades and that the loss and degradation of nature may ultimately jeopardize humanity (IPBES, 2019). At the same time, there is an increasing recognition of the importance of nature conservation or restoration as a strategy to tackle various societal challenges, such as climate change and the deterioration of public health (Seddon et al., 2020). In line with this, three important trends can be observed that have implications for GLOBIO development.

First, **more ambitious targets** for nature conservation and restoration are being formulated. Important international nature policy developments are the Kunming-Montréal Global Biodiversity Framework (GBF; Table 2.3), the UN Decade on Restoration (2021-2030), and the European Green Deal (including the EU Biodiversity Strategy and the recently provisionally adopted EU Nature Restoration Law). These different frameworks and agreements call for a move from halting the loss of biodiversity towards restoring nature and putting it on a path to recovery. Specifically in the CBD-context, an important new development is the focus on transparency and accountability: will commitments by countries and non-state actors realize the goals and targets agreed upon – and at the required speed? There will be an increasing need for *ex ante* policy evaluation scenarios that explore the extent to which commitments of countries and non-state actors will contribute to realizing the GBF targets.

Second, the **connections between nature and other policy domains** are increasingly recognized, as highlighted by for example the UN Sustainable Development Goals (SDGs) and the European Green Deal, which placed nature at the centre of the EU's sustainability policies (see e.g., the Farm to Fork Strategy, the Strategy on Adaptation to Climate Change, and the Circular Economic Action Plan). In a similar way, the IPBES/IPCC joint workshop report (Pörtner et al., 2021) and the clause on protecting, conserving and restoring nature as a means to mitigate climate change in the Sharm el-Sheikh implementation plan (COP-27) highlight the increasing recognition of the connections between climate and biodiversity policies.

Third, there is an increasing attention for the diversity of values underpinning **human-nature relationships**. The global discourse on the pluralistic perspective on biodiversity has been especially brought forward by the IPBES, which is elaborating a framework for scenario-based assessments that explicitly account for the multiple values of nature and the way we understand human-nature relationships (Nature Futures Framework, NFF) (Pereira et al., 2020). Traditionally, biodiversity scenario analyses put strong emphasis on the dichotomy between the intrinsic values of nature (e.g., through the mapping of threatened species or habitats; 'nature for nature' perspective) and the instrumental values of nature (e.g., through the mapping of ecosystem services; 'nature for people' perspective. However, future assessments need to recognize the larger diversity of values when evaluating (future) policy strategies, with attention also for the relational values, reflecting elements of cultural identity, social cohesion and moral responsibility towards nature ('nature as culture' perspective) (Pascual et al., 2017; Pereira et al., 2020).

Table 2.3
Headline indicators of the Kunming-Montréal Global Biodiversity Framework (CBD, 2022) and the ability or potential of the GLOBIO framework to model them. I = Included; P = potential to be included in or provided with the help of GLOBIO. An overview of all headline indicators (including those that cannot be modelled by GLOBIO) is provided in Appendix 1.

Goal/target	Indicator name	In GLOBIO?	Explanation/notes
Goal A	A.1 Red List of Ecosystems	P	Requires distribution models for ecosystem types
	A.2 Extent of natural ecosystems	I	Extent of MSA_{LU} = 1
	A.3 Red List Index	I [b]	GLOBIO-Species
	A.4 The proportion of populations within species with an effective population size > 500	P	Can be included based on GLOBIO-Species abundance estimates [b]
Goal B	B.1 Services provided by ecosystems [a]	I/P	GLOBIO-ES + IMAGE
Target 1	A.1 Red List of Ecosystems	P	Requires distribution models for ecosystem types
	A.2 Extent of natural ecosystems	I	Extent of MSA_{LU} = 1
	1.1 Percent of land and seas covered by biodiversity-inclusive spatial plans*	P	Requires definition + map of biodiversity-inclusive plans
Target 2	2.2 Area under restoration	P	Based on increases in indicator values over time
Target 3	3.1 Coverage of protected areas and OECMS	I	Based on protected areas and OECMs areas map
Target 4	A.3 Red List index	I	GLOBIO-Species
	A.4 The proportion of populations within species with a genetically effective population size > 500	P	Can be included based on GLOBIO-Species abundance estimates [b]
Target 5	5.1 Proportion of fish stocks within biologically sustainable levels	P	Freshwater fish; requires an abundance module + fishing pressure module in GLOBIO-Species
Target 6	6.1 Rate of invasive alien species establishment	P	Based on GLOBIO-Species habitat invasibility + potential IAS invasiveness

Goal/target	Indicator name	In GLOBIO?	Explanation/notes
Target 9	9.1 Benefits from the sustainable use of wild species	P	GLOBIO-ES (wild food provision module)
Target 11	11.1 Services provided by ecosystems [a]	I/P	GLOBIO-ES (+ IMAGE)
Target 15	15.1 Number of companies reporting on disclosures of risks, dependencies and impacts on biodiversity	P	Impacts can be disclosed via biodiversity impact factors obtained from GLOBIO outputs

a) An agreed up-to-date methodology does not exist (CBD, 2022). For the GBF, the following ES have been suggested as headline indicators (see https://www.post-2020indicators.org/metadata/headline/B-1): 1) Air filtration services; 2) Water regulation services; 3) Global climate regulation services; 4) Soil and sediment retention services; 5) Pollination services and 6) Mitigation services (number of properties and people with reduced risk of landslide/flood/storm).

b) Currently included only for terrestrial mammals.

2.4 Priorities for GLOBIO development

The ongoing decline of biodiversity combined with the increasing recognition of the importance of nature within the broader sustainability science-policy agenda requires GLOBIO to contribute to evaluating policy-supporting biodiversity scenarios that are i) **ambitious** (‘bending the curve’, transformative change (IPBES, 2019; Leclère et al., 2020)), ii) **comprehensive** (addressing the multiple values of nature as well as potential trade-offs and synergies with other sustainable development goals; nexus assessments), iii) **solution-oriented** (nature-based solutions), and iv) **actor-explicit** (analysing the possible contributions of for example specific sectors or countries to reaching biodiversity/nature targets as well as evaluating ambition and implementation gaps).

Enabling GLOBIO to contribute to the evaluation of such scenarios implies two main needs for further model development:

1) To **broaden the indicator set** in the GLOBIO framework such that it is able to i) quantify progress towards recently agreed international nature/biodiversity policy targets (notably those of the Kunming-Montréal Global Biodiversity Framework), ii) capture the diverse relationships between nature and people and feedbacks from nature to society, iii) account for connections with other policy domains (e.g., climate change, food security), and iv) quantify the contributions of societal actors to biodiversity loss, conservation and restoration.
2) To **improve the representation of ecological responses** to (anthropogenic) environmental change, so as to allow for a credible assessment of the impacts of specific policy interventions on biodiversity and ecosystem services.

In the next two chapters, these main needs are translated to specific objectives and priorities for the further development of the biodiversity and ecosystem services components of GLOBIO, respectively.

