

Land Use in Life Cycle Assessment: Global Characterization Factors Based on Regional and Global Potential Species Extinction

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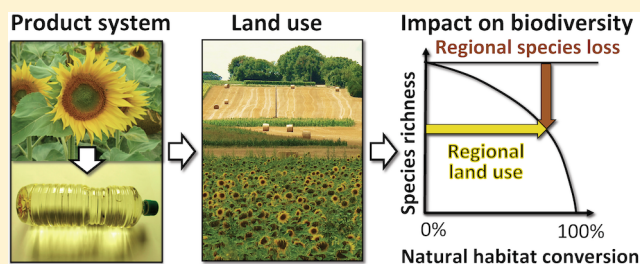
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S Supporting Information

ABSTRACT: Land use is one of the main drivers of biodiversity loss. However, many life cycle assessment studies do not yet assess this effect because of the lack of reliable and operational methods. Here, we present an approach to modeling the impacts of regional land use on plants, mammals, birds, amphibians, and reptiles. Our global analysis calculates the total potential damage caused by all land uses within each WWF ecoregion and allocates this total damage to different types of land use per ecoregion. We use an adapted (matrix-calibrated) species-area relationship to model the potential regional extinction of nonendemic species caused by reversible land use and land use change impacts. The potential global extinction of endemic species is used to assess irreversible, permanent impacts. Model uncertainty is assessed using Monte Carlo simulations. The impacts of land use on biodiversity varied strongly across ecoregions, showing the highest values in regions where most natural habitat had been converted in the past. The approach is thus retrospective and was able to highlight the impacts in highly disturbed regions. However, we also illustrate how it can be applied to prospective assessments using scenarios of future land use. Uncertainties, modeling choices, and validity are discussed.



INTRODUCTION

Life cycle assessment (LCA) is a methodology for quantifying the environmental impacts of products and processes over their entire life cycle.¹ LCA results can highlight reduction potentials of environmental impacts and help to avoid solutions that simply shift burdens between different environmental compartments (e.g., reducing CO₂ emissions but increasing pressure on biodiversity) or between different life cycle stages of products. LCA studies should ideally capture all environmentally relevant aspects of economic activities, but for some aspects, such as land use impacts on biodiversity, reliable methods are still lacking.^{2,3} Because land use is a main driver of global biodiversity loss,^{4–7} it cannot be ignored in environmental decision-making.

Biodiversity is a multifaceted concept that encompasses different hierarchical levels of life (genes, species, populations, and ecosystems) and their various attributes (composition, function, and structure),⁸ including strong spatial and temporal dynamics. Different indicators have been proposed for measuring land use impacts on biodiversity in life cycle impact assessment (LCIA).^{9,10} Many existing methods quantify biodiversity loss based on differences in local species richness between land use types; however, some studies included other biodiversity indicators, such as ecosystem scarcity and vulnerability,^{11,12} functional species diversity,¹³ and the biophysical impacts of land use on ecosystem services.^{14–16}

For assessing impacts on species richness, most methods were developed for specific world regions, such as Central and Northern Europe,^{17–23} Malaysia/Indonesia,²² Japan,²⁴ and California.²⁵ Extrapolating results from one region to others poses a challenge because biodiversity varies strongly across regions, and the required input data are often only available for one or a few countries or regions. Data availability also limits the range of taxonomic groups that are evaluated within LCA. Although results have been shown to depend on the assessed taxonomic groups,^{21,26} most methods are based on only a single taxon, mainly vascular plants,^{12,17,19,22–24,27} but also vertebrates.²⁵ Only a few authors proposed globally applicable land use LCIA methods. Two early studies combine global plant species richness maps with information on the impact of different land use types.^{12,27} One recent study used empirical data for multiple taxonomic groups to calculate the relative difference in species richness of different land use types and regional reference habitats for various biomes.²⁶ However, this previous study considered only *local* land use impacts and did not consider impacts of land use *change* and results remained at a coarse spatial resolution (biomes).

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In the present study, we focus on quantifying potential species extinction due to land use. The concept of extinction is highly relevant to public debates about biodiversity loss and is clearly communicable to decision-makers. Land use activities can contribute to local, regional, or even global species extinction, which show different degrees of reversibility. For example, converting one hectare of rain forest to cropland can lead to a local displacement of about 50% of all species.²⁶ If viable populations of these locally displaced species still exist in adjacent rain forest areas, they can gradually recolonize the cleared field after it is abandoned. In this case, local impacts are (to a large extent) reversible, although decades or centuries might be needed for full biodiversity recovery.²⁸ The risk of regional extinction of species increases if only small remnants of rain forest habitat remain.²⁹ Reintroducing regionally extinct species might still be possible if sufficient suitable habitat can be provided in the region and species have the ability to recolonize the area. However, if the region contains the full geographic range of a species (i.e., it is endemic), there is a high risk that it will become globally extinct,³⁰ which is totally irreversible.

