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D3.1 Integrated indicators and test simulations for the assessment of biodiversity impacts

Climate change and land use response relationships for local ecosystem intactness, species population declines, and global species extinctions

LEGAL DISCLAIMER

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Scope of the document	In this task we identify, further develop and integrate indicators to quantify and analyse the impacts of multiple human drivers on biodiversity. We evaluate responses of biodiversity to climate change and land use change by modelling biodiversity impacts on local ecosystem intactness building on our biodiversity model GLOBIO, on species population declines using our biodiversity model GLOBIO-Species, and on global species extinctions via the LC-IMPACT method.

EXECUTIVE SUMMARY

Scope: Biodiversity is declining globally, exemplified by losses of local ecosystem intactness, species population declines, and global species extinctions. In order to halt and/or bend the curve of biodiversity loss, urgent strategies are required that contribute to reaching the biodiversity goals as agreed upon in the Kunming-Montreal Global Biodiversity Framework. In order to evaluate the effectiveness of biodiversity policies, models should to be able to quantify impacts of changes in human drivers on biodiversity. To do so requires a key set of operational biodiversity indicators, covering multiple aspects of biodiversity and different drivers of biodiversity decline.

Goal. Here, we present response relationships of two main drivers of biodiversity loss (climate change and land use), considering three complementary indicators: the mean species abundance (MSA; indicator of local ecosystem intactness), the Living Planet Index (LPI; indicator of species population declines), and the potentially disappeared fraction of species (PDF; indicator of global species extinctions).

Response relationships: The response relationships for MSA are established via meta-analysis studies and quantify the influence of various land use types (such as cropland, pasture and forestry) and greenhouse gas emissions on plants and warm-blooded vertebrates compared to an undisturbed situation. The response relationships for the LPI are based on species distribution and habitat suitability models and quantify the average global decline of mammal populations for the two drivers of biodiversity loss. Finally, response relationships for PDF for plants and vertebrates were established for land use by combining species area relationships with regionalised information on species endemism and for climate change by using a comprehesive meta-analysis. All response relationships derived for climate change require the global mean temperature increase (GMTI in °C), or alternatively greenhouse gas (GHG) emissions, as input. The response relationships for land use require the area of certain land use categories for all indicators, either further differentiated by land use intensities (for MSA and PDF) and/or by country (for PDF). The response relationships are derived from state-of-the-art biodiversity modelling approaches and can be linked to integrated assessment models to quantify the combined impacts of land use and climate change on three dimensions of biodiversity.

Case study: To showcase how the implementation can work in practice, we linked the response relationships to the SSP2 Middle of the Road (representing a baseline scenario that follows historical trends in social, economic, and technological development). Based on global mean temperature increase and global land use areas from the SSP2 scenario, we quantified the changes in the three biodiversity indicators for the years 2015, 2030, 2050 and 2070. We show that trends in MSA, LPI and PDF are consistent over time, with decreases in MSA of ~18M km^2 and ~12M km^2 between

2015 and 2070 for plants and warm-blooded vertebrates, respectively, a decrease in the LPI for mammals of ~27% between 2015 and 2070, and increases in the PDF of ~4% and ~14% between 2015 and 2070 for plants and vertebrates, respectively.

Conclusions: We presented response relationships for land use and climate change impacts for three key biodiversity indicators based on complementary biodiversity modelling approaches, showed how these response relationships can be used to evaluate policy scenarios and discussed how the response relationships can be further developed. The results presented highlight that strategies to halt and/or bend the curve of biodiversity loss are urgently needed to reach globally agreed goals.

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Long text
AOH	Area of habitat
FRS	Fraction of remaining species
IUCN	International Union for the Conservation of Nature
LCIA	Life cycle impact assessment
GEP	Global extinction probability
GHG	Greenhouse gas
GMTI	Global mean temperature increase (C°)
LPI	Living Planet Index
LPIL	Living Planet Index loss (1 – LPI)
MSA	Mean species abundance
MSAL	Mean species abundance loss (1 – MSA)
PDF	Potentially disappeared fraction of species
SAR	Species-area relationship

1. Introduction

Biodiversity is declining globally, exemplified by local ecosystem changes (Schipper et al., 2020), species population declines (WWF, 2022), and species extinctions (Barnosky et al., 2012; Ceballos et al., 2015; Ceballos & Ehrlich, 2023). In response to the global biodiversity crisis, 196 countries have agreed upon a framework to protect biodiversity (CBD, 2022). Policy scenarios are important tools that support the identification of strategies that contribute to reaching the biodiversity goals (Pereira et al., 2020). In order to evaluate the effectiveness of policies to reach biodiversity goals, policy scenarios need to be able to quantify impacts of changes in human drivers on biodiversity.

Biodiversity is a multifaceted concept that cannot be expressed by a single indicator. Hence, to quantify different dimensions of biodiversity change, several indicators are required that each may reveal distinct trends (Crenna et al., 2020; Santini et al., 2017). Biodiversity indicators are complementary if they assess different dimensions of biodiversity, such as changes in local ecosystem intactness, global species populations, and species extinction risks or rates (Steffen et al., 2015).