3 Biodiversity modelling

3.1 Objectives

For the biodiversity components of the GLOBIO framework (GLOBIO, GLOBIO-Aquatic and GLOBIO-Species), we identified the following specific objectives:

- To include additional policy-relevant biodiversity indicators, with a focus on indicators included in the Kunming-Montréal Global Biodiversity Framework (section 3.2).
- To obtain pressure-impact relationships for relevant pressures not yet included in GLOBIO and improve pressure-impact relationships where needed (section 3.3).
- To develop biodiversity impact factors that can be used to attribute losses or changes in biodiversity to specific societal actors (section 3.4).

3.2 Additional biodiversity indicators

3.2.1 Global extinction risks and rates

Currently, GLOBIO-Species generates the Red List Index (RLI) only for terrestrial mammals; we will implement the indicator also for freshwater fishes. If it turns out feasible to add abundance models for fishes, we will consider a combination of distribution and abundance; if not we will apply only Red List criteria for distribution. Next to RLI, we will implement two complementary indicators of global extinction. The reason for this is twofold: i) data on distribution and abundance, as required as input for species' Red List status, are virtually impossible to obtain (model) for non-vertebrate species (Moreira et al., 2023); ii) extinction risk estimates are highly uncertain and practically impossible to validate based on empirical data, calling for multi-modelling approaches.

For vertebrates, we will complement the RLI estimates with estimates of global extinction rate. To that end, we will estimate prospective ecoregion-level and global extinction rates (in extinctions per million species-years; E/MSY) due to the impacts of specific pressures based on the half-life of extinction, i.e. the time it takes to reach 50% of the expected species loss. The latter is estimated based on the average population size of species (Halley et al., 2016), as generated with GLOBIO-Species. To quantify global extinction risk for non-vertebrate species (notably plants), we will develop a new module (provisional name: GLOBIO-SAR) that integrates multi-pressure species-area relationship (SAR) models with endemism richness, following the approaches developed by Gallego-Zamorano et al. (2022) and Moreira et al. (2023). Specifically, we will establish a multi-pressure SAR model to quantify the combined threats of land use, nitrogen deposition and climate change to vascular plant diversity per ecoregion and then scale the regional extinction threats to global extinction threat using data on endemism richness.

3.2.2 Further species-based indicators

Next to the extinction rate and risk indicators, we will develop novel modules to obtain additional indicators from the outputs of the GLOBIO-Species model. Candidate indicators include the proportion of populations within species with an effective population size > 500 (GBF Target 4; Table 2.3) and the rate of invasive species establishment (GBF Target 6; Table 2.3). The proportion of species above the effective population size threshold can be obtained from the GLOBIO-Species outputs on abundance. For invasive species establishment, we will combine habitat suitability estimates for potentially invasive species, as obtained with GLOBIO-Species, with data on their dispersal capacity and potential dispersal barriers.

Further relevant species-level indicators include range-size rarity and the species threat abatement and restoration (STAR) metric. Range size rarity is an important conservation measure because species with more restricted ranges are considered at greater risk of extinction and contribute to biological uniqueness (Guerin and Lowe, 2015). The STAR metric is designed to quantify the contributions that particular actions in particular places could make towards abating threats to and restoring habitat for threatened species worldwide, to support achievement of the goals of the Kunming-Montréal Global Biodiversity Framework (Mair et al., 2021). We will implement a module to calculate range size rarity from the area of a grid cell within the AOH of each species divided by its total AOH (i.e., the proportion of the species' AOH contained within a given grid cell). These values are then summed across all species to show the aggregate importance of each cell to the species occurring there. To calculate STAR values, we use species' current and restorable AOH, its extinction risk (IUCN Red List category), and the relative contribution of (the mitigation of) each threat to the species' extinction risk, following Mair et al. (2021). The $STAR_T$ score (T) for a grid cell (i) and threat (t) is calculated among all species as:

$$T_{t,i} = \sum P_{s,i} * W_s * C_{s,t}$$

where $P_{s,i}$ is the current AOH of each species s within location i (expressed as a percentage of the species' current AOH), W_s is the IUCN Red List category weight of species s (Near Threatened = 1; Vulnerable = 2; Endangered = 3; Critically Endangered = 4), and $C_{s,t}$ is the relative contribution of threat t to the extinction risk of species s. The relative contribution of each threat to the species' extinction risk is calculated as the population decline resulting from that threat relative to the sum of the population declines across all threats.

3.2.3 Red List of Ecosystems

To enable evaluation of the Red List of Ecosystems criteria, we will develop global distribution models of ecosystem or vegetation types. We will model the occurrence of these types either as a direct function of the underlying abiotic variables, or based on the distributions or traits of the constituent species (Boonman et al., 2022). Based on current and projected spatial distributions of the ecosystem types, we will apply the Red List of Ecosystems criteria concerning i) ongoing declines in distribution, ii) restricted distribution, and iii) degradation of the abiotic environment, following the Red List of Ecosystems protocol (Rodriguez et al., 2015).

3.3 Pressure-impact relationships

3.3.1 GLOBIO and GLOBIO-Aquatic

We will extend or update the MSA-based pressure-impact relationships in GLOBIO and GLOBIO-Aquatic by collecting new or additional data and establish or update meta-regression models (Tables 3.1, 3.2). In parallel to data needed to quantify MSA, we will collect data required to quantify local relative species richness, which is needed to quantify global species extinction risk (via so-called affinity values in the multi-pressure SAR approach; see section 3.2.1). We quantify the responses of these metrics to the selected pressures based on geo-referenced data on species richness or species' abundances in relation to different levels or intensities of each pressure compared to a reference situation where the pressure of concern is presumed absent (Schipper et al., 2020). For each pressure and level of intensity, we first calculate species-specific abundance ratios by dividing each species' abundance in the disturbed situation by its abundance in the corresponding reference site, and then retrieve MSA values by averaging the truncated abundance ratios. For local species richness, we calculate ratios of species richness in the affected sites relative to the corresponding controls. We then establish meta-regression models relating the MSA or species richness ratios to the pressure intensity, accounting for non-independence of observations, differences in quality of the underlying data sources, and possible influences of moderators (Gallego-Zamorano et al., 2022; Kuipers et al., 2023; Schipper et al., 2020).

We prioritize the extensions and updates based on i) needs and requirements from applied projects, ii) the adequacy of the current relationships (see Table 2.1), iii) the magnitude of the (expected) impact of the pressure, and iv) the expected availability of data, including data required to quantify the pressure-impact relationships, as well as data needed to quantify the pressure itself. Given these considerations, we prioritize establishing novel pressure-impact relationships for mining and updating the land-use impact relationships for GLOBIO. For GLOBIO-Aquatic, we prioritize updating the existing relationships, in particular those with limited empirical underpinning, and adding new relationships for pressures that are expected to have a large impact and where data is expected to be available (fragmentation and mining).

Table 3.1
Proposed improvements of the pressure-impact relationships in GLOBIO.