When species extinction is used in LCA as a measure of biodiversity loss, it is therefore essential to define clearly the spatial scale of impacts. Existing LCIA methods of land use differ in the spatial scales at which they assess impacts. Some studies address both local and regional impacts,^{12,17,19,22,23} whereas others consider only local^{20,21,26,27} or regional impacts.^{24,25} To our knowledge, no existing land use LCIA method assessed global species extinction, despite its irreversible nature and high political relevance.³¹

We present a spatially explicit approach to assess the impacts of land use on biodiversity at both regional and global scales. We model the potential regional species loss caused by total accumulated land use activities within all global ecoregions³² and use these data to calculate damage scores (so-called characterization factors) per land use activity, ecoregion, and taxon (mammals, birds, amphibians, reptiles, and plants). Following a convention of LCA,^{2,3} we calculate characterization factors for reversible impacts caused by occupation (land use) and transformation (land use change) as well as permanent impacts (further explained in the Methods section). Finally, using Monte Carlo calculations, we analyze and quantify the uncertainties of the characterization factors.

MATERIALS AND METHODS

Modeling Species Extinction. A species-area relationship (SAR) model was used to assess the number of species that might be driven to extinction because of land use. This model is derived from island biogeography theory,³³ which describes a power relationship between the area A of an ecosystem and the number of species S it contains, as follows

$$S = cA^z \quad (1)$$

where c and z are constants.³⁴

SAR models are commonly used to predict species extinction caused by habitat loss.^{5,35,36} The number of species S_{new} of an area A_{new} is then calculated as a function of the number of species S_{org} occurring in the original habitat area A_{org} .³⁷

$$\frac{S_{new}}{S_{org}} = \left(\frac{A_{new}}{A_{org}} \right)^z \quad (2)$$

A shortcoming of the SAR model is that it traditionally focuses on natural habitats and assumes that no species persist

on human-modified land (the so-called “matrix”), although in reality this land provides habitat for some species groups (e.g., farmland birds).^{26,38} We therefore used the adapted, matrix-calibrated species-area relationship model (hereafter, matrix SAR) developed by Koh and Ghazoul.³⁷ This model predicts lower species extinction risks due to habitat conversion when the converted region contains suitable habitat for some species groups. Mathematically, it lowers the curve of the species-area relationships³⁷ by adapting the z value (eq 3³⁷) of the power model (eq 2). The suitability of the matrix depends on the sensitivity σ of the species group to all land use types, i to n , and on the composition of the matrix, expressed as the relative area share p of each land use type i from the total converted land area:

$$z' = z \sum_i^n p_i \sigma_i \quad (3)$$

The sensitivity σ is quantified as the relative decrease in species richness (S) between a land use type i (S_i) and a (natural) reference habitat (S_{ref}). This equals local land occupation characterization factors $CF_{loc,i}$ as calculated by de Baan et al.²⁶ based on median values of CF_{loc} per biome.

$$\sigma_i = CF_{loc,i} = \frac{S_{ref} - S_i}{S_{ref}} \quad (4)$$

The species lost S_{lost} per taxonomic group g due to cumulative land use in a region is thus given by substituting eqs 3 and 4 into eq 2.³⁷

$$S_{lost,g} = S_{org,g} - S_{new,g} = S_{org,g} - S_{org,g} \cdot \left(\frac{A_{new}}{A_{org}} \right)^{z \sum_i^n p_i CF_{loc,i}} \quad (5)$$

Following the suggestions of Koellner et al.,³⁹ we chose ecoregions delineated by the World Wide Fund for Nature (WWF)³² as spatial units for calculating species loss caused by land use. Ecoregions contain distinct communities of species, and their boundaries approximate the original extent of natural ecosystems prior to major land use change.³²

Because $CF_{loc,i}$ ranges from positive to negative values (representing a higher species richness on used land than on the reference habitat),²⁶ the exponential term in eq 5 could be negative, resulting in a gain in regional species richness (negative S_{lost}). Although human land use can sometimes increase the regional species pool,^{40,41} the matrix SAR was not developed to model this aspect. We thus did not allow an overall regional species gain (negative S_{lost}) by setting $\sum p_i CF_{loc,i} < 0$ to $\sum p_i CF_{loc,i} = 0$ resulting in $S_{lost,g} = 0$. The beneficial impacts of individual land use types (i.e., $CF_{loc,i} < 0$) on species richness were permitted, which resulted in negative characterization factors (see below).

Calculation of Characterization Factors. According to the UNEP/SETAC Life Cycle Initiative,^{2,3} three types of land use impacts can be distinguished in LCA, which are quantified as the reduction of biodiversity over time and space (see SI Figure S1). The *transformation impact* quantifies the original change in diversity due to natural habitat conversion and additionally includes the time lag in the eventual recovery of the site back to a natural state (at some undetermined point in the future). The *occupation impact* captures the biodiversity loss attributed to preventing this recovery from taking place (i.e.,

because the site is occupied for human land use, it is unavailable for a proportion of species to occupy). These two impacts are considered fully reversible, given sufficiently long time horizons. *Permanent impacts* account for the irreversible damages due to incomplete biodiversity recovery. Here, we consider the global extinction of endemic species irreversible (i.e., permanent impact), whereas the regional extinction of nonendemic species is treated as potentially reversible (i.e., transformation and occupation impacts).

