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Original Articles

Global extinction probabilities of terrestrial, freshwater, and marine species groups for use in Life Cycle Assessment

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ABSTRACT

Human activities put pressure on the natural environmental and the Life Cycle Assessment methodology (LCA) is becoming a more prevalent tool to assess the relevant environmental impacts from products and processes on terrestrial, marine and freshwater ecosystems. The Global Life Cycle Impact Assessment Method (GLAM) project of the Life Cycle Initiative hosted by the UN Environment Programme aims at making recommendations for new impact assessment models (such as for land use, water consumption and eutrophication) and improving the consistency and comparability across impact categories. An important aspect to ensure the comparability of these categories across geographic regions is to identify and quantify the scale of impacts, i.e., distinguish if an impact to an area results in local species losses or global species extinctions. This distinction is of high relevance because a species lost at a local level may still exist in other regions of the world and could potentially reestablish in that area, whereas global extinctions are irreversible. A consistent approach to scale impacts from local to global scales is currently not implemented within the LCIA framework, but is crucial to appropriately consider potential biodiversity impacts across impact categories. Here we present an updated approach for calculating a scaling factor, called the Global Extinction Probability (GEP), and calculate it for more than 98 000 species in 20 species groups across marine, terrestrial and freshwater ecosystems. We also provide the GEPs for different spatial scales, such as grid cells, ecoregions or watersheds and country averages. We found that GEP varies over orders of magnitude across the world, emphasizing the relevance of considering the spatial dimension of such extinction probabilities. We recommend quantifying global extinctions based on local species loss by multiplying local species loss within a certain spatial unit with the GEP corresponding to the same spatial unit. GEPs harmonize the quantification of biodiversity impacts across impact categories, improving information to support environmental decision-making.

1. Introduction

Life Cycle Assessment (LCA) is a tool to estimate the relative significance of various environmental and human health impacts associated with the production, use, and disposal of a product (ISO, 2006a; ISO, 2006b). LCAs can be particularly helpful in identifying potential “hot spots” in a value chain, i.e., the emissions or resource uses that have the most significant impact on the environment or human health (Hellweg et al., 2014). Since LCAs strive to take a systems-approach and to be comprehensive, it is imperative to ensure that the number of potential impacts are represented appropriately within the framework. Accordingly, there has been increased effort to incorporate and harmonize a

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broader suite of factors into potential impact categories and areas of protection (AoP) (Bulle et al., 2019; Verones et al., 2020). In this context, the Global Life Cycle Impact Assessment Method (GLAM) project of the Life Cycle Initiative hosted by the UN Environment Programme has aimed to give recommendations for several impact categories, and amongst others, provide guidance for the “ecosystem quality” AoP.

The ecosystem quality AoP mostly relates to impacts on biodiversity (Woods et al., 2018). Since biodiversity plays an essential role in providing ecosystem services (Mace et al., 2012; Driscoll et al., 2018) minimizing potential impacts is viewed as an important component of sustainable development (Visseren-Hamakers et al., 2021). Biodiversity impacts are currently considered in the ecosystem quality AoP through the summing of various human-driven impact pathways including climate change, land use, water use, ecotoxicity, freshwater and marine eutrophication, terrestrial acidification (Verones et al., 2017), and potentially also impacts from marine plastics and fisheries. The comprehensive, and potentially disparate nature of these pathways leads to complexity in compiling and interpreting the data and the calculations of damage levels (Curran et al., 2011; Woods et al., 2018). These complexities highlight the tradeoffs between having multiple metrics to more accurately reflect different impacts and having fewer metrics to help facilitate interpretation of outcomes (Curran et al., 2011; Woods et al., 2018).

The potentially disappeared fraction of species (PDF) is the most used ecosystem quality damage point metric in LCA (Verones et al., 2017). PDF was originally developed to model land-use impacts on plants, and is presented as the mean change in species richness, relative to a local reference site, within a known area and time frame (e.g., PDF × m2 × yr; (Müller-Wenk, 1998; Goedkoop et al., 2000). PDF is a convenient metric in the LCA framework as it can be calculated across taxonomic groups (e.g., birds, fishes, plants) and environmental compartments (e.g., land, freshwater systems). Furthermore, it can potentially be applied, via species sensitivity distributions, to specific stressors (i.e., ecotoxicity), (De Zwart and Posthuma, 2005), and is underpinned by the most robust biodiversity data available, species richness (Teixeira et al., 2016; Verones et al., 2017). Despite this apparent utility, there are still inherent limitations associated with the application and interpretation of PDF across various spatio-temporal scales (Udo de Haes, 2006; Curran et al., 2011; Woods et al., 2018; Côté et al., 2021). For example, PDF estimates at regional and global scales can be very different for widespread (i.e., cosmopolitan) versus geographically constrained (i.e., endemic) species groups; if a cosmopolitan species becomes lost within a specific region, it may persist at a global scale, while an endemic species may become globally extinct if it is lost at a regional level. As a result, there are ongoing efforts to update PDF to more appropriately account for these aspects (Curran et al., 2011; Marques et al., 2017; Woods et al., 2018; Dorber et al., 2019; Kuipers et al., 2019).

Kuipers et al. (2019) presented a scaling approach (Global Extinction Probability (GEP)) that uses species range sizes, global conservation status (IUCN, 2021a), and species richness to indicate the extent to which regional species loss in the respective area may contribute to global species loss. Through the scaling from regional to global extinctions, this methodology allows for species groups in different impact categories within the life cycle impact assessment (LCIA) framework to be more closely aligned with each other. LCIA is the phase of LCA where impact models are developed and where consistency and comparability among these models needs to be ensured. In this manuscript, we update the taxonomic coverage presented in Kuipers et al. (2019) with more species groups, more individual species, and updated data for reported species. We also present a recommendation for a scaling factor that can be consistently applied across impact categories related to the ecosystem quality AoP within the GLAM project and discuss key assumptions and uncertainties.