Pressure/State	Current impact relationship	Proposed improvement	Priority
Climate change	Based on meta-analysis of published bioclimatic envelope models (Nuñez et al., 2019)	Establish new relationship based on bioclimatic envelope modelling output of GLOBIO-Species and explore whether responses differ among biomes or climate zones	Medium
Eutrophication (atmospheric nitrogen deposition)	Based on meta-analysis of nitrogen addition experiments (Midolo et al., 2019)	Differentiate responses between vegetation types and/or climate zones	Low
Land use	Based on meta-analysis of PREDICTS database (2016 release) (Hudson et al., 2017)	Refine relationship to include more fine-grained effects of differences in management (including diversification and restoration practices)	High
Habitat fragmentation	Based on meta-analysis of PREDICTS database (2016 release) (Hudson et al., 2017)	Increase the sample size of the impact relationship through a targeted literature review focused on species assemblages in relation to patch area	Low
Road disturbance	Based on meta-analysis of species abundance at different distances to roads (Benítez-López et al., 2010)	Update MSA relationship and establish new species richness relationship based on extended database (De Jonge et al., 2022) and account for potential additional moderators, notably traffic volume (van Strien and Gret-Regamey, 2024).	Low
Exploitation	Based on meta-analysis of species abundance at different distances to hunters' access points (Benítez-López et al., 2017)	Update MSA relationship and establish new species richness relationship based on extended database (Benítez-López pers. comm.)	Low

Pressure/State	Current impact relationship	Proposed improvement	Priority
Mining	-	Establish impact relationship based on recently developed database with species occurrence and abundance in areas affected by mining (Barbarossa et al. in prep.)	High
Pollution	-	Establish new pressure-impact relationships for toxic substances	Low
Invasive species	-	Establish new relationship based on novel database with comparisons of (plant) species composition in invaded and uninvaded plots (see e.g. (Hejda et al., 2009))	Medium

Table 3.2
Proposed improvements of the pressure-impact relationships in GLOBIO-Aquatic.

Pressure/State	Current impact relationship	Proposed improvement	Priority
Hydrological alteration	Based on meta-analysis of species assemblages in relation to flow deviation (for floodplain wetlands and rivers; (Janse et al., 2015; Kuiper et al., 2014)	Update impact relationship for hydrological alteration	Medium
Climate change	Included only via hydrological alteration (Janse et al., 2015; Kuiper et al., 2014); impact of changes in water temperature missing	Establish new relationship for impacts of changes in water temperature	High
Eutrophication	For lakes: based on meta-analysis of species assemblages in relation to N and P concentrations (Janse et al., 2015). For rivers: based on land use in the upstream catchment (Janse et al., 2023).	Update relationships based on meta-analysis of recently established database of nutrient addition experiments (Neijnens et al., 2024)	High
Habitat fragmentation	-	Establish new relationship for impacts of fragmentation	High
Exploitation	-	Establish new relationship for impacts of exploitation (freshwater fisheries)	Medium
Mining	-	Establish impact relationship based on recently developed database with species occurrence and abundance in areas affected by mining (Barbarossa et al. in prep.)	Medium

Pressure/State	Current impact relationship	Proposed improvement	Priority
Pollution	-	Establish new pressure-impact relationships for toxic substances	Low
Invasive species	-	Establish new pressure-impact relationship for invasive species	Low

3.3.2 GLOBIO-Species

For GLOBIO-Species we plan two main types of improvement. First, we aim to improve and expand the pressure-impact relationships for the species groups that are currently included. For both mammals and freshwater fishes, we will improve the representation of the impacts of climate change and land use (Table 3.3, 3.4). More specifically, we aim to account for the potential of species to disperse in response to climate change, and we will refine the habitat affinity values of terrestrial species to better account or differences in land management. Further, we will develop novel pressure-impact relationships for relevant pressures that are currently missing, with a focus on habitat fragmentation (freshwater fishes) and mining (both species groups). As a second main improvement, we will expand GLOBIO-Species such that terrestrial vertebrate species groups other than mammals are also included (birds, reptiles and amphibians). In addition, we will explore the possibilities to expand the model also to plants, building upon the BioScore modelling framework (Hellegers et al., 2020).

Table 3.3
Proposed improvements of the pressure-impact relationships in GLOBIO-Species for mammals.

Pressure/State	Current impact relationship	Proposed improvement	Priority
Climate change	Based on bioclimatic envelope modelling with no dispersal assumption (Kok et al., 2023)	Implement dispersal assumption based on species-specific (imputed) dispersal capacity	Medium
Land use	Based on a cross-walk between land-use classes and species' habitat suitability (Gallego-Zamorano et al., 2020; Kok et al., 2023)	Refine the cross-walk to account for differences in land management (including diversification practices and restoration)	High
Habitat fragmentation	Based on an estimate of population density combined with patch size (Santini et al., 2019)	-	Low
Road disturbance	Based on meta-analysis of species abundance at different distances to roads (De Jonge et al., 2022)	-	NA
Exploitation	Based on meta-analysis of species abundance at different distances to hunters' access points (Benítez-López et al., 2017)	-	NA
Mining	-	Establish impact relationship based on recently developed database with species occurrence and abundance in areas affected by mining (Barbarossa et al. in prep.)	Medium

Table 3.4
Proposed improvements of the pressure-impact relationships in GLOBIO-Species for freshwater fish species.

Pressure/State	Current impact relationship	Proposed improvement	Priority
Climate change	Based on bioclimatic envelope modelling with no or unlimited dispersal assumption (Barbarossa et al., 2021)	- Implement dispersal assumption based on (imputed) species-specific dispersal capacity - Use (imputed) species-specific flow and temperature thresholds to delineate bioclimatic envelopes (Keijzer et al. in prep.)	Medium
Habitat fragmentation	-	Quantify impacts on distribution based on minimum viable range size (Keijzer et al., 2024)	High
Mining	-	Establish impact relationship based on recently developed database with species occurrence and abundance in areas affected by mining (Barbarossa et al. in prep.)	Medium
Exploitation	-	Implement freshwater fish abundance module	Low
Water quality (toxicants)	-	Account for impacts of hypoxia and toxicants based on (imputed) species-specific tolerance	Low

3.4 Biodiversity impact factors

In order to facilitate the attribution of biodiversity loss to specific actors (producers, consumers, governments), we will establish biodiversity impact factors (BIFs): the loss in biodiversity associated with a unit of resource extraction of substance emission, as included in life cycle inventory databases or environmentally extended input-output models. Using the spatially explicit outputs of GLOBIO and GLOBIO-Species, we will establish BIFs both for local biodiversity intactness (MSA), following the approach of Wilting et al. (2017), and for global species extinction risk (RLI), based on changes in global species distributions and abundance associated with the pressures included in GLOBIO. For the species-level modelling, we will initially focus on mammals in relation to land use and climate change (via greenhouse gas emissions), later expanding the approach to other pressures and species groups.