We used eq 5 to calculate the total number of nonendemic species lost per ecoregion j and taxonomic group g because of the cumulative land use within the ecoregion. This total regional damage was then allocated to the different land use types i according to their relative frequency p_{ij} in the region j and their habitat quality $CF_{loc,ij}$. The allocation factor a is then calculated for each land use type i and ecoregion j as follows (eq 6):

$$a_{ij} = \frac{p_{ij} CF_{loc,ij}}{\sum_i p_{ij} CF_{loc,ij}} \quad (6)$$

Regional characterization factors for occupation of each land use type, $CF_{Occ,reg,ij,g}$ were calculated by multiplying the potentially lost nonendemic species per region j with the corresponding allocation factor a_{ij} and dividing this by the area occupied by the land use type, A_{ij} (eq 7). This finally gives us the unit [potentially lost nonendemic species] for occupying 1 square meter for 1 year.

$$CF_{Occ,reg,ij,g} = \frac{S_{lost,nonend,j,g} \cdot a_{ij}}{A_{ij}} \quad (7)$$

Regional characterization factors for transformation, $CF_{Trans,reg,ij,g}$ were calculated as a multiplication of $CF_{Occ,reg,ij,g}$ with half the regeneration time,^{2,3} t_{reg} (eq 8, see SI Figure S1). Here, the unit is [potentially lost nonendemic species · years] for transforming 1 square meter.

$$CF_{Trans,reg,ij,g} = \frac{1}{2} \cdot t_{reg,ij,g} \cdot CF_{Occ,reg,ij,g} \\ = \frac{1}{2} \cdot t_{reg,ij,g} \cdot \frac{S_{lost,nonend,j,g} \cdot a_{ij}}{A_{ij}} \quad (8)$$

Finally, *regional characterization factors for permanent impacts*, $CF_{Perm,reg,ij,g}$ were calculated based on the total number of potentially lost endemic species, $S_{lost,end,j,g}$ per ecoregion j and taxonomic group g caused by all the accumulated land uses within the region (eq 9). This total damage was allocated to the different types of land use within the region (multiplication by a_{ij}) and divided by the area of each land use. Because global extinction is fully irreversible, and the impacts potentially continue during an infinite time, we calculated the impacts only over the modeling period, $t_m = 10^6$ years, representing the estimated time for a new species to evolve.^{42,43} The unit is [potentially lost endemic species · years] for transforming 1 m² of land.

$$CF_{Perm,reg,ij,g} = t_m \cdot \frac{S_{lost,end,j,g} \cdot a_{ij}}{A_{ij}} \quad (9)$$

For application in an LCA study, the CF_{Occ} are multiplied by the inventory flow of occupation, that is, the land requirements of a product given in [m²·years]. The CF_{Trans} and CF_{Perm} are multiplied by the inventory flow of transformation, that is, the

amount of land use change per product in [m²]. The three impacts can be summed up into the total regional biodiversity depletion potential for each taxonomic group g ($rBDP_g$) expressed in the unit [potentially lost species·m²·year]. By choosing the modeling time for the permanent impacts, t_m , a weighting can be performed to indicate the relative importance of global species extinction relative to regional extinction. The Supporting Information (SI) includes a proposed method for aggregating CFs across taxa (SI section C6) and deriving world average CFs for land use flows with unspecified locations (SI section C7).

Input Data for Model Parameters. For each of the aforementioned parameters, we used globally available data and, where possible, created an uncertainty distribution for each parameter (see overview in SI Table S1). CF_{loc} ,^{6,26} z ,⁴⁴ and t_{reg} ²⁸ were derived from global meta-studies, and the data were subset into various configurations based on data availability and relevance. The CF_{loc} were shown to differ significantly across biome and land use types.²⁶ Thus, we split the data into CF_{loc} specific to land use type and biome. If less than five data points per land use type and biome were available, world average CF_{loc} was used for the land use type. The z -values strongly differed between broad habitat types⁴⁴ and were calculated specifically for islands, forests, and nonforest ecoregions (see spreadsheet EcoregionDescription in SI2 for how ecoregions were assigned to these habitat types and SI Table S2 for the applied z -values).