2. Materials and methods

2.1. Calculation approach

We follow the approach published in Kuipers et al. (2019), who calculated a scaling factor called the global extinction probability (GEP) to upscale potential regional species loss to potential global extinctions. The GEP of species group g in region j (which can be a grid cell, an ecoregion, or any other spatial unit) is calculated as shown in Equation (1).

$$GEP_{g,j} = \frac{\sum_s \frac{\sum_i A_{s,j,i} \bullet O_{s,j,i} \bullet TL_s}{\sum_{j,i} A_{s,j,i} \bullet O_{s,j,i}}}{\sum_s TL_s} \tag{1}$$

where $A_{s,j,i}$ is the part of the range area of species s (belonging to species group g) in region j and grid cell i at a resolution of 0.5° [ha] (i.e. $A_{s,j,I}$ corresponds to the area of grid cell i in e.g. ecoregion j occupied by species s). If j equals a grid cell, j contains a single grid cell, i, only. $O_{i,j}$ is the occurrence-weight value [0–1, dimensionless, see Table 1] of occurrence certainty O of species s in pixel i and region j; and TL_s is the IUCN threat level weight value [1–8, categorical approach, dimensionless] of species s (belonging to group g). This equation shows that GEPs of regions larger than individual grid cells are the sum of the cell-level GEPs within the larger region. The sum of the regional GEPs of a certain species group ($\sum_j (GEP_{g,j})$) equals one, meaning that if all species of the group are lost in all regions, the species group will be extinct globally. A calculation example, including a visual representation of example ecoregions, is included in the Supporting information (SI), section 2.

Kuipers et al. (2019) suggested three different manners to translate the IUCN threat scores into numerical values, namely a linear, a categorical and a logarithmic scale (see Table 2). Note that the certainty of presence (Table 1) is independent of whether a species is data deficient or not (Table 2). Species are classified as “data deficient” if either their “provenance” is unknown, or there is taxonomic uncertainty and data is very uncertain (IUCN, 2022). It is important to note that, in many cases, background knowledge about changes in habitat or their causes are sufficient to assign a threat category, in spite of little knowledge about a species (IUCN, 2022).

We decided on following the categorical approach, as suggested in Montesino Pouzols et al. (2014). A logarithmic approach gives extremely different values to species at the ends of the threat level spectrum, while there is not much difference between the species in a linear approach. The categorical approach lies in between these two extremes. The sensitivity of the choice of approach is discussed in Kuipers et al. (2019) and further discussed in section 4.2 on value choices.

Given the similar scope between GEP and the IUCN Range-size Rarity metric, RR (IUCN, 2021b), a comparison was conducted between cell-level GEP and normalized RR. IUCN spatial data (IUCN, 2021c) were used to calculate the RR exemplarily for terrestrial mammals, terrestrial reptiles and amphibians. More details about the comparison are provided in the SI (section 3).

Table 1
Values for occurrence certainty per pixel and species (as used in Kuipers et al. (2019), taken from Montesino Pouzols et al. (2014)).

Species presence	Occurrence certainty
Extant	1.0
Probably extant	0.5
Possibly extant	0.5
Possibly extinct	0.1
Extinct	0.0
Presence uncertain	0.0

Table 2
Overview of approaches to translate the IUCN Red List Threat level categories into numbers, as used in Kuipers et al. (2019). We focus on using the categorical approach (shown in italics), which is taken from Montesino Pouzols et al. (2014).

Threat level category	Linear approach	*Categorical approach*	Logarithmic approach
Extinct (incl. extinct in the wild and regionally extinct)	0.0	*0.0*	0.0
Critically endangered	1.0	*8*	1.0
Endangered	0.8	*6*	0.1
Vulnerable	0.6	*4*	0.01
Lower risk	0.4	*2*	0.001
Near-threatened	0.4	*2*	0.001
Least concern	0.2	*1*	0.0001
Data deficient	0.2	*2*	0.0001

2.2. Species coverage and data

We cover plant and animal species groups from all three major ecosystem types – terrestrial, freshwater, and marine – and across seven phyla/divisions as well as fungi species in freshwater ecosystems across two divisions (Table 3). For terrestrial ecosystems, we developed scaling factors for vascular plants, terrestrial mammals, terrestrial reptiles, amphibians, and birds. For freshwater ecosystems, we developed scaling factors for vascular plants, freshwater bony fishes, various other animal species groups, and, as mentioned, fungi. For marine ecosystems, we developed scaling factors for seagrasses, marine mammals, marine reptiles, marine ray-finned fishes, cartilaginous fishes, lobsters, sea cucumbers, and stony corals.

Kuipers et al. (2019) based their data for ranges and threat levels reported by IUCN. We downloaded all spatial datasets to have the most up-to-date species numbers and threat scores available. The IUCN data covers all species groups analysed here, except for freshwater fish and terrestrial vascular plants. For freshwater fishes, we expanded the IUCN data with a dataset from Barbarossa et al. (2021) who compiled additional geographic range polygons based on point occurrence records following IUCN's procedure. For the latter, we assumed a presence of 1 (i.e., the species is "extant", see Table 1). Moreover, we added terrestrial vascular plants from a dataset of Borgelt et al. (2022), as this species group has limited spatial data available from IUCN. These authors modelled the native distribution of red-listed species based on point occurrence records and environmental data and provided the probability of presence at a resolution of 0.5°.