The five major drivers of global biodiversity change are land use, climate change, pollution, overexploitation, and invasive species (Díaz et al., 2019; IPBES, 2019). With ~70% of the terrestrial surface area (excluding ice) being subjected to some form of human influence, land use is the largest driver of terrestrial biodiversity loss (Arneth et al., 2019). Whereas land use impacts are local in nature, affecting only species whose habitat is being converted, climate change impacts are global, affecting all species on Earth. To cover biodiversity impacts comprehensively, it is key to cover more than a single driver of biodiversity change (Pörtner et al., 2023).

Here, we present response relationships for two of the main drivers of biodiversity loss (climate change and land use) (IPBES, 2019), considering three complementary biodiversity indicators: local ecosystem intactness (Section 2), species population declines (Section 3), and global species extinctions (Section 4). These response relationships can be linked to integrated assessment models to enable the quantification of various dimensions of biodiversity. In addition, we apply the response relationships to scenarios to illustrate how they can be used to predict biodiversity loss due to climate change and land use in 2015, 2030, 2050, and 2070 (Section 5). Finally, we present a future outlook for the further development of biodiversity reponse relationships and their integration with scenario and impact assessment models to support the identification of strategies to halt and reverse global biodiversity loss (Section 5).

2. Local community intactness

2.1 GLOBIO-MSA

The GLOBIO-MSA model quantifies local terrestrial biodiversity intactness based on the impacts of six drivers (climate change, land use, fragmentation, road disturbance, atmospheric nitrogen deposition, and hunting) on mean species abundance (MSA) (Alkemade et al., 2009; Schipper et al., 2020). MSA ranges from 0 (all original species are locally extinct) to 1 (the assemblage is fully intact). MSA is calculated based on the abundance (*N*) of individual species (*k*) in response to a given driver (*d*) compared to their abundance in an undisturbed natural reference situation (*r*; Equation 1). To consider intactness relative to the natural reference situation, increases in individual species abundance and species that are not present in the natural reference situation are not considered. That is, the number of species (*S*) does not exceed the number of species in the reference situation.

$$MSA_d = \sum_k^S min\left(\frac{N_{k,r,d}}{N_{k,r}}, 1\right) S^{-1} \qquad \text{(Equation 1)}$$

MSA per driver intensity is calculated based on response relationships, distinguishing between plants and warm-blooded vertebrates (i.e., mammals and birds). Figure 1 shows the response relationships for climate change (MSA by increasing global mean temperature increase) and land use (MSA by land use class). The GLOBIO-MSA response relationships are spatially generic.

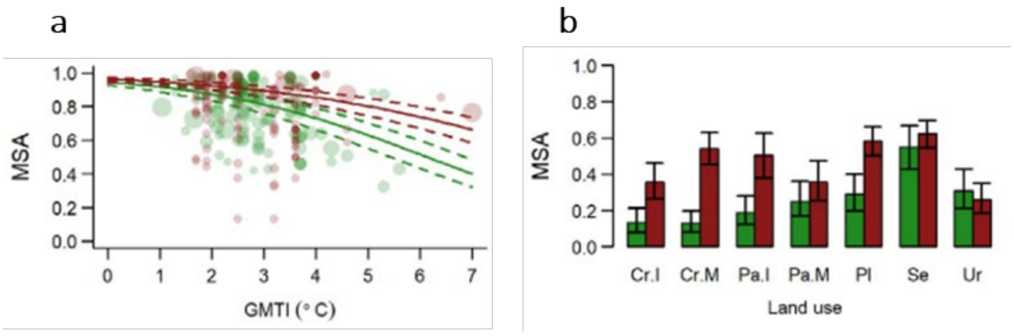

Figure 1. GLOBIO-MSA response relationships for (a) climate change (via global mean temperature increase) and (b) land use for plants (green) and warm-blooded vertebrates (red). For land use the following land use classes are considered: intensive cropland (Cr.I), minimal intensity cropland (Cr.M), intensive pasture (Pa.I), minimal intensity pasture (Pa.M), forest plantations (Pl), secondary vegetation (Se), and urban area (Ur) (Schipper et al., 2020).

We use the GLOBIO-MSA model to quantify response relationships for climate change (Section 2.2) and land use (Section 2.3) in terms of MSA loss (MSAL = 1 - MSA). We use the area-integrated MSAL.km^2 indicator by considering the local MSA response to global mean temperature increase and land use impacts as well as the total area that the driver affects.

2.2 Climate change response relationships

The GLOBIO-MSA response relationships for climate change are based on the database from Nuñez et al. (2019), which contains information on local fractions of remaining species (FRS) in response to temperature change estimated based on bioclimate envelope models. The FRS represents the ratio between the number of species remaining after temperature change and the original number of species in a grid cell, which is used as a proxy for MSA in GLOBIO-MSA (Schipper et al., 2020). The driver-impact curve is derived by mixed beta-regression models that relate the FRS values of 135 plants and 141 warm-blooded vertebrates to the global mean temperature increase since pre-industrial times (GMTI in °C; Figure 1).