Recovery times, t_{reg} , were estimated based on a meta-analysis by Curran et al.²⁸ This study reviewed 108 peer-reviewed publications that compared the diversity of old growth (OG) and secondary growth (SG) habitats of different ages, using the occurrence-based Sørensen similarity index as a measure of diversity. Curran et al.²⁸ used generalized linear models to predict the time it would take for SG–OG similarity to reach average OG–OG values, based on within-study comparisons. Predictors of recovery included habitat age, taxon, latitude, altitude, previous disturbance intensity, biogeographic realm, and a simplified biome classification. Based on the model parameters for these predictors, we calculated land use-, taxon- and region-specific recovery times for 520 archetypical situations (parameter combinations): recovery after “intensive” land use (agriculture and urban land, pasture in forest ecosystems, and managed forests in nonforest ecosystems) or “extensive” land use (pasture in open ecosystems and managed forests in forest ecosystems) for each taxonomic group (plants, birds, mammals, and herpetofauna) in 65 world regions (WWF biomes-realm combinations). For each region, the median distance from the equator, median elevation, and biome type (forest or nonforest) were specified and used to calculate the recovery times (see SI Table S3 for input parameters and resulting median recovery times).

Data on original species richness and endemism of mammals, birds, amphibians, and reptiles were derived from the WWF WildFinder database.^{32,45} Because no data on plant endemism are available per ecoregion (Holger Kreft, Pers. comm.), permanent impacts could not be calculated for plants. Total plant species richness (Kier et al.⁴⁶) was used to calculate occupation and transformation impacts.

Several global land cover and land use maps are available, but their agreement on cover types and distribution is limited.^{47–49} Most maps do not distinguish between natural, managed, or inhabited forests or grassland.^{50,51} We thus chose two maps, Land Degradation Assessment in Drylands (LADA, 1998–2008)⁵² and Anthromes⁵³ (2000–2005), for deriving land use

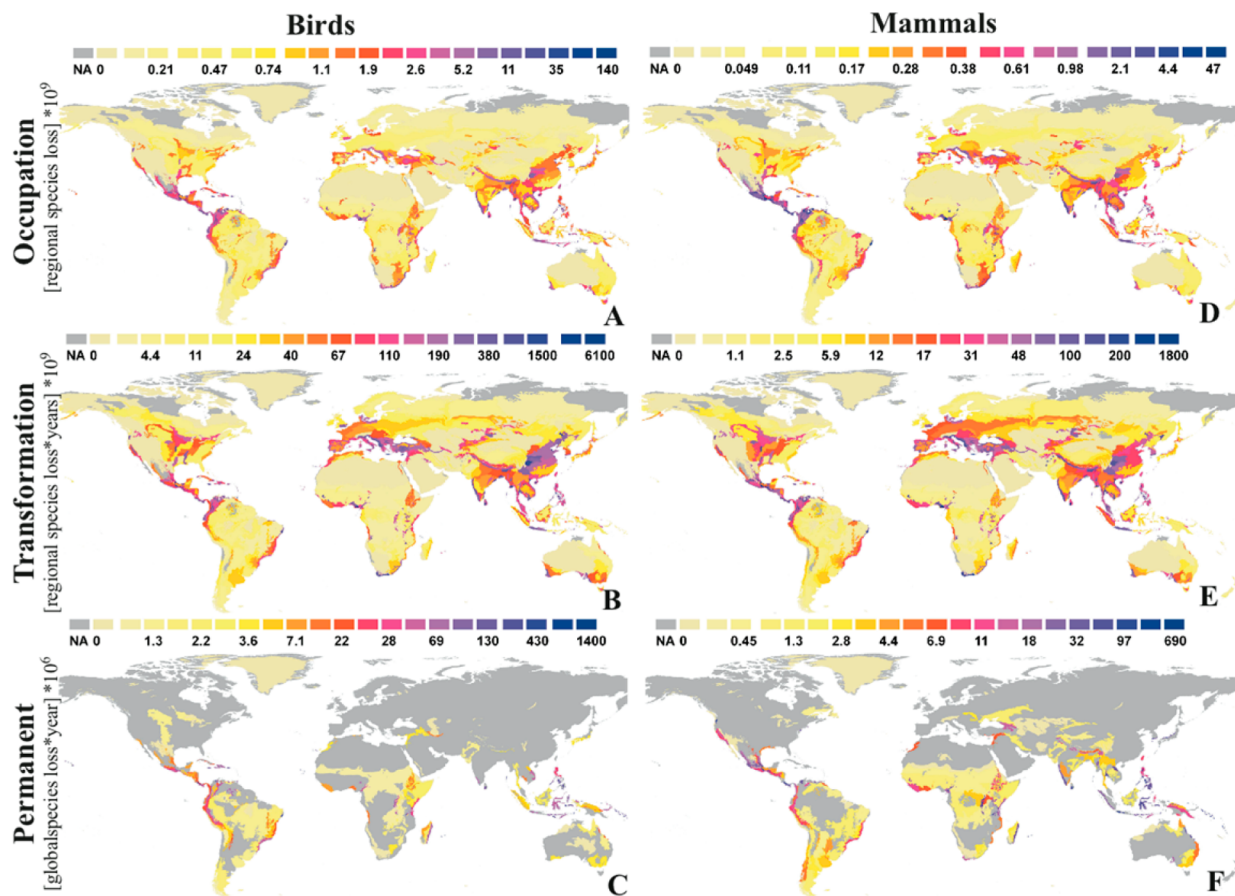


Figure 1. Median characterization factors of agricultural land, based on birds (left) and mammals (right), for occupation (top), transformation (middle), and permanent impacts (bottom). NA: No data available. Maps for other land use types and taxa (amphibians, reptiles, and plants) are given in SI Figures S2–S6. Symbolology based on the Jenks natural breaks classification method.⁶¹