4 Ecosystem services modelling

4.1 Objectives

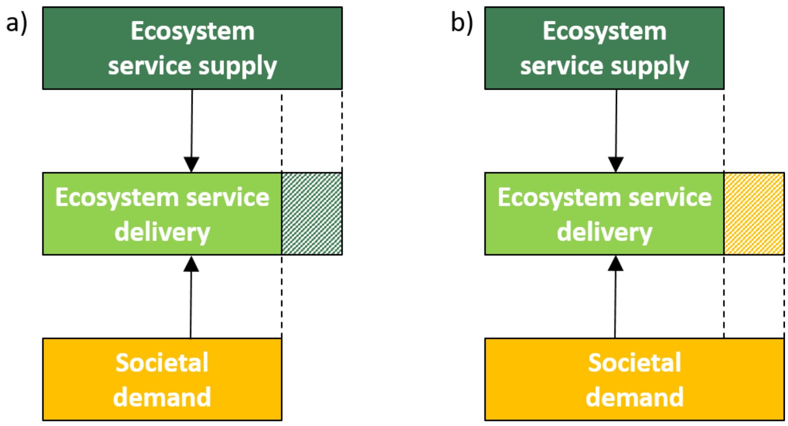
For the further development of GLOBIO-ES, we identified the following specific objectives:

- To harmonize the modelling of ES in line with a consistent conceptual framework (section 4.2).
- To improve existing ES models based on state-of-the art approaches and data (section 4.3).
- To develop new models for additional policy-relevant ES indicators, with a focus on ES distinguished in the GBF indicator framework (Table 2.3) and ES emphasizing the relational value of nature (section 4.4).
- To improve the representation of nature-society interactions by accounting for feedbacks between nature and the economy, and allocating losses in ES to specific actors (accountability) (section 4.5).

4.2 Conceptual ES framework

As ES modelling is a relatively young field, there are numerous approaches and conceptual frameworks to capture the benefits that people obtain from nature (Veerkamp, 2024). Even within GLOBIO-ES, (slightly) different approaches are currently being used (Table 2.2). To increase consistency and salience, we will revise and develop ES models in line with a consistent supply-demand framework, where each ES is quantified in terms of the extent to which the supply of that ES meets the societal demand for it (Figure 4.1). Depending on the characteristics of the ES, societal demand can be quantified based on consumptive needs (e.g. crops, wild food), the need to avoid or reduce potential impacts of environmental changes (e.g. flooding, heat stress), peoples preferences (e.g., for a service or certain environmental setting) or the need to meet common policy goals or standards (e.g. climate neutrality) (Wolff et al., 2015).

Figure 4.1
Conceptual representation of a supply-demand approach to ecosystem service modelling.



Supply-demand ecosystem service modelling framework, showing that a) the capacity of an ecosystem to supply a service may exceed the societal demand, resulting in unused capacity and b) the societal demand for an ES may exceed the ecosystem's capacity to supply it, resulting in unfulfilled or unmet demand or ecosystem overuse (unsustainable exploitation) (adapted from La Notte et al. (2019)).

A consistent supply-demand approach brings forth three methodological advantages. First, the explicit consideration of both supply and demand provides a measure of sustainability as it may uncover mismatches, revealing, for example, where a reduction of demand or enhancement of supply (e.g. through nature restoration) is required to avoid overexploitation of nature or safeguard human well-being (Chaplin-Kramer et al., 2019; Richards et al., 2022). Second, quantifying different ES on the same scale allows to compare them based on their relative contribution to addressing societal challenges (Richards et al., 2022). Such insights can help to identify and prioritize which ES may need to be enhanced, which can facilitate the development of more targeted policy actions. Third, the common measurement scale allows for integrating multiple ES into a single, aggregated indicator (Veerkamp et al., submitted). This in turn helps to see the 'bigger picture' and might facilitate communication to decision-makers.

4.3 Refining existing models

4.3.1 Global climate regulation

Complementary to the process-explicit carbon sequestration model included in IMAGE (Table 2.2), we will develop a simpler carbon sequestration and storage model based on a so-called bookkeeping or look-up table approach, where empirical carbon storage and sequestration values are assigned to specific land-cover or land-use (LCLU) classes and soil types (Schulp et al., 2008; Veerkamp et al., submitted). Having such a model in place offers two advantages: i) it allows for relatively quick assessments of the ES as compared to running a process-explicit model and ii) it provides an independent approach allowing for evaluating model uncertainty (multi-model assessment). We will collect typical sequestration rate and storage values for both urban and non-urban LCLU and soil types from existing databases and literature. We will also explore the possibility to account for the contribution of biodiversity to carbon storage and sequestration, building upon the increasing evidence that more diverse plant assemblages are better able to capture and store atmospheric carbon (Duffy et al., 2017; O'Connor et al., 2017). We will model the demand for storage and sequestration based on carbon emissions in combination with net emission reduction targets, similar to the current model (Table 2.2).

4.3.2 Soil retention

We will improve the modelling of soil retention (erosion control) in three aspects. First, we will improve the representation of the supply of the ES (i.e., the reduction of erosion by vegetation) by adopting and parameterizing a state-of-the-art version of the revised universal soil loss equation (RUSLE). Second, we will consider not only the prevention of on-site soil loss, but also the prevention of off-site sedimentation of detached soil (e.g., in downstream reservoirs or water bodies). Third, we will improve the representation of soil retention demand by considering explicit thresholds for maximum permissible soil loss and/or sediment loads. We will implement these improvements building upon Panagos et al. (2015) and the InVEST model (Hamel et al., 2015). In addition, we will explore the possibilities to account for the contribution of soil fauna (earthworms) to reducing soil erosion risks (Orgiazzi and Panagos, 2018).

4.3.3 Pollination

We will revise the pollination model such that it accounts more explicitly for the role of pollinators in providing the service, building upon the increasing evidence of a positive relationship between crop pollination and the abundance of wild pollinators (Woodcock et al., 2019). To that end, we will establish two complementary model components: one that quantifies the abundance of wild pollinators in cropland based on characteristics of the cropland as well as the surrounding landscape, and one that quantifies the proportion of realized yield of pollinator-dependent crops as a function of pollinator abundance. For building these relationships, we will collect georeferenced data on pollinator abundance from existing databases and literature (e.g., (Hudson et al., 2017)) and use paired data on pollinator abundance and crop yield from the recently published CropPol database (Allen-Perkins et al., 2022).

4.3.4 Pest control

The current pest control model assumes a positive relationship between agricultural pest-predating species and the proportion of natural habitat in the landscape (Table 2.2). However, recent meta-analytical studies indicate that there is no equivocal evidence for such a relationship (Karp et al., 2018). Hence, revising the pest control model requires, as a first step, the development of a new conceptual pest control model, building upon a more solid understanding of how landscape effects on pest predation are modulated by local farm management and by the biology of pests and their enemies. From there, a (mechanistic) pest control model might be developed that accounts for additional drivers of pest predation, including habitat characteristics as well as the traits of the predating species, balancing the trade-off between generality and context-dependence (Alexandridis et al., 2022; Tamburini et al., 2020).

4.3.5 Wild food foraging

Currently, GLOBIO-ES models wild food as a provisioning ES (Table 2.2), defined by the amount of terrestrial wild food (i.e., game, mushrooms and berries) potentially available (supply; based on a correlation between national and international hunting and gathering statistics and LULC classes) and accessible (demand; based on the travel time between people and nature) (Schulp et al., 2012; Veerkamp et al., 2020). But this ES can also be considered as a cultural ES, as the act of foraging may connect people to the landscape, supporting (cultural) identities, sense of place and traditional knowledge (O'Connor et al., 2021; Schulp et al., 2014). First modelling efforts have been developed and applied for Europe, estimating species richness of wild edible plants and mushrooms and culturally important areas for wild food foraging (O'Conner et al., 2021). Based on the latest model developments, we will revise the current implementation of the wild food service in GLOBIO-ES, particularly exploring the potential of including wild food foraging beyond European territories. In this context, we will also explore the possibility to differentiate between subsistence hunting and hunting for commercial purposes, using the same database that was used to determine biodiversity loss due to hunting (Benítez-López et al., 2017; Benítez-López et al., 2019) (see section 2.2.2).