To consider the global scale of climate change impacts on plants and warm-blooded vertebrates we consider the total terrestrial surface area, excluding area permanently covered by snow or ice as well as consolidated bare area (129 M km^2). Combined with the impact relatonships, this results in the response function for plants and warm-blooded vertebrates (Equations 2-3; Appendix B1). Inserting the GMTI in °C results in the total MSA impact (MSAL.km^2). The total MSA impact (MSAL.km^2) can also be calculated from greenhouse gas (GHG) emissions by multiplying the GMTI with the global temperature potential of the GHGs (in GMTI / kg GHG) (Appendix B2). The total MSAL impact is then the sum of the impacts of all GHGs (Iordan et al., 2023).

$$MSAL_{CC,plants}.\,km^2 = \left(1-\left(1+e^{-(2.87-0.47GMTI)}\right)^{-1}\right)\cdot 1.29\cdot 10^8 \quad \text{(Equation 2)}$$

$$MSAL_{CC,vertebrates}.\,km^2 = \left(1-\left(1+e^{-(3.21-0.36GMTI)}\right)^{-1}\right)\cdot 1.29\cdot 10^8 \quad \text{(Equation 3)}$$

2.3 Land use response relationships

The GLOBIO-MSA response relationships for land use are based on the PREDICTS database (Hudson et al., 2014, 2017), which contains information on local species abundance in land use sites and in corresponding natural reference sites. Based on this data, GLOBIO-MSA calculates plant and warm-blooded vertebrate MSA values of 'cropland – minimal use' (n_{plants} = 5, $n_{vertebrates}$ = 8), 'cropland – intense use' (n_{plants} = 1, $n_{vertebrates}$ = 3), 'pasture – minimal use' (n_{plants} = 6, $n_{vertebrates}$ = 3), 'pasture – intense use' (n_{plants} = 3, $n_{vertebrates}$ = 2), 'forest plantation' (n_{plants} = 11, $n_{vertebrates}$ = 23), 'secondary vegetation' (n_{plants} = 27, $n_{vertebrates}$ = 42), and 'urban area' (n_{plants} = 2, $n_{vertebrates}$ = 4). Response relationships are derived by mixed beta-regression models that quantify average MSA responses to the land use classes (Figure 1).

Because land use impacts are expressed in terms of area of land use of a certain land use class, the land use MSA response relationships (MSAL) themselves do not contain an area component. Hence, the GLOBIO-MSA response relationships are directly used for the land use response relationships (Table 1; Appendix B1). Multiplying the land use area (in km^2) per land use class results in the MSA impact ($MSAL.km^2$).

Table 1. GLOBIO-MSA land use response relationships (MSAL)

Land use class	$MSAL_{LU, plants}$	$MSAL_{LU, vertebrates}$
Cropland – minimal use	0.87	0.46
Cropland – intense use	0.87	0.64
Pasture – minimal use	0.75	0.64
Pasture – intense use	0.81	0.50
Forest plantation	0.71	0.42
Secondary vegetation	0.45	0.38
Urban area	0.69	0.74

Source: (Schipper et al., 2020)

2.4 Aggregating response relationships

To obtain an overall effect on local terrestrial biodiversity intactness of plants (Equation 4a) and/or warm-blooded vertebrates (Equation 4b), global average GLOBIO-MSA climate change MSA is multiplied with global area-weighted land use MSA (i.e., 1 – MSAL). The driver-combined global MSA is then back-transformed to MSAL (i.e., MSAL = 1 – MSA) and multiplied by the total global land surface area (*A*; km^2).

$$MSAL_{plants}.\, km^2 = \left(1 - \left(\left(\frac{1}{1+e^{-(2.87-0.47GMTI)}}\right)\left(1 - \frac{\sum_{LU} MSAL_{LU} \cdot A_{LU}}{A}\right)\right)\right) \cdot A \qquad \text{(Equation 4a)}$$

$$MSAL_{vertebrates}.\, km^2 = \left(1 - \left(\left(\frac{1}{1+e^{-(3.21-0.36GMTI)}}\right)\left(1 - \frac{\sum_{LU} MSAL_{LU} \cdot A_{LU}}{A}\right)\right)\right) \cdot A \qquad \text{(Equation 4b)}$$

3. Species population declines

3.1 GLOBIO-Species

The GLOBIO-Species model quantifies the distribution and abundance of individual terrestrial mammal species based on IUCN spatial data (IUCN, 2022), elevation data, and the impacts of four drivers (climate change, land use, fragmentation, and road disturbance) (Kok et al., 2023). GLOBIO-Species can quantify various species-level indicators, such as species area of habitat (AOH) and species abundance (by combining the AOH with species density estimates) (Santini et al., 2018). Based on these species-level indicators, GLOBIO-Species can quantify multispecies biodiversity indicators as well, such as the Living Planet Index (LPI) based on average change in species populations in year *t* relative to 1970 (Equation 4) (Collen et al., 2009; WWF, 2022).

$$LPI_t = 10^{\sum_k^S \log_{10}\left(\frac{N_{k,t}}{N_{k,1970}}\right) S^{-1}} \qquad \text{(Equation 5)}$$

where S represents the total number of species. Here, we consider climate change and land use impacts. We use the GLOBIO-Species model to quantify response relationships for climate change (Section 3.2) and land use (Section 3.3) in terms of LPIL (LPIL = 1 – LPI) per GMTI and land use area (*A*; km^2). To do so, we run GLOBIO-Species for two years: 1970 (the reference year used in LPI calculations (Collen et al., 2009; WWF, 2022)) and 2015. The response relationships thus reflect the recent effect of climate change and land use on mammal species populations globally. LPIL per driver intensity is then calculated based on the difference between the LPIL quantified based on all drivers (*d*) and the LPIL quantified based on all but a certain driver (-*d*) (Equation 5). The response relationships are spatially generic.

$$LPIL_{t,d} = LPIL_t \frac{LPIL_{t,-d} - LPIL_t}{\sum_p LPIL_{t,-d} - LPIL_t} \qquad \text{(Equation 6)}$$

We based the calculations of the response relationships per driver intensity on 3,928 terrestrial mammal species for which sufficient data was available to model climate change impacts, land use impacts and fragmentation impacts as a response of climate and land use change.