3. Results

3.1. Spatial pattern of global extinction probabilities

Fig. 1 to Fig. 3 show results for grid level (0.05°, i.e., ~5.5 km^2 near the equator) GEPs for vascular plants, freshwater ray-finned fish and marine ray-finned fish, as well as GEPs per terrestrial ecoregion and per catchment for vascular plants and freshwater ray-finned fishes, respectively. The maps for the remaining species are shown in the supporting information (Figures S1 to S60). The grid level GEP can vary over several orders of magnitude, depending on the present species' threat level, their range areas and their occurrence certainty. A pixel may, for example, contain a high GEP if many species of the group assessed present there are listed as more endangered on the IUCN Red List, if they are very small-ranged or even endemic, or both. The absolute number of present species is irrelevant (see Equation (1)). Thus, the GEP shows pixels that contain species communities that are at a higher risk of becoming extinct. Aggregated to ecoregion levels, it is, for example, evident, that Madagascar's vascular plants and terrestrial mammals are facing large pressures due to many endemic species and thus have a large GEP (Fig. 1 and Figure S2). The highest GEP for freshwater fish is found in the Congo basin (Fig. 2), and for marine ray-finned fish, the highest GEPs (considering the potential bias for data availability) are located along the coastlines and around islands (Fig. 3).

3.2. Comparison with previous version and the range rarity maps of IUCN

The update of the GEPs presented in this study, compared to Kuipers et al. (2019), resulted in an increase of 115 % of species covered globally, from 45,595 to 98,212 species (Table 4). The increase in total cumulative area covered (i.e., the sum of all species geographic ranges) is

Table 3
Species groups included in the GEP calculations.

Ecosystem type	Species group (common name)	Species group (scientific name)	Taxonomic rank	Phylum/Division/Kingdom
Terrestrial	Vascular plants	Tracheophyta	Division	Tracheophyta
	Birds	Aves	Class	Chordata
	Reptiles	Reptilia	Class	Chordata
	Amphibians	Amphibia	Class	Chordata
	Mammals	Mammalia	Class	Chordata
Freshwater	Freshwater plants	Tracheophyta	Division	Tracheophyta
	Birds	Aves	Class	Chordata
	Reptiles	Reptilia	Class	Chordata
	Amphibians	Amphibia	Class	Chordata
	Mammals	Mammalia	Class	Chordata
	Freshwater fishes	Osteichthyes	Superclass	Chordata
	Crabs	Brachyura	Infraorder	Arthropoda
	Crayfishes	Astacoidea and Parastacoidea	Superfamilies	Arthropoda
	Dragonflies and damselflies	Odonata	Order	Arthropoda
	True shrimps	Caridea	Infraorder	Arthropoda
	Molluscs	Mollusca	Phylum	Mollusca
	Fungi	Agaricomycetes, Lecanoromycetes	Class	Fungi
	Branchiopods	Branchiopoda	Class	Arthropoda
	Clitellates	Clitellata	Class	Annelida
Marine	Seagrasses	Alismatales	Order	Tracheophyta
	Mammals	Mammalia	Class	Chordata
	Reptiles	Reptilia	Class	Chordata
	Ray-finned fishes	Actinopterygii	Class	Chordata
	Cartilaginous fishes	Chondrichthyes	Class	Chordata
	Lobsters	Nephropidae	Family	Arthropoda
	Sea cucumbers	Holothuroidea	Class	Echinodermata
	Stony corals	Scleractinia	Order	Cnidaria