4.3.6 Urban ES models

In our first efforts to model urban ES, we have included global climate regulation (through carbon sequestration) local climate regulation (heat stress reduction), flood risk reduction, and potential improvements of mental and physical health through interaction with (urban) nature (Table 2.2). In addition, we have developed a tentative indicator (proxy) for urban biodiversity as regulating and maintenance service (Veerkamp et al., submitted). In follow-up work, we will refine the models with a focus on i) cultural ES, in line with the new Global Biodiversity Framework (Table 2.3) and ii) the indicators of demand, accounting for, e.g., city-specific policies, physical conditions or differences in demand between groups of people with different physical and socio-economic characteristics (Veerkamp, 2024). This will enhance the added value of the urban GLOBIO-ES models and provides them a unique niche, as other available (urban) ES models commonly focus on the ES supply side (IPBES, 2016). Furthermore, we will upscale the urban ES models, currently developed for Europe, to the entire globe, in line with the global scope of the GLOBIO framework. This implies that some model equations and variables need to be tested and refined (e.g., societal demand and preferences) and/or global and national data sets need to be collected (e.g., global layers of cities and urban nature, (urban) human population density, urban development).

4.4 Developing new models

In line with the ES indicators proposed in the new Global Biodiversity Framework (Table 2.3) and the increasing attention for human-nature relationships, we will develop a set of models for ES currently missing from GLOBIO. In subsequent sub-sections we describe the approaches proposed for a selection of cultural (recreation (including aesthetic quality), culturally important species) and regulating and maintenance services (air quality regulation, services provided by wetlands). We note that this is a provisional list; priorities for ES models to develop may change in response to relevant policy developments and the needs of applied projects.

4.4.1 Nature-based recreation

It is increasingly recognized that regular contact with nature comes with various physical and mental health benefits, including, for example, decreases in the incidence of psychological disorders (e.g.: anxiety, depression) (Bratman et al., 2019; Yang et al., 2021). This is also underlined by the indicator set of the Kunming-Montréal Global Biodiversity Framework, where nature-based tourism (and related services) is proposed as a relevant ES indicator (Table 2.2). Building upon ongoing efforts to score and rank, for example, landscape aesthetic quality (Tisma et al. in prep.) and heritage landscapes (Tieskens et al., 2017), we will develop a new recreation module in which the supply of the service (i.e., the recreation potential of the landscape) will be combined with the demand for recreation, based on human population density and willingness to travel. We will distinguish different types of recreation, acknowledging that contact with nature may come in different forms, each characterized by their specific demand (e.g., demands for a hike or wildlife watching differ from demands for water recreation).

4.4.2 Culturally important species

It is increasingly acknowledged that biodiversity conservation assessments and policies primarily based on biological criteria miss out on the social, cultural, and livelihood needs and aspirations held by local communities, which may introduce inequalities and injustice in conservation practices (Reyes-García et al., 2023). Building upon the GLOBIO-Species model (see Chapter 3), we will develop a novel module that quantifies the distribution and abundance of culturally important species (CIS). We will quantify the demand for this cultural service by identifying CIS from National Biodiversity Strategies and Action Plans (NBSAPs) and additional grey and scientific literature. The supply can be obtained from the outputs of GLOBIO-Species, which allows us to quantify the multi-species indicators included in the outputs specifically for CIS.

4.4.3 Air quality control

Air pollution is a common problem particularly in cities, caused by factors such as traffic and industry. One of the most harmful components of air pollution for human health is particulate matter, which is associated with respiratory and cardiovascular diseases and increased mortality (Goodkind et al., 2019). Vegetation and water can contribute to reducing these health risks by capturing fine particles from the atmosphere (Paulin et al., 2020). The importance of this ES is highlighted by the indicator set of the Kunming-Montréal Global Biodiversity Framework, where air filtration services are explicitly listed as a relevant ecosystem service (Table 2.3). We will establish a new (urban) ES model where we link the ability of vegetation and water to capture fine particulate matter (ES supply) with the extent to which particulate matter concentrations in air exceed air quality thresholds (ES demand).

4.4.4 Wetland ES model

While wetlands cover a relatively small (and decreasing) proportion of the planet, they have a major contribution to various regulating and maintenance ES, including climate regulation (via carbon sequestration and storage), water quality regulation and flood protection (Zedler and Kercher, 2005). Building upon a conceptual model (Janse et al., 2019) and a proof of concept (De Klein et al. in prep.), we will develop a global process-explicit wetland ES model. The model discerns two types of wetlands: i) flooded (or riverine) wetlands (fed by surface water) and ii) 'ponded wetlands' (rain- or groundwater-fed). Both have a permanently and an intermittently inundated part; the division is dynamic in time. The model covers four functional vegetation types: i) submerged, ii) floating, iii) emergent and iv) riparian. The model calculates the growth, carbon sequestration, and N and P retention by these vegetation types, as well as the uptake and emissions of CO_2 and CH_4. It also complements PCR-GLOBWB by deriving the effect of wetlands on water retention and discharge dynamics, which influence water provision (or stress) and flood risk. Demand for these ES will be modelled based on regulatory thresholds for carbon emissions, water quality and flood risks.

4.5 Closing the loop: connecting ecosystem services to societal actors

4.5.1 Feedbacks from nature to the economy

We will explore the possibilities for modelling feedbacks from nature to the economy by using output of GLOBIO-ES as input to integrated assessment or macro-economic models (specifically IMAGE or the MAGNET model within IMAGE). To that end, we will first review the literature in order to get an overview of the state of the art in this field, and develop a general framework for modelling the contributions of nature to the economy. Thereafter, we will test this conceptual framework by applying it in a case study, focusing on carbon sequestration.

4.5.2 Ecosystem services impact factors

Similar to the impact factor development as proposed for the biodiversity components of GLOBIO (see section 3.2.4), we will develop impact factors for ecosystem services, i.e., factors that can be used to attribute the change in a service to a unit of resource extraction of substance emission, as included in life cycle inventory databases or environmentally extended input-output models.