3.2 Climate change response relationships

GLOBIO-Species models the impact of climate change on individual mammal species via bioclimatic envelope modelling (Čengić et al., 2020; Kok et al., 2023). For each species, a bioclimatic envelope is fitted by using present natural ranges (from the PHYLACINE database v1.2.1 (Faurby et al., 2018)) and monthly precipitation and temperature data for 1960 – 1979 (from the WorldClim database (https://www.worldclim.org/data/monthlywth.html)) which are transformed into 19 bioclimatic variables relevant for species distribution modelling (Hutchinson et al., 2009; Kok et al., 2023). The fitted bioclimatic envelope models were used to project the suitable climate space within their current native extant range (IUCN, 2022) for each species for 1970 and 2015. The required climate data were again obtained from the WorldClim database, using 1960-1979 data for 1970 and 2000 – 2019 data for 2015 (following Kok et al. (2023)).

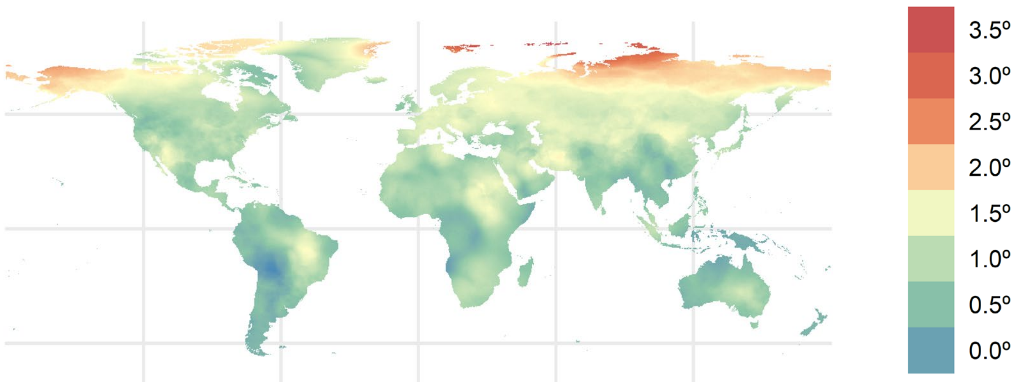

Figure 2. Annual mean temperature difference between 1970 and 2015.

We derive climate change response relationships (in LPIL per GMTI) following Equation 6 by quantifying LPIL based on all drivers and LPIL based on all drivers but climate change. This equates to how much climate change contributes to the loss of the Living Planet index, and thus to the average global decline in mammal abundance. The LPIL for climate change was divided by a GMTI of 0.976 °C, which is the difference between the global annual mean temperature data used for 1970 and 2015 (Fig. 2), to arrive at an LPIL per GMTI. Because GMTI has a global impact, the climate change response relationship is spatially generic. Multiplying the GMTI compared to 1970 with the climate change response relationship (in LPIL / GMTI) results in the LPIL impact. The total LPIL impact can also be calculated from greenhouse gas (GHG) emissions by multiplying the GMTI compared to 1970 with the global temperature potential of the GHGs (in GMTI / kg GHG) (Appendix B2). The total LPIL impact is then the sum of the impacts of all GHGs (Iordan et al., 2023).

Table 2. GLOBIO-Species climate change response relationships (LPIL.GMTI^{-1})

	$LPIL_{CC}$
Climate change	0.0867

3.3 Land use response relationships

GLOBIO-Species models the impact of land use on individual mammal species by combining land-use maps with species-specific information on the current native extant range, habitat preferences and elevation limits (IUCN, 2022). First, areas at unsuitable altitudes are removed from the current native extant ranges using elevation data from the MERIT Digital Elevation Model (Yamazaki et al., 2017) and species-specific elevation preferences (IUCN, 2022). Second, areas containing unsuitable land cover and/or land use are removed using land-use maps derived by Kok et al. (2023) for 1970 and 2015, species-specific habitat preferences (IUCN, 2022) and a cross-walk that links the habitat preferences to the land cover and use classes in the land-use maps (Gallego-Zamorano et al., 2020).

We derive land use response relationships (in LPIL per km^2) following Equation 6 by quantifying LPIL based on all drivers and LPIL based on all drivers but a certain land use category. Here, we include the following land use categories: urban, cropland, pasture, rangeland and forestry. The land use response relationships reflect how much the land use category contributes to the loss of the Living Planet index, and thus to the average global decline in mammal abundance. The LPIL for each land use category was divided by the difference in total land area that the land use category occupied between 1970 and 2015 to arrive at an LPIL per km^2. Multiplying the difference in total land area of a land category (in km^2) compared to 1970 (Appendix B3) with the corresponding land use response relationship (in LPIL / km^2) results in the LPIL impact.