shares per ecoregion, which combine remote sensing data with statistics on human activities (both at a 5 arc minutes resolution). Five broad land use types were distinguished (agriculture, pasture, managed forests, urban area, and natural habitat) in our model. To estimate parameter uncertainty, we calculated the area shares of each land use type per ecoregion in a GIS separately for each land use map. The maps were first transformed from WGS1984 projection to equal-area projections, using seven globally applicable equal-area projections. This resulted in $n = 2 \times 7 = 14$ different estimates of land use shares for all global ecoregions.

Uncertainty Assessment. Parameter uncertainty was propagated into the characterization factors using Monte Carlo simulation (1000 iterations). For each parameter, a distribution was directly derived from the data using non-parametric Kernel density estimation (KDE); if only data ranges were available, a triangular distribution was assumed (see SI Table S1). For recovery times, a log-normal distribution was assumed.²⁸ With the exception of plants, no uncertainty information was available for species richness and endemism. Thus, these parameters were modeled without uncertainty. Median, upper, and lower 95% confidence intervals were calculated for each characterization factor.

To assess the influence of each parameter on the uncertainty of characterization factors, their contribution to variance (CTV)⁵⁴ was calculated. In this method, the Spearman's rank-order correlation coefficient (ROCC) of each parameter with

the characterization factor results is calculated for the set of Monte Carlo iterations. The CTV is calculated as follows

$$CTV_i = \frac{ROCC_i^2}{\sum_i^n ROCC_i^2} \quad (10)$$

where i is the calculated parameter, and n is the set of all parameters (see also Mutel et al.⁵⁵).

Validation of Species Extinction. To test the validity of the model, we compared our prediction of the global extinction of endemic species ($S_{lost,end}$) with the observed numbers of extinct and threatened species.³⁷ Because it can take decades or centuries for a species with nonviable populations to disappear completely (extinction debt^{56,57}), we considered the following species “condemned to extinction”: all species classified by the International Union for Conservation of Nature (IUCN) as “vulnerable”, “endangered”, “critically endangered”, or “extinct”. Data per ecoregion were extracted from the WWF WildFinder database⁴⁵ for endemic mammals, birds, amphibians, and reptiles. No validation could be performed for the regional extinction of nonendemic species ($S_{lost,nonend}$) because only information on global extinction was available.

Comparison of Model Choices. The above-presented model to derive land use characterization factors calculates the average impacts of past land use changes and is thus *retrospective*. Alternatively, *prospective* impacts can be calculated as *marginal* changes,^{58,59} that is, the impact of one additional m² of future land use change. To illustrate how these model