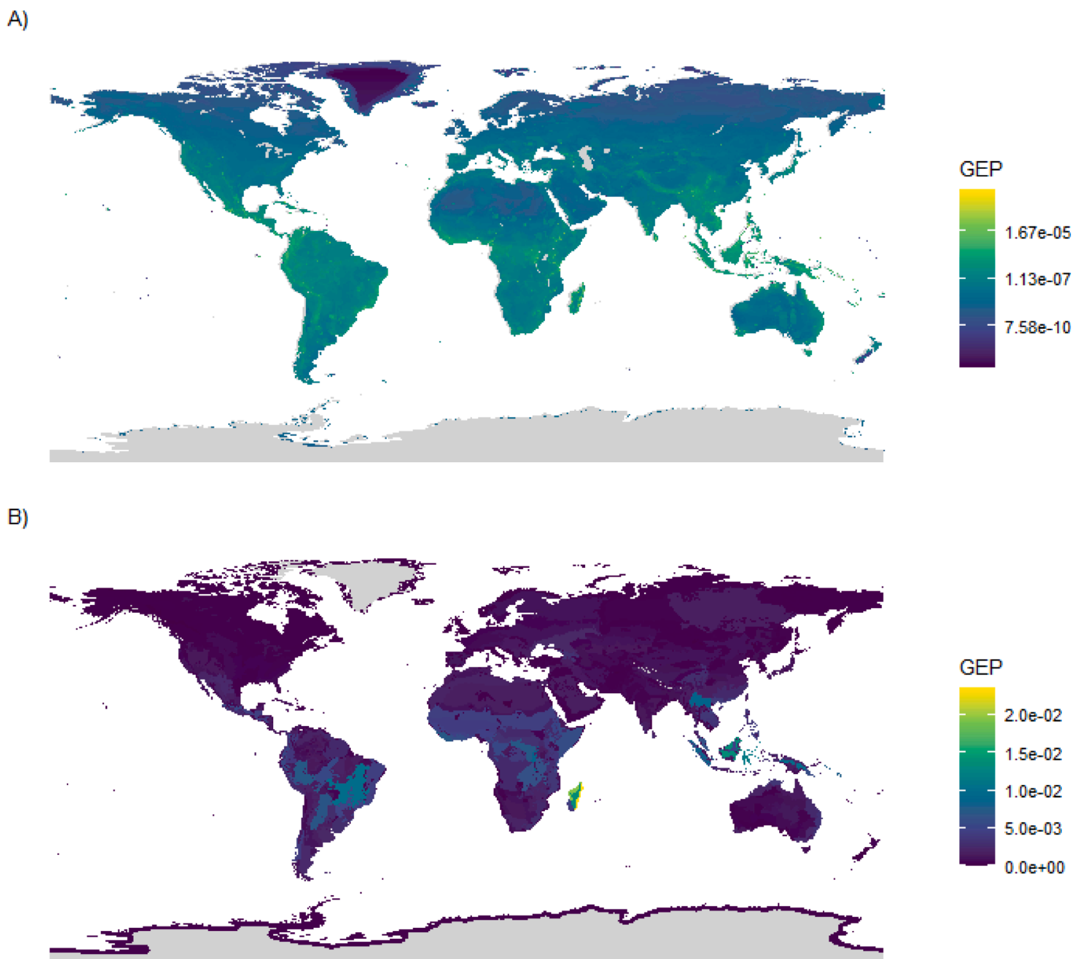

Fig. 1. GEP (log-scale) for terrestrial vascular plants (n = 26,976) on A) grid level (0.05°) and B) per terrestrial ecoregion.

71 %, from 98 to 168 billion km^2 across all realms (Table 4). Several new species groups are introduced in this study - most notably vascular plants (n = 26,976) in the terrestrial realm (Table 4). In addition, many species have been added to existing groups from updated IUCN geographic range records and/or external datasets. Freshwater species show the largest update, with an increase of 150 % species covered (from 13,069 to 32,662 species), closely followed by terrestrial species, with a 110 % increase in coverage, from 27,836 to 58,466 species (Table 4). Marine species report the smallest update in terms of species, with an increase of 51 %, from 4,690 to 7,084 species. Cumulative area covered increase is highest for freshwater categories, which reported a 241 % increase (from about 11 to 36 billion km^2), followed by terrestrial categories (80 % increase, from 51 to 91 billion km^2). While the increase in species is substantial in the marine realm, cumulative area covered is higher only by 10 % (from 37 to 41 billion km^2).

The spatial pattern of RR and GEP is similar. However, because the GEP considers species IUCN threat levels in addition to range rarity richness, regional differences are more extreme compared to RR. Furthermore, this may result in highlighting regions that are characterised by many endangered species (Fig. SI1, SI3, SI5, SI61, SI62, SI64, SI65, SI67, SI68).

For the three species groups analysed for this comparison, the minimum and maximum values of the GEP are one order of magnitude larger and smaller than the minimum and maximum values, respectively, of the normalized RR. On a 0.05° grid cell resolution, 95 % of GEP values for terrestrial mammals fall between 2.9E and 10 and 8.8E-07, those for amphibians between 4.9E and 11 and 6.9E-07, and those for terrestrial reptiles between 6.6E and 11 and 9.7E-07. Although 95 % of normalized RR values for terrestrial mammals fall in the same range as the GEPs for the same species group, this is not the case for the other two species groups: 95 % of RR values for amphibians range from 3.7E to 10 to 1.1E-06, and those for terrestrial reptiles from 2.6E to 10 and 1.1E-06 (see SI section 3 for more details).

The relative difference, calculated as the difference per grid cell between the GEP and the normalized RR divided by the average of the two values, take values between −2 and 2 (Fig. SI63, SI66, SI69), analogous to the results above. That means that high- and low-priority areas are characterized by a bigger contrast in GEP than in RR. Furthermore, by definition, GEP highlights locations with threatened species and host small-ranged species (because of the combination of the TL and the occurrence), which is not the case with RR.

For the comparison of vascular plant GEP in this work to normalized endemic species richness from Kier et al. (2009) for 300′000 species, we processed the 90 regions of Kier and colleagues to half degree resolution, in the same way as it was done for the use as proxy vulnerability score of the LCIA land use method recommended by the UNEP-SETAC working group (Frischknecht et al., 2016; Verones et al., 2019). The results showed in general a similar pattern (Figures S70 and S71). Comparability is limited, because while species coverage of the method based on Kier et al. (2009) is about 10 times larger than in our approach, the regional resolution is considerably lower. The low resolution can explain some of the regional differences, especially the larger difference in low GEP values, which is probably an overestimation in the previous work due to the aggregation into 90 regions of the world. Additional details on the comparison are available in SI section 4 (Figs. S70-72).