5 Implementation

5.1 Team and collaborations

Within PBL, a core team of permanent staff is responsible for the further development and maintenance of GLOBIO. This core team is relatively small (currently 4 people with a permanent position) and its members are also engaged in other projects (50 - 75% of their time). Hence, strategic collaborations are key. We follow three complementary routes for bringing in additional expertise and workforce for further model development:

- **Temporary staff**: the engagement of temporary junior staff members has been an important pillar of further GLOBIO model developments. Currently, nine externally funded projects provide opportunities to further develop GLOBIO, the majority of which funded by the European Union (Table 5.1).
- **Structural collaborations**: strategic long-term collaborations with external partners (typically universities) allow for a structural engagement of external researchers in the further GLOBIO development. These engagements can take the shape of a secondment of external researchers at PBL as well as specific projects outsourced from PBL to the external partners. Either way, there is always a permanent GLOBIO staff member involved in order to ensure alignment with the GLOBIO project goals. Partners currently included in structural collaborations are Radboud University, Wageningen University and Leiden University.
- **Occasional collaborations**: in addition to the structural long-term collaborations, we have a large network of occasional collaborators both within and outside PBL (e.g., from the International Institute for Applied Systems Analysis (IIASA), Potsdam Institute for Climate Impact Research (PIK), Joint Research Centre (JRC), German Centre for Integrative Biodiversity Research (iDiv), The Netherlands Institute of Ecology (NIOO), UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), and Utrecht University (UU)). Occasional collaborations may take the shape of paid outsourced projects, but are often in-kind.

Table 5.1
Ongoing externally funded projects at PBL with a link to further GLOBIO development. PM represents person months funded by the respective funding scheme.

Project	Funding scheme	Period	PM	Link to GLOBIO development
GoNEXUS	Horizon 2020	2021-2025	36	GLOBIO-Species (freshwater fish species)
BIOMONDO	ESA	2021-2024	12	GLOBIO-Species (freshwater fish species)
sIntESE	sDiv	2022-2024	6	Connecting GLOBIO to macro-economic models
BAMBOO	Horizon Europe	2022-2026	24	GLOBIO-ES (pollination, pest control) and impact factors (biodiversity and ecosystem services)
Brightspace	Horizon Europe	2022-2026	6	GLOBIO (biodiversity responses to agricultural land management practices)
ForestPaths	Horizon Europe	2022-2026	36	GLOBIO (biodiversity responses to forest management practices)
LAMASUS	Horizon Europe	2022-2026	3	GLOBIO (biodiversity responses to agricultural and forestry land management practices)

Project	Funding scheme	Period	PM	Link to GLOBIO development
NaturaConnect	Horizon Europe	2022-2026	72	GLOBIO-ES (soil retention, pollination, wild food foraging, carbon sequestration)
SUSTAIN	Horizon Europe	2022-2026	24	GLOBIO-ES (carbon sequestration)

5.2 Organization

The modular approach of GLOBIO facilitates further model development in small teams focused on a specific component. These teams consist of 3-4 people, usually including one junior researcher, typically with a temporary contract funded by an external project (see Table 5.1), and 2-3 supervisors or close collaborators. The supervisor team always includes at least one member from the GLOBIO core team in PBL to ensure alignment with the goals of the GLOBIO project.

Teams are responsible for translating the general project goals into a more detailed work plan, for performing the actual research, and for reporting through project deliverables (for externally funded projects), scientific papers, and presentations at project meetings and conferences. The development of novel modules takes place outside of the GLOBIO model environment; implementation in the framework follows upon finalization.

Various regular meeting series are in place to facilitate exchange within the larger GLOBIO team and with associated researchers. Within PBL, these include a general GLOBIO project meeting (every 3-4 weeks), regular meetings with the IMAGE team, and regular meeting dedicated to the broader context of international biodiversity policy. Every other year a one-day GLOBIO symposium is organized to share progress and updates among a broader group of biodiversity and ecosystem researchers in the Netherlands, including researchers from both PBL and partner institutes.

5.3 Acquisition strategy

The engagement of temporary junior staff members facilitated by externally funded project has been instrumental to the further development of GLOBIO. As we aim to maintain a steady inflow of external funds, we actively monitor calls for proposals. To ensure alignment between externally funded projects and the GLOBIO development strategy, we carefully consider the objectives of specific calls and project consortia before we apply, and we tune our contributions accordingly.

While we appreciate the opportunities for further GLOBIO development facilitated by recent successes in funding acquisition, we also acknowledge the risks associated with relying on temporary staff financed through external projects:

- Temporal variability in both the availability of suitable calls and the application success rate leads to fluctuations in available resources hence team size, which may compromise the feasibility of our ambitions. For example, it is as of yet uncertain whether there is scope to further develop our ecosystem services models for the urban environment (section 4.3.6), as the external project that facilitated the initial development (NATURVATION) has ended and there is currently no follow-up.
- Although we tune our contributions to project proposals to our GLOBIO development ambitions, a seamless alignment is rare, as the external projects have their own specific goals and scope (e.g., focus on Europe rather than the globe). This may lead to tensions between project aims and GLOBIO development aims, which in turn typically necessitate compromises of the latter.
- The temporary nature of the funding and the large ratio of temporary-to-permanent staff comes with challenges related to transfer and maintenance of the (often quite specialized) knowledge and skills developed. Currently, we face a clear backlog in terms of newly developed model components

that have been finalized and peer-reviewed but not yet implemented in the GLOBIO model code, such as the GLOBIO-Species modules for freshwater fishes (Barbarossa et al., 2021; Barbarossa et al., 2020; Keijzer et al., 2024). A similar challenge is associated with the model components developed by collaboration partners, such as the multi-pressure species-area relationship module developed at Radboud University (Gallego-Zamorano et al., 2022; Moreira et al., 2023).

In view of these threats to the further development and maintenance of GLOBIO, we consider it a priority to increase the team of permanent staff. Given the expertise within the current team of permanent staff, we see pressing needs to increase capacity in particular with regard to the biodiversity components of the model (currently largely dependent on temporary staff and external collaborators), and for technical support (currently only 0.5 fte).

5.4 Quality control

To ensure scientific rigour and reproducibility, two complementary mechanisms are currently in place:

- **Peer-review**: newly developed model components are peer-reviewed in two stages: i) by team members and ii) by external reviewers. The latter is mostly achieved by submitting GLOBIO developments and applications to scientific journals, where the peer review ensures external quality control and the eventual publication helps to disseminate the work (see further section 5.5). In addition, the model framework as a whole is subject to (occasional) external audits. The next audit is intended to be organized in 2025.
- **Version control**: all GLOBIO model code is stored and maintained in a version control system (GitHub). As the modelling framework is modular, each of the four components has its own versioning numbering. Major changes (e.g., the addition of a new pressure) lead to a new main version, while minor changes (e.g., the update of an existing pressure-response relationship) will lead to changes in version number further down in the hierarchy.

To ensure that the GLOBIO framework also meets up with other relevant criteria related to model quality (e.g., description of user requirements and applicability domain; governance and management structure of the model), the GLOBIO model framework will be subject to a systematic evaluation against PBL's model quality criteria in 2024. Based on the outcomes of this evaluation, relevant quality aspects will be improved where needed.

5.5 Dissemination

Dissemination of GLOBIO takes place along the following routes:

- **Public code repository**: once new model components have been peer-reviewed and a published in a report or scientific publication, we disseminate a consolidated version of the code via a publicly accessible code repository (https://github.com/GLOBIO4/GlobioModelPublic).
- **Technical model documentation**: descriptions of how the model works are provided through technical reports, made available via de GLOBIO website (www.globio.info), and a wiki that accompanies the code repository (see above).
- **Scientific papers**: we aim to have all relevant GLOBIO model developments as well as applications of the model published in the peer-reviewed scientific literature. An overview of recent publications (2018-2023) resulting from the GLOBIO project and from applications of GLOBIO is provided in Appendix 2.
- **Presentations**: members of the GLOBIO team regularly present GLOBIO developments at external project meetings or conferences.