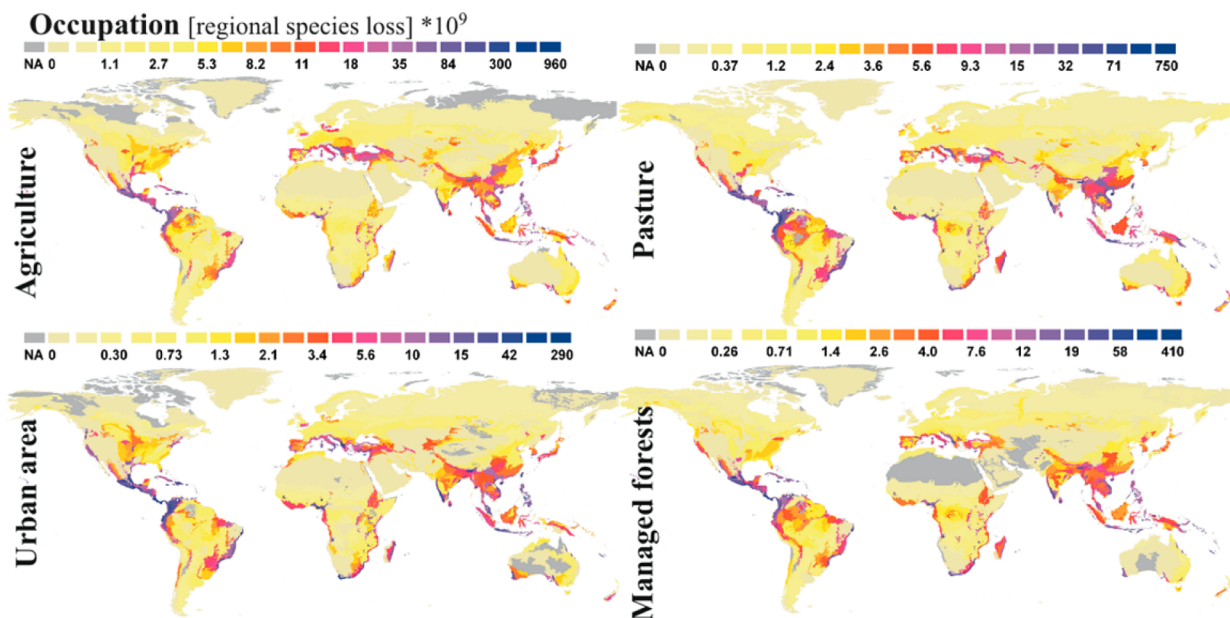


Figure 2. Median occupation characterization factors based on plant species, for agriculture, urban, pasture, and managed forests. NA: No data available. Symbology based on the Jenks natural breaks classification method.⁶¹

choices can be implemented to the matrix SAR model, we calculated average and marginal impacts for all forest ecoregions of the Amazon ($n = 19$) under both retrospective (i.e., the current state) and prospective approaches. This region was selected because future land use scenarios for agriculture, pasture, forestry, and urban areas are not available on a per-ecoregions basis. The Amazon contains some relatively undisturbed ecoregions, which are expected to be converted for human use in the near future. Best- (good governance) and worst-case (business-as-usual) land use scenarios per ecoregion were derived from Soares-Filho et al.⁶⁰ for the year 2050 and used to calculate prospective CFs. The equations for calculating marginal CFs in addition to details of the applied method and scenarios are given in the SI section C4.

RESULTS

Regional Characterization Factors. All median regional CFs including upper and lower 95% confidence intervals are displayed in spreadsheets in SI2. The regions with high median CFs largely overlapped for occupation, transformation, and permanent impacts and for all five taxa (mammals, birds, amphibians, reptiles, and plants; see correlation analysis in SI Tables S5–S6). The regions with high CFs largely corresponded to regions that had been heavily converted in the past (see Figures 1 and 2 for a selection and SI Figures S2–S6 for all CFs). CFs were very low in regions with large shares of undisturbed habitat. Globally across ecoregions, median CF values ranged over several orders of magnitude and showed large differences within biomes, indicating that a resolution finer than biomes is required for regionalized biodiversity assessments. For most ecoregions, the median occupation CFs of different land use types were within the same order of magnitude (Figure 2 and SI2), but transformation CFs showed larger differences between land use types. Generally, to determine land use CFs, the region where land was being used seemed more important than the type of land use. In most ecoregions, agriculture had the highest median CFs, but the ranking of the CFs of the other three land use types (pasture,

urban areas, and forestry) was not consistent across taxa, type of impact, or ecoregion. In all but 5 ecoregions, CFs differed significantly across land use type ($p < 0.05$, evaluated by Kruskal–Wallis tests) for both occupation and transformation impacts. In general, the CFs (expressed in number of species lost) were highest for the most species rich taxa, plants, followed in decreasing order by birds, mammals, reptiles, and amphibians (the least species rich taxa).

Median recovery times, t_{reg} , used for calculating transformation CFs (eq 8) ranged between 81 and 1231 years (SI Table S3). For most ecoregions, the median CFs of transformation were larger than of occupation, but the medians did not directly mirror their mathematical relationship (see eq 8, $CF_{Trans} = 0.5 \bullet t_{reg} \bullet CF_{Occ}$). This is due to the high uncertainties and skewed distributions of recovery times as well as CF_{Occ} and highlights the importance of considering CF uncertainties in LCA applications.

Contribution to Uncertainty. Uncertainty of the CFs was considerable. Local characterization factors $CF_{loc,i}$ contributed the most to the variance of regional CFs of occupation (67%–96%) and transformation (30%–84%, SI Tables S7 and S8). This result can be attributed to the value range of the local CFs, which spanned both positive and negative values²⁶ (i.e., both damaging and beneficial impacts on biodiversity). The highly uncertain regeneration times resulted in higher uncertainties of transformation CFs compared to occupation CFs. Regeneration times contributed about half the uncertainty to the transformation CFs of agriculture (34%–54%) but were slightly less relevant for the other land use types (6%–28%, SI Table S7). Moreover, z -values ($<0.3\%$) and the parameters for area (original area A_{org} ($<3\%$), remaining natural habitat A_{new} ($<5\%$), and area of each land use type A_i ($<5\%$)) did not contribute greatly to the overall uncertainty of CFs.

Model Evaluation. To evaluate our predictions of global extinction ($S_{lost,end}$), we compared them with the observed numbers of threatened and extinct endemic species. The observed numbers were mostly within the uncertainty ranges of

our predictions, but our median values were generally smaller than the observed values (SI Figure S10).