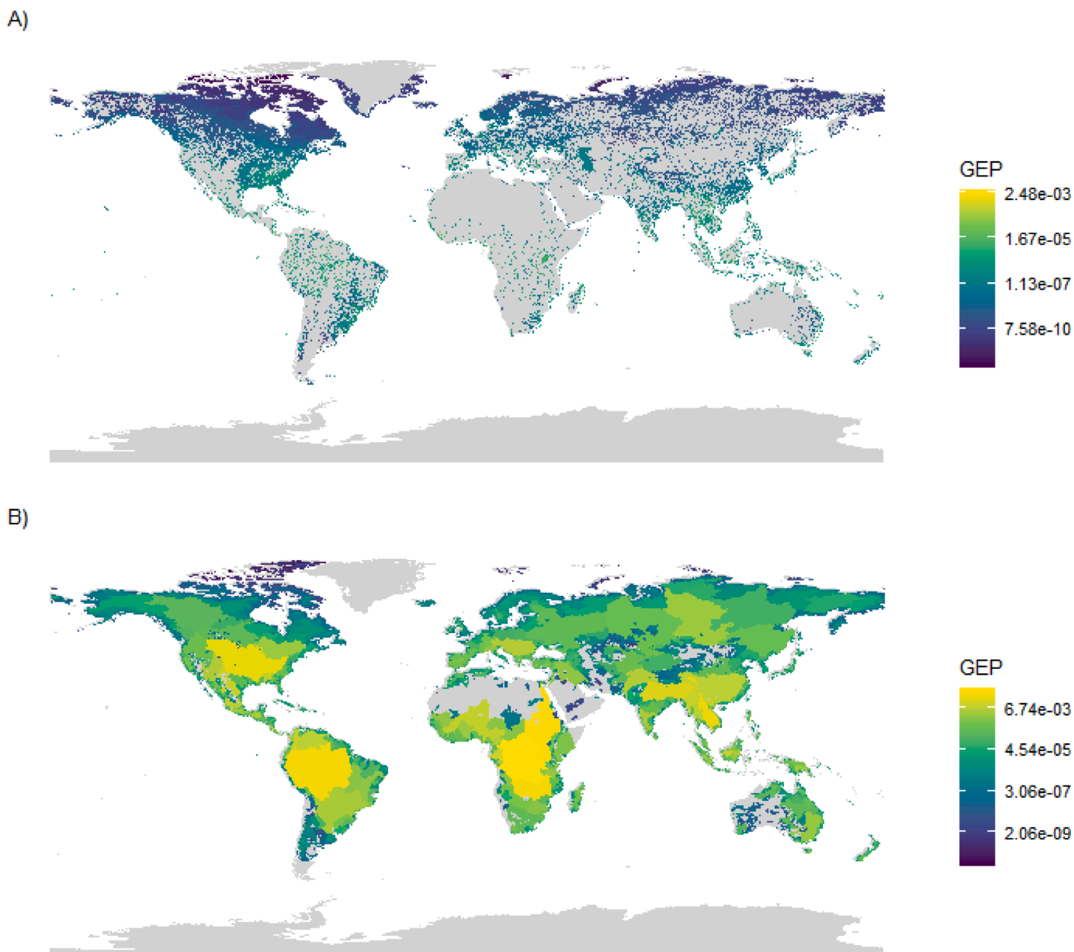

Fig. 2. GEP (log-scale) for freshwater fish (n = 14,506) on A) a grid level (0.05°) and B) for watersheds.

4. Discussion

4.1. Applicability

GEP can be applied by multiplying the characterization factors (CFs) of an impact category representing local species loss with the GEP for the same species group. We distinguish two types of impact category indicators for GEP applicability: 1) those where CFs correspond to individual species groups (e.g., separated sets of CFs for terrestrial vascular plants, mammals, birds, reptiles, and amphibians in the land use impact category, as e.g. in (Chaudhary et al., 2015; Kuipers et al., 2021b)), see Equation (2) for application, and 2) those where CFs correspond to several species groups combined (e.g., CFs for the freshwater ecosystem in ecotoxicity consider freshwater fish and gastropods together (Rosenbaum et al., 2008)). That means that in the latter case we consider all available species groups that are included in the calculation of the mixture CFs for the calculation of the GEP as shown in Equation (1). For ecotoxicity this means, for example, that we consider all species groups g of which species were included in the derivation of the species sensitivity distributions (SSDs). Imagine for example an SSD containing information on a freshwater fish species, a freshwater bird and a freshwater insect. The corresponding GEP will include *all* available freshwater fish, *all* freshwater birds, and all freshwater insects for which we have information available, even if they do not match the individual species included in the SSDs. The implicit assumption is that both the species included in the SSD and the species included in the GEP (even though not necessarily the same) are proxies for representing the "freshwater ecosystem".

$$CF_{global} = \sum_{g} CF_{regional,g} \bullet GEP_g \tag{2}$$

Also, as highlighted in Kuipers et al. (2019), the spatial scale of the CF and GEP must be the same to properly translate impacts on the regional biodiversity to global biodiversity loss. For all impact categories, except ecotoxicity, the finer, common spatial scale of GEPs is the country scale, terrestrial ecoregion or watershed level, which means that contribution from different categories to global PDFs can be done at these scales of analysis. Ecotoxicity CFs are spatially generic (i.e., emissions happen in a generic world, or a world reparametrized as an average continent at best), which render comparisons of impacts on global biodiversity across categories only feasible at continental scale.

The GEPs presented here match the requirements of the species groups covered within the GLAM methodology for ecosystem quality currently under development (Life Cycle Initiative, 2020). The implementation of the updated GEP allows for a consistent quantification of global species loss across the impact categories that are collected under the ecosystem quality Area of Protection. In addition, all impact categories themselves allow for an assessment of regional species loss. We believe that it is important to be able to assess both regional and global consequences of human impacts. Notwithstanding, GEP can also be applied within any other LCIA model that estimates damages on ecosystem quality in terms of regional PDFs, using the same GEPs per impact category as here, if the underlying LCIA method, thus species covered, is the same. New GEPs can be calculated with the provided code, if needed. For instance, land occupation impacts on biodiversity are characterized in Impact World+ (Bulle et al., 2019) based on de Baan