- **Open data**: GLOBIO model results as well as empirical input data collected by the GLOBIO team are made publicly accessible, either via our website (https://www.globio.info/resources) or via other repositories such as Zenodo or DANS Easy (see, for example, De Jonge et al. (2022), Neijnens et al. (2024)). To disseminate GLOBIO outcomes to a broader audience, we have developed a user-friendly online viewer and download interface (GLOBIOweb; https://www.globio.info/globioweb).
- **GLOBIO website:** a general (laymen's) introduction to the model framework, news from the GLOBIO project, and GLOBIO results (data, papers) are disseminated via our website (www.globio.info).
- **Online information platforms**: GLOBIO is regularly included in (global) information platforms and inventories on biodiversity data, models and projects, such as the Freshwater Information Platform (www.freshwaterplatform.eu).
- **Learning module**: as part of the NaturaConnect project (see Table 5.1), we will develop a learning module that provides an introduction to the general principles of GLOBIO.

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Appendices

Appendix 1: Headline indicators of the GBF

Headline indicators of the Kunming-Montréal Global Biodiversity Framework (CBD, 2022) and the ability or potential of the GLOBIO framework to model them. I = Included; P = potential to be included in or provided with the help of GLOBIO; NA = not applicable.

Goal/target	Indicator name	In GLOBIO?	Explanation/notes
Goal A	A.1 Red List of Ecosystems	P	Requires distribution models for ecosystem types
	A.2 Extent of natural ecosystems	I	Extent of MSA_{LU} = 1
	A.3 Red List Index	I [b]	GLOBIO-Species
	A.4 The proportion of populations within species with an effective population size > 500	P	Can be included based on GLOBIO-Species abundance estimates [b]
Goal B	B.1 Services provided by ecosystems [a]	I/P	GLOBIO-ES + IMAGE
Goal C	C.1 Indicator on monetary benefits received	NA	
	C.2 Indicator on non-monetary benefits	NA	Measure the number of publications and research results arising from the implementation of access and benefit-sharing instruments
Goal D	D.1 International public funding, including official development assistance (ODA) for conservation and sustainable use of biodiversity and ecosystems	NA	-
	D.2 Domestic public funding on conservation and sustainable use of biodiversity and ecosystems	NA	-
	D.3 Private funding (domestic and international) on conservation and sustainable use of biodiversity and ecosystems	NA	-
Target 1	A.1 Red List of Ecosystems	P	Requires distribution models for ecosystem types
	A.2 Extent of natural ecosystems	I	Extent of MSA_{LU} = 1
	1.1 Percent of land and seas covered by biodiversity-inclusive spatial plans*	P	Requires definition + map of biodiversity-inclusive plans
Target 2	2.2 Area under restoration	P	Based on increases in indicator values over time
Target 3	3.1 Coverage of protected areas and OECMS	I	Based on protected areas and OECMs areas map

Goal/target	Indicator name	In GLOBIO?	Explanation/notes
Target 4	A.3 Red List index	I	GLOBIO-Species
	A.4 The proportion of populations within species with a genetically effective population size > 500	P	Can be included based on GLOBIO-Species abundance estimates [b]
Target 5	5.1 Proportion of fish stocks within biologically sustainable levels	P	Freshwater fish; requires an abundance module + fishing pressure module in GLOBIO-Species
Target 6	6.1 Rate of invasive alien species establishment	P	Based on GLOBIO-Species habitat invasibility + potential IAS invasiveness
Target 7	7.1 Index of coastal eutrophication potential	NA	Global Nutrient Model
	7.2 Pesticide environment concentration	NA	-
Target 9	9.1 Benefits from the sustainable use of wild species	P	GLOBIO-ES (wild food provision module)
	9.2 Percentage of the population in traditional employment	NA	-
Target 10	10.1 Proportion of agricultural area under productive and sustainable agriculture	NA	IMAGE
	10.2 Progress towards sustainable forest management	NA	IMAGE
Target 11	11.1 Services provided by ecosystems [a]	I/P	GLOBIO-ES (+ IMAGE)
Target 12	12.1 Average share of the built-up area of cities that is green/blue space for public use for all	NA	-
Target 13	C.1 Indicator on monetary benefits received	NA	-
	C.2 Indicator on non-monetary benefits	NA	-
Target 15	15.1 Number of companies reporting on disclosures of risks, dependencies and impacts on biodiversity	P	Impacts can be disclosed via biodiversity impact factors obtained from GLOBIO outputs
Target 18	18.1 Positive incentives in place to promote biodiversity conservation and sustainable use	NA	-
	18.2 Value of subsidies and other incentives harmful to biodiversity, that have been eliminated, phased out or reformed	NA	-
Target 19	D.1 International public funding, including official development assistance (ODA) for conservation and sustainable use of biodiversity and ecosystems	NA	-
	D.2 Domestic public funding on conservation and sustainable use of biodiversity and ecosystems*	NA	-

Goal/target	Indicator name	In GLOBIO?	Explanation/notes
	D.3 Private funding (domestic and international) on conservation and sustainable use of biodiversity and ecosystems*	NA	-
Target 21	21.1 Indicator on biodiversity information for monitoring the global biodiversity framework	NA	-

a) An agreed up-to-date methodology does not exist (CBD, 2022). For the GBF, the following ES have been suggested as headline indicators (see https://www.post-2020indicators.org/metadata/headline/B-1): 1) Air filtration services; 2) Water regulation services; 3) Global climate regulation services; 4) Soil and sediment retention services; 5) Pollination services and 6) Mitigation services (number of properties and people with reduced risk of landslide/flood/storm).

b) Currently included only for terrestrial mammals.

Appendix 2: GLOBIO publications 2018-2023

(Contributions to) peer-reviewed journal papers

Alkemade, R., van Bussel, L.G.J., Rodriguez, S.L., Schipper, A.M. (2022) Global biodiversity assessments need to consider mixed multifunctional land-use systems. Current Opinion in Environmental Sustainability 56.

Barbarossa, V., Bosmans, J., Wanders, N., King, H., Bierkens, M.F.P., Huijbregts, M.A.J., Schipper, A.M. (2021) Threats of global warming to the world's freshwater fishes. Nature Communications 12, 1701.

Barbarossa, V., Schmitt, R.J.P., Huijbregts, M.A.J., Zarfl, C., King, H., Schipper, A.M. (2020) Impacts of current and future large dams on the geographic range connectivity of freshwater fish worldwide. Proceedings of the National Academy of Sciences of the United States of America 117, 3648-3655.

De Jonge, M.M.J., Gallego-Zamorano, J., Huijbregts, M.A.J., Schipper, A.M., Benitez-Lopez, A. (2022) The impacts of linear infrastructure on terrestrial vertebrate populations: A trait-based approach. Global Change Biology 28, 7217-7233.

Gallego-Zamorano, J., Huijbregts, M.A.J., Schipper, A.M. (2022) Changes in plant species richness due to land use and nitrogen deposition across the globe. Diversity and Distributions 28:745-755.