Table 3. GLOBIO-Species land use response relationships (LPIL.km^{-2})

Land use category	$LPIL_{LU}$
Urban area	1.44e-08
Cropland	2.24e-08
Pasture	3.43e-08
Rangeland	4.96e-08
Forestry	7.74e-09

3.4 Aggregating response relationships

To obtain an overall effect on the average change in mammal populations, the LPIL impacts for climate change and land use can be combined by summing the LPIL per driver d:

$$LPIL = LPIL_{CC}(GMTI - GMTI_{1970}) + \sum_{LU}\left(LPIL_{LU}(A_{LU} - A_{LU,1970})\right) \qquad \text{(Equation 7)}$$

4. Global species extinctions

4.1 LC-IMPACT

The LC-IMPACT methodology quantifies global species extinctions based on the impacts of five drivers (climate change, land use, acidification, particulate matter formation, and photochemical ozone formation) on the potentially disappeared fraction of species (PDF) (Verones et al., 2020). PDF ranges from 0 (no species extinctions) to 1 (all species have gone extinct globally). PDF is calculated based on the FRS and the global extinction probability (GEP; Figure 3) corresponding to the spatial unit (*j*) of the FRS (Equation 8). FRS is quantified as the number of species (*S*) in response to a given driver (*d*) compared to the number of species in an undisturbed natural reference situation (*r*): $FRS_p = S_p / S_r$. The GEP is a species endemism index that estimates how species loss in a spatial unit may contribute to global species extinctions based on the global species distributions (Verones et al., 2022).

$$PDF_{d,j} = (1 - FRS_d)GEP_j \qquad \text{(Equation 8)}$$

PDF per driver intensity is calculated based on individual impact models that distinguish between plants and vertebrates (i.e., mammals, birds, amphibians, and reptiles). Climate change response relationships are spatially generic because climate change acts at the global scale. Because land use impacts are local and because extinction probabilities differ per spatial unit, land use response relationships are spatially differentiated.

We use the most recent models related to the LC-IMPACT methodology for response relationships for climate change (Section 4.2) and land use (Section 4.3) in terms of PDF per GMTI (°C) and land use area (A; km^2).

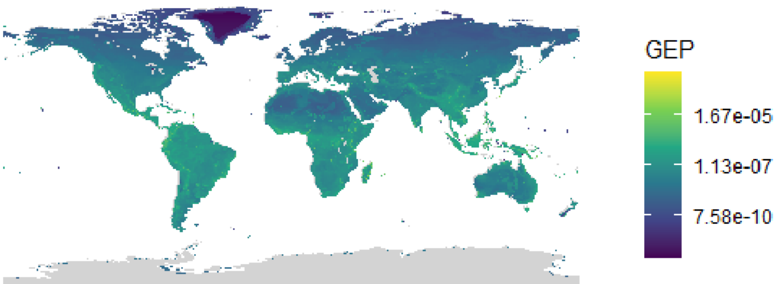

Figure 3. Global extinction probability of terrestrial mammals indicating the probability that regional species loss in a grid cell leads to global species extinctions (Verones et al., 2022).

4.2 Climate change response relationships

The LC-IMPACT response relationships for climate change are based on a meta-analysis of species extinctions in response to GMTI (Urban, 2015). Recently, climate change response relationships have been derived based on climate envelope models considering the spatial distribution and temperature niche of 22,913 vertebrate species (mammals, birds, amphibians and reptiles) (Iordan et al., 2023). The global species extinction response relationships are calculated based on the PDF across 1.875° km grid cells and the GMTI (C°) in 2100 relative to 2010 (Figure 4; Equation 9; Table 4).

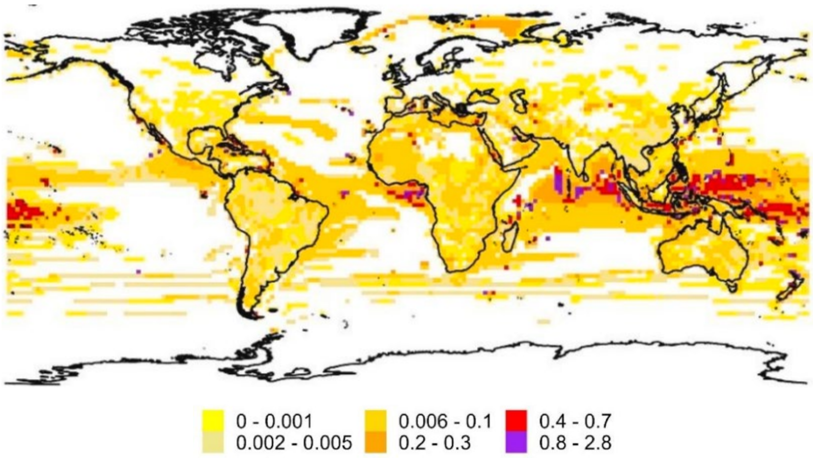

Figure 4. The fraction of affected species (1 – FRS) due to climate change between 2010 and 2100 across various taxonomic groups (including terrestrial vertebrates) based on climate envelope models. White indicates no affected species, yellow few affected species, and purple many affected species (Iordan et al., 2023).

$$PDF.GMTI^{-1} = \frac{\sum_j (1 - FRS_{2010-2100,j}) GEP_j}{GMTI_{2010-2100}} \quad \text{(Equation 9)}$$

We derive taxonomic kingdom-aggregated (vertebrate) response relationships (in PDF/GMTI) based on Iordan et al. (2023). Because GMTI has a global impact, the climate change response relationship is spatially generic. Multiplying the GMTI with the climate change response relationship (in PDF / GMTI) results in the PDF impact. The total PDF impact can also be calculated from greenhouse gas (GHG) emissions by multiplying the GMTI (°C) with the global temperature potential (GTP) of the GHGs (in GMTI / kg GHG) over a certain time horizon (Appendix B2). The total PDF impact is then the sum of the impacts of all GHGs (Iordan et al., 2023).