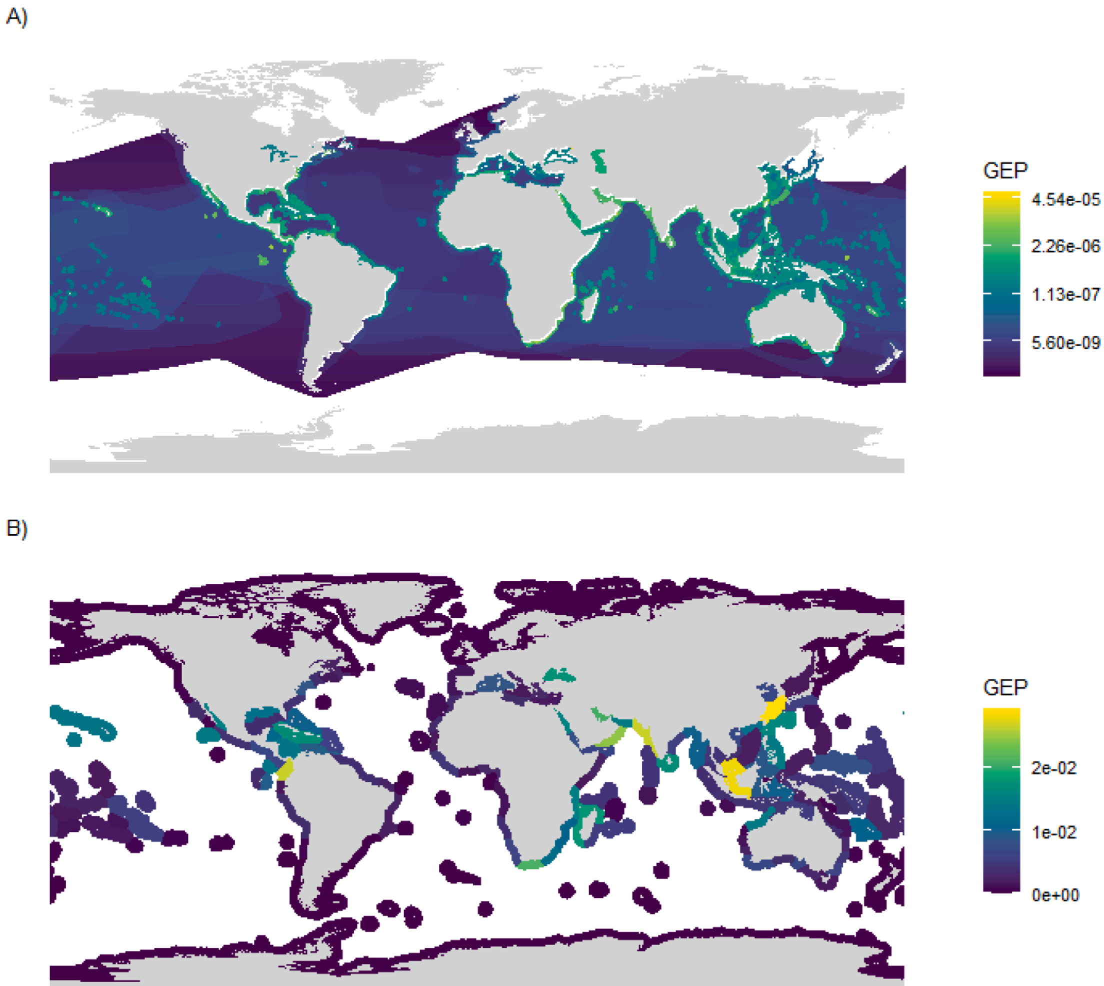

Fig. 3. GEP for marine ray-finned fishes (n = 4173) on a A) grid level (0.05°) and B) in the marine ecoregions of the world.

et al. (2013a), who distinguished plants (split into mosses and vascular plants), arthropods, other invertebrates, and vertebrates (split in birds and a group with mammals, reptiles, and amphibians) as species groups. In this case, a new GEP that lumps together mammals, reptiles, and amphibians has to be calculated based on the individual GEPs, while the translation from regional to global impacts can be easily made for vascular plants and birds. Additionally, to ensure future applicability, new GEPs will have to be developed or updated when the GLAM method is revised with additions of, for instance, new species groups (see Table 4), in this case mosses, arthropods and other invertebrates, and improved spatial resolution. It is also possible to calculate, if needed, GEPs for smaller and more specific species groups, e.g. for different orders or functional groups.

4.2. Value choices

To calculate GEPs, the IUCN threat level needs to be converted to a numeric value and several approaches to do so exist. For this paper we used a “categorical approach” (ranging from 1 to 8), as suggested in Montesino Pouzols et al. (2014). Kuipers et al. (2019) also suggested a “linear” approach (ranging from 0.2 −1) and a “logarithmic” approach (ranging from 1 × 10ˆ-4 to 1) (see also Table 2). In addition, Mooers et al. (2008) suggested five different approaches: “Isaac” (ranging from 0.025 to 0.4), “IUCN100” (ranging from 0.0001 to 0.99), “IUCN50” (ranging from 0.00005 to 0.97), “IUCN500” (ranging from 0.005 to 1) and “Pessimistic” (ranging from 0.2 to 0.99). The “Pessimistic” approach is in its range similar to the “linear” approach and “IUCN50”, “IUCN100”, “IUCN500” relate to the “logarithmic” approach. In summary, each of the arbitrarily defined approaches gives a different weight to endangered species (Kuipers et al., 2019). However, Kuipers et al. (2019) highlighted that the GEP will show the same pattern, independent of which approach will be used. The main difference is that the bigger the difference between lowest and highest value in the approach, the more pronounced the regional differences are. Consequently, the “linear” and “categorial” approaches will likely result in a more similar pattern, while the “logarithmic” approach will have more emphasis on areas with high species richness and many endemic species (e.g., equatorial regions and tropics). Although Mooers et al. (2008) and Kuipers et al. (2019) suggested several potential approaches, neither author exclusively recommended one approach. The absence of a clearly preferred methodology is because the conversion of the qualitative IUCN threat scores into a quantitative scheme is arbitrary and includes value choices for how much weight should be placed on the different levels of threat. For example, we ranked the “Data Deficient” category similarly to “Near-threated” and “Vulnerable” (Table 2) to reflect both the uncertainty in classification and general belief that “Data Deficient” species may actually be endangered (Parsons, 2016). Overall, we opted for the “categorical” approach, which was viewed as a middle ground between the linear and logarithmic approaches. While the overall pattern of the GEP will not change because of a given approach, the results would likely become more or less pronounced between different regions, leading to different weights per region.

Table 4
Updated number of species and cumulative range area covered. The table reports the total number of species and cumulative range area (i.e., the sum of all range areas of the species) for this study and Kuipers et al. (2019).