Janse, J.H., van Dam, A.A., Hes, E.M.A., de Klein, J.J.M., Finlayson, C.M., Janssen, A.B.G., van Wijk, D., Mooij, W.M., Verhoeven, J.T.A. (2019) Towards a global model for wetlands ecosystem services. Current Opinion in Environmental Sustainability 36, 11-19.

Kim, H., Rosa, I.M.D., Alkemade, R., Leadley, P., Hurtt, G., Popp, A., van Vuuren, D.P., Anthoni, P., Arneth, A., Baisero, D., Caton, E., Chaplin-Kramer, R., Chini, L., De Palma, A., Di Fulvio, F., Di Marco, M., Espinoza, F., Ferrier, S., Fujimori, S., Gonzalez, R.E., Gueguen, M., Guerra, C., Harfoot, M., Harwood, T.D., Hasegawa, T., Haverd, V., Havlík, P., Hellweg, S., Hill, S.L.L., Hirata, A., Hoskins, A.J., Janse, J.H., Jetz, W., Johnson, J.A., Krause, A., Leclère, D., Martins, I.S., Matsui, T., Merow, C., Obersteiner, M., Ohashi, H., Poulter, B., Purvis, A., Quesada, B., Rondinini, C., Schipper, A.M., Sharp, R., Takahashi, K., Thuiller, W., Titeux, N., Visconti, P., Ware, C., Wolf, F., 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.

Keijzer, T., Barbarossa, V., Marques, A., Carvajal-Quintero, J.D., Huijbregts, M.A.J., Schipper, A.M. (2024) Threats of dams to the persistence of the world’s freshwater fishes. Global Change Biology 30:e17166.

Kok, M.T.J., Alkemade, R., Bakkenes, M., van Eerdt, M., Janse, J., Mandryk, M., Kram, T., Lazarova, T., Meijer, J., van Oorschot, M., Westhoek, H., van der Zagt, R., van der Berg, M., van der Esch, S., Prins, A.-G., van Vuuren, D.P. (2018) Pathways for agriculture and forestry to contribute to terrestrial biodiversity conservation: A global scenario-study. Biological Conservation 221, 137-150.

Kok, M.T.J., Meijer, J.R., van Zeist, W.-J., Hilbers, J.P., Immovilli, M., Janse, J.H., Stehfest, E., Bakkenes, M., Tabeau, A., Schipper, A.M., Alkemade, R. (2023) Assessing ambitious nature conservation strategies in a below 2-degree and food-secure world. Biological Conservation 284.

Kuipers, K.J.J., Sim, S., Hilbers, J.P., van den Berg, S.K., de Jonge, M.M.J., Trendafilova, K., Huijbregts, M.A.J., Schipper, A.M. (2023) Land use diversification may mitigate on-site land use impacts on mammal populations and assemblages. Global Change Biology 29, 6234-6247.

Leclère, D., Obersteiner, M., Barrett, M., Butchart, S.H.M., Chaudhary, A., De Palma, A., DeClerck, F.A.J., Di Marco, M., Doelman, J.C., Duerauer, M., Freeman, R., Harfoot, M., Hasegawa, T., Hellweg, S., Hilbers, J.P., Hill, S.L.L., Humpenoeder, F., Jennings, N., Krisztin, T., Mace, G.M., Ohashi, H., Popp, A., Purvis, A., Schipper, A.M., Tabeau, A., Valin, H., van Meijl, H., Van Zeist, W.-J., Visconti, P., Alkemade, R., Almond, R., Bunting, G., Burgess, N.D., Cornell, S.E., Di Fulvio, F., Ferrier, S., Fritz, S., Fujimori, S., Grooten, M., Harwood, T., Havlik, P., Herrero, M., Hoskins, A.J., Jung, M., Kram, T., Lotze-Campen, H., Matsui, T., Meyer, C., Nel, D., Newbold, T., Schmidt-Traub, G., Stehfest, E., Strassburg, B.B.N., van Vuuren, D.P., Ware, C., Watson, J.E.M., Wu, W., Young, L. (2020) Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature 585, 551-556.

Meijer, J.R., Huijbregts, M.A.J., Schotten, C.G.J., Schipper, A.M. (2018) Global patterns of current and future road infrastructure. Environmental Research Letters 13, 10.

Midolo, G., Alkemade, R., Schipper, A.M., Benítez-López, A., Perring, M.P., De Vries, W. (2019) Impacts of nitrogen addition on plant species richness and abundance: A global meta-analysis. Global Ecology and Biogeography 28, 398-413.

Moreira, H., Kuipers, K.J.J., Posthuma, L., Zijp, M.C., Hauck, M., Huijbregts, M.A.J., Schipper, A.M. (2023) Threats of land use to the global diversity of vascular plants. Diversity and Distributions 29:688-697.

Neijnens, F.K., Moreira, H., De Jonge, M.M.J., Linssen, B.B.H.P., Huijbregts, M.A.J., Geerling, G.W., Schipper, A.M. (2024) Effects of nutrient enrichment on freshwater macrophyte and invertebrate abundance: a meta-analysis. Global Change Biology 30, 17094.

Nuñez, S., Arets, E., Alkemade, R., Verwer, C., Leemans, R. (2019) Assessing the impacts of climate change on biodiversity: Is below 2°C enough? Climatic Change 154, 351–365.

Rashidi, P., Patil, S.D., Schipper, A.M., Alkemade, R., Rosa, I. (2023) Downscaling global land-use scenario data to the national level: a case study for Belgium. Land 12, 1740.

Schipper, A.M., Hilbers, J.P., Meijer, J.R., Antão, L.H., Benítez-López, A., De Jonge, M.J.M., Leemans, L.H., Scheper, E., Alkemade, R., Doelman, J.C., Mylius, S., Stehfest, E., Van Vuuren, D.P., Van Zeist, W.-J., Huijbregts, M.A.J. (2020) Projecting terrestrial biodiversity intactness with GLOBIO 4. Global Change Biology 26, 760-771.

Veerkamp, C.J., Dunford, R.W., Harrison, P.A., Mandryk, M., Priess, J.A., Schipper, A.M., Stehfest, E., Alkemade, R. (2020) Future projections of biodiversity and ecosystem services in Europe with two integrated assessment models. Regional Environmental Change 20, 103.

Veerkamp, C.J., Van Rijn, F., Spoon, M., Loreti, M., Remme, R.P., Dassen, T., Schipper, A.M. (submitted) Assessing multiple ecosystem services in 708 European urban areas.

Wilting, H.C., Schipper, A.M., Ivanova, O., Ivanova, D., Huijbregts, M.A.J. (2020) Subnational greenhouse gas and land-based biodiversity footprints in the European Union. Journal of Industrial Ecology 25:79-94.

(Contributions to) reports

CBD (2020) Global Biodiversity Outlook 5. Secretariat of the Convention on Biological Diversity, Montreal.

IPBES (2019) Global assessment report on biodiversity and ecosystem services. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.

WWF (2020) Living Planet Report 2020 - Bending the curve of biodiversity loss. World Wildlife Fund, Gland, Switzerland.

WWF (2022) Living Planet Report 2022 – Building a nature-positive society. World Wildlife Fund, Gland, Switzerland.