Table 4. LC-IMPACT climate change response relationships (PDF.GMTI^{-1})

	$PDF_{CC, vertebrates}$
Climate change	0.0514

4.3 Land use response relationships

The LC-IMPACT response relationships for land use are based on a countryside species-area relationship (cSAR) model that considers the local FRS per land use class (*p*), the total ecoregional (*j*) area size (*A*) of each land use class relative to an undisturbed natural reference situation (*r*) (Olson et al., 2001), a regional-specific nonlinear slope for the decline in species richness by a reduction in habitat size (*z*), and a region-specific global extinction probability (Chaudhary et al., 2015). Recently, land use impact models have been advanced by differentiating between land use intensities (Chaudhary & Brooks, 2018) and considering habitat fragmentation (Equation 10) (Scherer et al., 2023). The newest land use impact model considers five land use classes (cropland, pasture, forest plantation, managed forest, and urban area) and three intensity levels (minimal, light, and intense use) and distinguishes biodiversity responses between plants, mammals, birds, amphibians, and reptiles (Scherer et al., 2023). Land use intensity impacts on FRS are derived by mixed linear regression models using PREDICTS data (Hudson et al., 2017; Newbold et al., 2014). Habitat fragmentation impacts are calculated based on the equivalent-connected area (ECA) that considers the extent to which habitat patches within a region are connected via dispersal (Saura et al., 2011; Saura & Pascual-Hortal, 2007).

$$PDF_j = \left(1 - \left(\frac{(ECA_{r,j} - \sum_{LU} ECA_{LU,j}) + \left(\sum_{LU} FRS_{LU,j}^{1/z_j} ECA_{LU,j}\right)}{ECA_{r,j}}\right)^{z_j}\right) GEP_j \quad \text{(Equation 10)}$$

Land use response relationships are calculated as the PDF/km² of land class-intensity *LU* in region *j* (Equation 11), based on the PDF due to total land use in region *j* (Equation 10), the FRS per land class-intensity, and the total area per land class-intensity.

$$PDF_{LU,j}.km^{-2} = PDF_j \frac{\left(1-FRS_{LU,j}^{z_j}\right)A_{LU,j}}{\sum_{LU}\left(1-FRS_{LU,j}^{z_j}\right)A_{LU,j}} \sum_{LU}\left(A_{LU,j}\right)^{-1} \quad \text{(Equation 11)}$$

We use the country- and taxonomic kingdom-aggregated response relationships (in PDF/km²) from Scherer et al. (2023), distinguishing land use impacts between 204 countries, plants and animals (including mammals, birds, amphibians, and reptiles), and five land use classes and three land use intensities (i.e., 15 land use class-intensity combinations) (Appendix B1).

Multiplying the land use area per year (in km²) per land use class-intensity results in the PDF impact (i.e., the number of species predicted to go extinct globally relative to the total number of species globally). To avoid underestimating land use impacts on biodiversity, we recommend to use the intense land use category if the land use intensity is unknown.

4.4 Aggregating response relationships

To obtain an overall effect on global species extinctions, the PDF impacts for climate change and land use can be combined by summing the PDF per driver d and country j:

$$PDF = PDF_{CC}GMTI + \sum_{LU,j}(PDF_{LU,j}A_{LU,j}) \qquad \text{(Equation 12)}$$

5. Application and outlook

5.1 Application

In this report we presented response relationships for global land use and climate change impacts on ecosystem intactness (via the MSA indicator), species populations (via the LPI indicator), and species extinction risks (via the PDF indicator) based on state-of-the-art biodiversity modelling approaches. These response relationships can be linked to integrated assessment models to enable the quantification of various dimensions of biodiversity.

To showcase this, we linked the derived response relationships in this report to the SSP2 Middle of the Road scenario which is a scenario that follows historical trends in social, economic, and technological development. We derived global land use and climate change impacts on ecosystem intactness, species population declines and species extinction risks for the years 2015, 2030, 2050 and 2070. To do so, input was required on the GMTI (in °C) for the corresponding years and on the land use area for each year (in km^2) per land use class. These input data were obtained through GMTI estimates and land use maps from Kok et al. (2023) (Figure 5).