		Species no.		Cumulative range area [km^2]	
Realm	**Species group**	**This study**	Kuipers et al., 2019	**This study**	Kuipers et al., 2019
Terrestrial	Vascular plants	26,976	–	3.97E + 10	–
	Birds	10,966	11,120	3.73E + 10	3.69E + 10
	Reptiles	7,723	4,923	4.61E + 09	2.76E + 09
	Amphibians	7,081	6,490	1.80E + 09	1.79E + 09
	Mammals	5,720	5,303	8.02E + 09	9.31E + 09
Freshwater	Freshwater plants (autotrophs)	1,722	1,323	5.93E + 09	5.83E + 09
	Birds	2,384	–	1.45E + 10	–
	Reptiles	427	–	4.03E + 08	–
	Amphibians	4,680	–	1.68E + 09	–
	Mammals	140	–	3.86E + 08	–
	Freshwater fish*	14,507	6,410	6.90E + 09	1.96E + 09
	Cartilaginous fishes	39	–	4.69E + 07	–
	Malacostracans (crabs + crayfish)	2,476	2,454	8.23E + 08	8.23E + 08
	Dragonflies and damselflies	3,800	1,476	3.49E + 09	1.06E + 09
	Molluscs	2,469	1,406	2.25E + 09	1.01E + 09
	Fungi	3	–	2.02E + 07	–
	Branchiopods	5	–	9.98E + 03	–
	Clitellates	10	–	3.97E + 06	–
Marine	Seagrasses	72	72	2.19E + 08	2.21E + 08
	Mammals	129	125	7.12E + 09	7.30E + 09
	Reptiles	95	–	1.25E + 09	–
	Ray-finned fishes	4,173	2,562	1.68E + 10	1.70E + 10
	Cartilaginous fishes	1,158	1,088	5.37E + 09	4.84E + 09
	Lobsters	246	–	9.09E + 08	–
	Sea cucumbers	369	–	1.24E + 09	–
	Stony corals	842	843	7.61E + 09	7.61E + 09
Total		*98,212*	*45,595*	*1.68E + 11*	*9.84E + 10*

* This group includes ray-finned fish, lobe-finned fish, cephalaspidomorphs.

4.3. Comparability among terrestrial and aquatic ecosystems

GEP on a grid cell represents the share of the range of all species covered within a species group that is present in the grid cell (adjusted by the threat level weighting). Since the cumulative range area depends on the species included, the selection of species used in the calculation influences the GEP. If we compare the total ranges of species covered per realm, we get 91 billion km^2 for terrestrial, 41 billion km^2 for marine and 36 billion km^2 for freshwater. However, we have quite a different number of species covered in these realms and thus the average range is 1.6 million km^2 for terrestrial, 5.7 million km^2 for marine and 1.1 million km^2 for freshwater species. Given that freshwater and terrestrial ranges are both calculated per terrestrial area, the average range area per realm is very similar (1.6 million km^2 vs 1.1 million km^2), while it is expected that marine ranges are larger per species, because these species are distributed over larger areas. If we investigate the details of the ranges, we see a bigger difference among species groups within the realms, especially for freshwater. This difference in average range area shows that it is relevant to include as many species as possible to also cover as much area as possible. On average, the GEP results should, however, be directly comparable among realms, under the assumption that the area is a good proxy for the relevance of each grid cell. This might be challenged for marine, as well as freshwater ecosystems, where a third dimension is present. However, most waterbodies feature some stratification which limits the vertical extent of the ecosystem. For marine ecosystems, coastal zones are often highly important (e.g., for breeding) and due to the limited depth in coastal regions, range area (rather than volume) might be an acceptable proxy for the purpose of comparing GEPs across realms. We are, however, acknowledging that the available knowledge on deep ocean species is limited. In general, there is a bias of knowledge with more knowledge in more accessible regions in human proximity and less knowledge in remote and unexplored regions.

4.4. Uncertainties and limitations

The taxonomic coverage of our work is still limited and reflects the bias in the availability of the underlying biodiversity data (Troudet et al., 2017), meaning that the existing species have to act as (rather) coarse proxies for the remainder of species. Insects or soil-dwelling organisms are, for example, missing sufficient knowledge and spatial information and are thus not included at this point in time and there is little knowledge on whether the included species are representative for the taxonomic group. Therefore, GEP values should be updated regularly, especially when new data becomes available. In addition, available data shows both a bias towards higher trophic levels, as well as a geographic (Hughes et al., 2021). Finally, data in the characterization factors themselves (e.g., in SSDs) may be biased towards more sensitive species.

Studies show a weak or no correlation between the species richness between different taxonomic groups and also how they respond to different anthropogenic pressures, such as land use changes (e.g. (Michelsen and Lindner, 2015)). However, taking such differences into account when modelling global biodiversity responses to anthropogenic impacts is very challenging and is strongly linked to the limited data availability for species, and therefore the inclusion of GEP as described in this paper is the most advanced approach to ensure an inclusion of global scale impacts when PDF is applied.

While PDF is the most commonly used biodiversity indicator in LCA (Verones et al., 2017; Crenna et al., 2020), and also the foundation of GEP, the extrapolation of it across all species and CFs should be carefully considered. It is also important to note that biodiversity is a multidimensional concept (e.g., it includes genetic diversity, species diversity, interactions and the diversity between ecosystems) and therefore cannot be captured by a single indicator (Pereira et al., 2013; Purvis, 2020). When applying CFs reported in PDF (with or without the GEPs provided by this study) and analyzing its results, it is important to keep in mind that impact assessments using other indicators (for example, functional diversity (e.g. (de Souza et al., 2013; Scherer et al., 2020) or genetic diversity) could potentially provide different results and interpretations. Coupling species richness with other biodiversity indicators has been discussed as a future way to add comprehensiveness to impact assessments using LCA (Marques et al., 2021).