Comparison of Model Choices. Using land use scenarios for 2050,⁶⁰ we calculated prospective characterization factors for 19 ecoregions in the Amazon. Compared to the retrospective approach, the median CFs increased in ecoregions with large projected deforestation rates but did not change notably in ecoregions with lower deforestation rates (SI Figure S9). The highest increase of 65% in median CFs was observed in ecoregions with a projected decrease in remaining natural forest area from 60% to 20%. Average and marginal CFs were similar in ecoregions with large remaining natural habitat areas. Marginal CFs were much larger than average in ecoregions with little natural habitat (Figure 3, SI Figures S7 and S9).

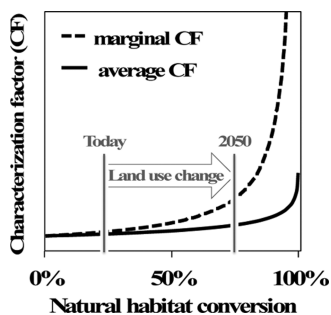


Figure 3. Illustration of average and marginal occupation characterization factors for current and future land use in a hypothetical region (assuming a constant composition of land use, p_{ij}).

DISCUSSION

Modeling Choices. The CFs of occupation and transformation of different taxa and land use types showed a relatively clear and consistent picture of regions with potentially high impacts of land use. High CFs occurred in highly vulnerable ecoregions where most natural habitat had been converted in the past, showing a strong overlap with biodiversity hotspots,⁶² which were classified by Brooks et al.⁶³ as a reactive global conservation priority scheme. Ecoregions with low CFs largely overlapped with proactive conservation priority maps, such as of the Last of the Wild,⁶⁴ which identifies large, undisturbed areas with high potential for conservation. The presented approach is clearly *retrospective* and reactive, because it considers only past changes in land use. In principle, the matrix SAR model can also be applied to future scenarios of land use change and provide a prospective assessment, which we illustrated in the example of 19 forest ecoregions of the Amazon. In ecoregions with high rates of projected future land use change, this *prospective* assessment might be more appropriate to represent the potential future loss of species. Global land use scenarios could be derived from global models, such as IMAGE,⁶⁵ but would add another dimension of uncertainty to the CFs.

Based on the matrix SAR, both *average* and *marginal* impacts can be calculated. Average and marginal CFs are similar in ecoregions with low levels of converted natural habitat, but marginal impacts are much higher at high levels of habitat conversion and tend toward infinity when all remaining natural habitat is converted (Figure 3). Differences between CFs of ecoregions at high and low levels of habitat conversion are clearly magnified in a marginal approach. We thus do not recommend using a marginal approach in combination with a

retrospective assessment because it ignores the conservation concerns of regions with large amounts of intact natural habitat that may be highly threatened by future land use pressure, such as the Amazon.

Data Availability and Uncertainty. In this study, we provided global CFs, which can be used in a range of LCA applications. We thereby relied on available global land use and biodiversity data, such as the WWF WildFinder database.^{32,45} Because the latter does not distinguish between ecoregions with missing data or zero species richness or endemism, we treated both cases as missing data. This resulted in missing data for many ecoregions, particularly for permanent impacts, and the reduced applicability of this type of impact assessment in standard LCAs. Data for amphibians and reptiles were less complete than for mammals and birds. As new data on these, or additional, species groups emerges, the presented CFs should be updated. For now we suggest to supplement missing values with average CFs for neighboring ecoregions of the same biome.

For most input parameters (e.g., local CFs and z -values), the available data were not taxa- or ecoregion-specific but instead were aggregated across larger spatial units (e.g., biomes or globally). As expected, the resulting regional CFs were highly uncertain, often ranging from positive (detrimental) to negative (beneficial) values. The parameter dominating the uncertainty of regional CFs were the local CFs. These were derived from a quantitative review of comparative biodiversity surveys of human-modified land^{6,26} and ranged between positive and negative values (the latter represented a higher species richness on the used land compared to a natural reference habitat). Better data on taxa- and region-specific habitat suitability for different land use types are required to reduce uncertainties in assessing the impacts of land use on biodiversity. In addition, the use of detailed and accurate global land use classification maps, such as those currently developed by the Geo-Wiki project⁶⁶ or van Asselen and Verburg,⁶⁷ could further reduce uncertainties. We only distinguished between four very broad land use classes, each of which contained a range of management practices. To compare management practices (e.g., organic vs conventional farming), global land management maps and more refined CFs would need to be developed, as impacts of different management practices on biodiversity differ considerably.⁶⁸