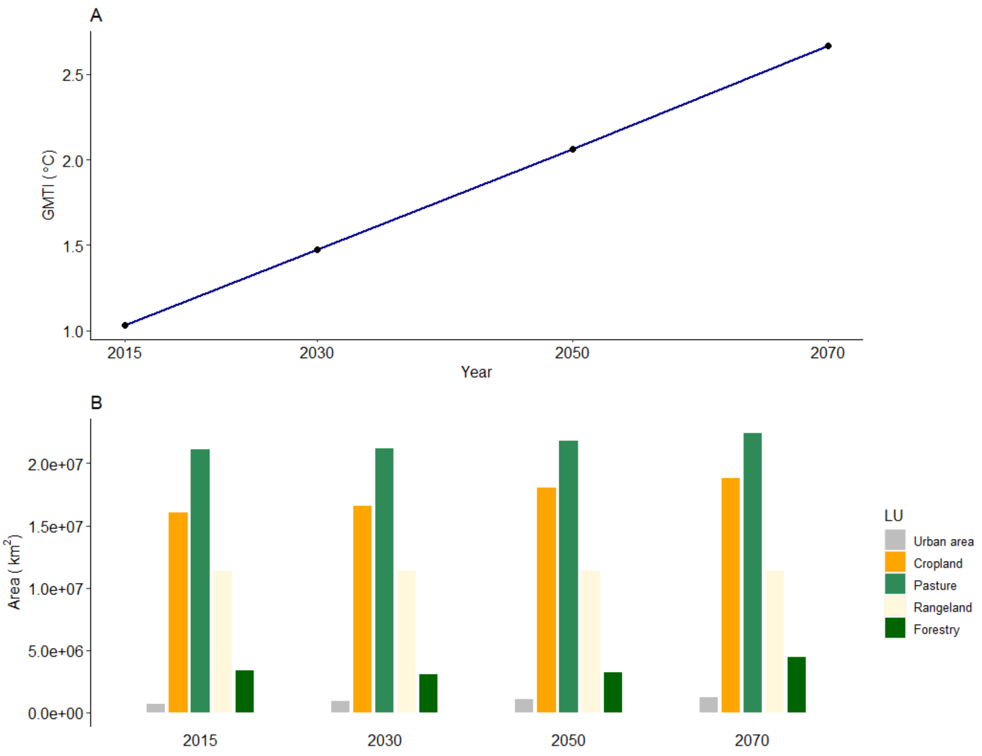

Figure 5. The input data related to the SSP2 scenario for GMTI (A) and area per land use category (B) (from (Kok et al., 2023)).

The global mean temperature increase estimates for 2015 (1.032 °C), 2030 (1.477 °C), 2050 (2.064 °C), and 2070 (2.667 °C) were included in equations 2 and 3 to obtain an MSAL.km^2 due to climate change for plants and vertebrates, multiplied (after subtracting the GMTI in 1970 of 0.056 °C) with the $LPIL_{cc}$ (Table 2) to obtain an LPIL due to climate change for mammals, and multiplied with the $PDF_{CC, vertebrates}$ (Table 4) to obtain a PDF due to climate change for vertebrates.

The land use area per land use class (in km^2) for 2015, 2030, 2050 and 2070 (Appendix B3, Figure 5) were multiplied with the $MSAL_{LU}$ (Table 1) to obtain an MSAL.km^2 due to land use for plants and vertebrates, multiplied (after subtracting the land use area per land use class in 1970 (Appendix B3)) with the $LPIL_{LU}$ (Table 3) to obtain an LPIL due to land use for mammals, and included in equation 11 to obtain the $PDF_{LU, j}$ due to land use in each country. For the $PDF_{LU, j}$, we used the response relationships for the intense land use categories to avoid underestimating land use impacts on biodiversity.

Finally, we combined the separate results according to equations 4, 7 and 12 to obtain overall impacts of climate change and land use on ecosystem intactness, species population declines and species extinctions.

Figure 6. Combined impacts of climate change and land use on (A) plant (green) and warm-blooded vertebrate (orange) local ecosystem intactness (MSAL.km^2); (B) mammal (orange) species population declines (LPIL); and (C) global species extinctions (PDF) of plants (green; only land use impacts) and vertebrates (orange).

The results show that the MSA loss for plants increases over time from ~42M km^2 in 2015 to ~60M km^2 in 2070, and for warm-blooded vertebrates from ~30M km^2 in 2015 to ~42M km^2 in 2070 (Figure 6). In other words, we would lose an extra ~18M km^2 of pristine habitat for plants (equivalent to an area the size of South America) and an extra ~12M km^2 of pristine habitat for warm-blooded vertebrates (equivalent to an area the size of Europe) due to climate change and land use alone. Dividing these numbers by the total terrestrial surface area, shows that the fraction of intact communities is predicted to decrease in 2070 to 53% and 67% for plants and warm-blooded vertebrates, respectively. These predictions are in line with Kok et al. (2023) and Schipper et al. (2020).

The average global decline in mammal populations is predicted to increase from ~21% in 2015 to ~47% in 2070. These results are similar to those found by Kok et al. (2023). Where the decline in mammal populations in 2015 is mainly caused by land use (57% of the total impact), climate change and land use contribute approximately the same proportion of the total impact (i.e., 51% due to land use and 49% due to climate change) in 2070. In other words, the results highlight that reducing the impacts of land use alone will not be sufficient to halt the decline of mammal populations if not accompanied by actions to reduce the impacts of climate change as well.

The number of species predicted to go extinct globally relative to the total number of species is predicted to increase from ~20% in 2015 to ~24% in 2070 for plants, and from ~25% in 2015 to ~38% in 2070 for vertebrates. The estimates for 2015 are in line with the estimated proportion of threatened plant species that range between 20% and 39% (Brummitt et al., 2008; Nic Lughadha et al., 2020) and the estimated proportion of threatened vertebrate species (mammals: 26%; amphibians 41%; birds 12%; and reptiles 21%) (IUCN, 2022). Based on an estimated number of 425,035 plant and 74,962 vertebrate species (IUCN, 2022), we would lose ~18,000 plant and ~10,000 vertebrate species between 2015 and 2070 under the baseline scenario.