5. Recommendations and guidelines for application

GEPs can be used both for impact categories that are species group specific (as is e.g., the case for land use, which takes several specific species groups into account, Equation (2)) or that contain a mixture of species groups (such as in ecotoxicity). For the latter case, we recommend using entire species groups and not just individual species for delineating a GEP (e.g., use all the fish species if some fish species were used for delineating the CF). All CFs aim to represent the "ecosystem quality", hence all included species always act as proxies for the rest of the ecosystems. By trying to take as large as possible a sample of the GEP into account, we want to ensure that we represent as many niches in the respective ecosystems as possible. The code to calculate a GEP based on a defined set of species groups is available for download on Zenodo (https://doi.org/10.5281/zenodo.6412149).

GEPs can be applied to any CFs included in the ecosystem quality AoP at a multitude of spatial scales (e.g., the native scale of the CF, country level) through a simple multiplication of the CF and the GEP. Since the GEP is first calculated at pixel level, it can be aggregated to all required spatial units. It is important to note that the GEP should always be multiplied by the local CFs with *corresponding* spatial units. That means that if e.g., the CF is at a native scale, the GEP has to be aggregated to the same spatial scale (e.g. terrestrial ecoregions or watersheds). The native scale of a CF is defined as the resolution that best represents the spatial characteristics of the impact category in question (Mutel et al., 2018). Examples are terrestrial ecoregions for land use impact assessments (de Baan et al., 2013b; Chaudhary et al., 2015; Kuipers et al., 2021a) or watersheds for water consumption (Hanafiah et al., 2011; Verones et al., 2013; Tendall et al., 2014). Similarly, if the CFs are at another level of aggregation (e.g., country or continental scales), the GEP needs to be aggregated to the same spatial units before they can be multiplied with the CFs.

$$CF_{country} = \frac{CF_{ecoregion1} \bullet Area_{ecoregion\ 1\ in\ country} + CF_{ecoregion2} \bullet Area_{ecoregion\ 2\ in\ country}}{Area_{country}} \bullet GEP_{country}$$
$$= \frac{CF_{PA0436} \bullet Pixels_{PA0436} + CF_{PA0412} \bullet Pixels_{PA0412}}{Pixels_{Lithuania}} \bullet GEP_{country} = 6.44 \bullet 10^{-17} PDF \Big/ m^2 \quad (3)$$

$$CF_{country\ \ WRONG\ \ APPROACH} = \frac{CF_{PA0436} \bullet Pixels_{PA0436} \bullet GEP_{PA0436} + CF_{PA0412} \bullet Pixels_{PA0412} \bullet GEP_{PA0412}}{Pixels_{Lithuania}}$$
$$= 1.21 \bullet 10^{-15} PDF \Big/ m^2 \quad (4)$$

Let us take the example of land use, more specifically looking at inundation of 1 m^2 of natural land in Lithuania. Lithuania is located in 2 terrestrial ecoregions, PA0412 and PA0436, and Dorber et al. (2019) provide a local ecoregion CF for mammals for each of these regions (Table 5.

Table 5
Terrestrial ecoregions in Lithuania, their corresponding local CFs, GEPs and number of pixels of these ecoregions within the country based on Dorber et al. (2019).

Lithuania	PA0436	PA0412
CF ecoregion level [PDF/m2]	1,49E-12	1,69E-12
GEP ecoregion level	0,00062	0,001049
GEP country level	4,13E-05	4,13E-05
Pixels	2443	1242

The CF at ecoregion level represents the local impact on the species communities, i.e., a local loss of species. The global consequences of this local loss are shown by multiplying the ecoregion level CF and the ecoregion level GEP and represent a global loss of species. It does not mean that more land or surrounding land is lost, but since species can be highly threatened or endemic or very common, the global consequences for the well-being of species communities will differ from the local ones.

If we want to use the CFs at a country level, we have to make sure both the CF and the GEP are aggregated on a country basis. This is implemented in the code for the GEP, and we suggest using an area-based average for converting the ecoregion CFs to a country level CF for land use before multiplying it with the GEP (Equation (3)). As shown in Equation (4), multiplying with the GEP before aggregating to another spatial aggregation will yield different results (and it will prevent the GEP from adding up to 1 globally). We strongly advise against using the GEP in this way. The correct application is the one in Equation (3).

LCIA covers now important impacts that are related to terrestrial, freshwater and marine ecosystems. All these ecosystems are very different from each other, and we recommend reporting impacts on ecosystems also separately for the different ecosystem types, to show the relevance of different impacts for each of them.

We want to stress that both the regional or local characterization factors and the global ones are equally important. The global ones are relevant for highlighting issues related to worldwide and irreversible loss of species, while local characterization factors are relevant to assess the impacts on the functioning of local ecosystems. We therefore recommend using whenever possible both types of characterization factors.

CRediT authorship contribution statement

Francesca Verones: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision. **Koen Kuipers:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Software, Formal analysis, Visualization, Data curation. **Montserrat Núñez:** Methodology, Writing – original draft. **Francesca Rosa:** Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Visualization. **Laura Scherer:** Methodology, Writing – original draft, Writing – review & editing, Formal analysis. **Alexandra Marques:** Methodology, Writing – original draft, Writing – review & editing. **Ottar Michelsen:** Methodology, Writing – original draft, Writing – review & editing. **Valerio Barbarossa:** Methodology, Writing – original draft, Writing – review & editing, Formal analysis. **Benjamin Jaffe:** Methodology, Writing – original draft, Writing – review & editing. **Stephan Pfister:** Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Visualization. **Martin Dorber:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Software, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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