These results for the three complementary biodiversity indicators highlight that integrated strategies are urgently needed that contribute to the halting and/or bending the curve of biodiversity loss.

5.2 Outlook

Although the presented response relationships on biodiversity due to climate change and land use covered different aspects of biodiversity, different taxonomic groups and were based on different biodiversity modelling approaches, we foresee several opportunities to further develop the representation of biodiversity responses to human drivers after the DECIPHER project, especially in relation to harmonising the methods underlying the three biodiversity indicators.

The PDF land use response relationships consider plants and terrestrial vertebrates (amphibians, birds, mammals and reptiles) (Scherer et al., 2023); and the PDF climate change response relationships consider terrestrial vertebrates only, excluding plants (Iordan et al., 2023). The MSA response relationships consider plants and terrestrial warm-blooded vertebrates (birds and mammals) (Schipper et al., 2020). The LPI response relationships consider terrestrial mammals only. To improve the harmonisation across the response relationships of the three biodiversity indicators, all response relationships (across the biodiversity indicators and land use and climate change drivers) should consider plants and terrestrial vertebrates (amphibians, birds, mammals, and reptiles). For PDF climate change response relationships this requires an expansion of the climate envelope models to plant species. For MSA response relationships this requires an expansion of the climate change and land use response relationships to amphibians and reptiles. For LPI response relationships this requires an expansion of the GLOBIO-Species model to plants, amphibians, birds, and reptiles. The development of additional plant response relationships is limited by the availability of plant species distirbution data (relevant for the PDF climate change and LPI response relationships). The development of additional plant response relationships is limited by the availability of driver-response relationships (relevant for the MSA and LPI indicators) – this also holds for bird LPI response relationships.

The PDF land use response relationships are differentiated by country because the conversion of land in countries characterised by little remaining natural habitat and high numbers of rare species has higher impacts on global biodiversity than land use in countries characterised by much remaining natural habitat and low species richness. LPI response relationships could potentially be differentiated by country as well, but this requires many computationally intensive GLOBIO-Species simulations (the number of countries times the number of drivers). Because MSA quantifies local ecosystem intactness of impacted sites relative to natural undisturbed sites, MSA response relationships remain spatially generic.

The MSA land use response relationships differentiate between seven land use classes, including differentiation between minimal and intense land use intensities for cropland and pasture (Table 1) (Schipper et al., 2020). The LPI land use response relationships differentiate between five land use classes, without differentiating between land use intensities (Table 3). The PDF response relationships differentiate between fifteen land use classes. Including differentiation between minimal, light and intense land use for cropland, managed forest, pasture, plantation, and urban area (Appendix B1) (Scherer et al., 2023). Ideally, MSA and LPI land use response relationships are further differentiated to match the PDF land use classification. This is currently hampered by the limited data availability on intactness driver-response relationships to different land use intensities and on species population abundance responses to different land use intensities.

Here, we have presented response relationships for two key drivers to global biodiversity (climate change and land use impacts). However, other drivers may also contribute substantially to the global biodiversity decline, such as pollution, invasive species, and direct exploitation (IPBES, 2019). Including response relationships for these additional drivers would enable a more comprehensive evaluation of impacts of human activity on biodiversity.

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Annex A

Table A1. GLOBIO-MSA impacts (MSAL)

Driver	Driver input	MSAL response function	
		Plants	Vertebrates
Climate change	*GMTI* (°C)	$\left(1-\left(1+e^{-(2.87-0.47GMTI)}\right)^{-1}\right)\cdot 1.29\cdot 10^{8}$	$\left(1-\left(1+e^{-(3.21-0.36GMTI)}\right)^{-1}\right)\cdot 1.29\cdot 10^{8}$
Cropland – minimal use	A (km^2)	$0.87A$	$0.46A$
Cropland – intense use	A (km^2)	$0.87A$	$0.64A$
Pasture – minimal use	A (km^2)	$0.75A$	$0.64A$
Pasture – intense use	A (km^2)	$0.81A$	$0.50A$
Forest plantation	A (km^2)	$0.71A$	$0.42A$
Secondary vegetation	A (km^2)	$0.45A$	$0.38A$
Urban area	A (km^2)	$0.69A$	$0.74A$

The value 1.29 x 10^8 represents the total terrestrial surface area, excluding area permanently covered by snow or ice as well as consolidated bare area

Source: (Schipper et al., 2020).

Table A2. GLOBIO-Species impacts (LPIL)

Driver	Driver input	LPIL response function
		Mammals
Climate change	*GMTI* (°C)	0.0867 x $(GMTI_t - GMTI_{1970})$
Urban area	A (km^2)	1.44e-08 x $(A_t - A_{1970})$
Cropland	A (km^2)	2.24e-08 x $(A_t - A_{1970})$
Pasture	A (km^2)	3.43e-08 x $(A_t - A_{1970})$
Rangeland	A (km^2)	4.96e-08 x $(A_t - A_{1970})$
Forestry	A (km^2)	7.74e-09 x $(A_t - A_{1970})$

Table A3. LC-IMPACT impacts (PDF)

Driver	Driver input	PDF response function	
		Plants	Vertebrates
Climate change	$GMTI$ (°C)	NA	$0.0514GMTI$
Land use	A (km^2)	See Appendix B1	See Appendix B1

Source: (Iordan et al., 2023) and (Scherer et al., 2023).