The uncertainty of transformation CFs was strongly influenced by the uncertainty of the biodiversity recovery times. This is the first global land use LCIA study that does not use recovery times based on expert estimates⁶⁹ but applies values derived from a meta-analysis of empirical data.²⁸ The recovery of biodiversity following disturbance is a complex process, and the predicted recovery times are highly uncertain and represent best-case scenarios.²⁸ The recovery time estimates implicitly assumed that adequate amounts of old growth habitat exist in a region, to act as a reservoir for old growth species to recolonize secondary growth areas. In some ecoregions, median recovery times exceeded 500 years (SI Table S3). It is doubtful whether recovery will occur at all in these regions,⁷⁰ given the unlikely assumptions of nonuse over the entire recovery period and future availability of source habitat. Even where these assumptions are met, Curran et al.²⁸ estimated that recovery of species similarity is likely to fail altogether in about 15% of all cases. In addition, a reintroduction of regionally extinct nonendemic species is not possible, if the species got regionally extinct in all the

ecoregions that it inhabits. The assumption that regional species loss is fully reversible is clearly too optimistic and leads to the underestimation of permanent impacts. Given these caveats, we believe that this study is important because it is the first to include reversibility into land use LCIA methods. Here, we modeled permanent impacts based on endemism. Future LCIA studies modeling permanent impacts should attempt to include additional risk factors for global species extinction, such as global rarity or vulnerability of species⁷¹ and the likelihood that recovery will fail in different regions or ecosystems.²⁸

Model Validity. Traditional species-area relationships (see eq 1) are commonly applied to assess species extinction caused by habitat change, but their validity has been questioned because they tend to overestimate extinction rates.⁷² Koh and Ghazoul³⁷ adapted the traditional SAR model to account for the habitat value of human-modified land. However, the matrix SAR has not yet been tested outside the tropics for nonendemic species and taxonomic groups other than birds^{37,73} or mammals.⁷⁴

For nonforest ecoregions, such as grassland, savanna, tundra, and deserts, CFs should be interpreted with caution because the ecological reactions to habitat change differ from those of forest ecosystems.⁷⁵ In the desert biome, the median of the five available data points for local CF of pasture²⁶ was negative (i.e., higher median richness in pastures than on reference habitat), and because pasture was the dominant land use type in most desert ecoregions, the power term of the damage model (eq 5) became negative and was capped at zero (see Methods). Therefore, the median species loss was assumed zero, resulting in regional CFs of zero for all land use types and taxa. Although local increases in species richness might occur because of irrigation,⁷⁶ for example, reduced water availability within the watershed might still lead to reduced regional biodiversity.⁷¹

In our global analysis, the matrix SAR tended to give lower estimates of global species extinction than “true” extinction estimates (SI Figure S10). We can attribute this to two factors. First, we optimistically assumed that endemic and nonendemic species share the same habitat suitability scores (i.e., local CFs). In reality, endemic species are likely more sensitive to anthropogenic disturbances as they are often habitat specialists relying on old growth natural habitat. Second, we assumed that all vulnerable and threatened species will inevitably become extinct and assumed a primary driver of land use alone, ignoring the effect of other drivers (e.g., invasive species, pollution, or global warming⁵). Therefore, it is important to interpret the global CFs as a measure of potential regional or global species extinction and not as explicit predictions.

Although the matrix SAR models the nonlinear effects of habitat loss on biodiversity, the CFs had to be linearized to match the LCA framework, which is typically linear and assumes steady-state conditions.⁷⁷ These linear CFs should not be applied to LCA studies in which the product system significantly changes the share of remaining natural habitat in one ecoregion and linearity no longer holds. The temporal dimension was captured only by the recovery rate of biodiversity (assumed to be linear). Historical land use dynamics and coevolution of species were ignored by comparing the current composition of land use with a potential “prehuman” situation, assuming that each ecoregion once consisted of a homogeneous ecosystem without any human influence.³² Conservation concerns in regions with a long history of land use, such as seminatural habitat loss,

fragmentation, and land use intensification or abandonment,^{78,79} are only partially represented in the model.

The matrix SAR predicts 100% species loss if no natural habitat remains within an ecoregion. For regions dominated by land use with high habitat value, where species loss is predicted to be very small, this leads to a sudden loss of all species at very low levels of remaining natural habitat (e.g., less than 0.1%). This model behavior is unrealistic and occurs because remaining habitat (A_{new} in eq 5) only considers pristine habitat. In this context, it might be worth testing alternative models of species extinction for application in global LCAs, such as the countryside SAR,³⁸ which predicts that species adapted to human-modified habitats also survive in the absence of natural habitat.

Applicability. To apply the developed CFs in LCA studies, information is needed on the location of land use activities in the product life cycle. Recent developments of life cycle inventory databases should facilitate the collection of these data (see EcoInvent v3.0⁸⁰). Because impacts differ strongly across regions, efforts to regionalize land use inventories on the level of ecoregions instead of countries are worthwhile; however, the CFs could also be employed in a probabilistic approach of determining the location of a particular land use.⁸¹ For unknown locations of land use, global average CFs can be applied (given in SI2). For the easier applicability, we also calculated aggregated CFs across all five taxonomic groups (given in SI2), by first normalizing by the median species richness per ecoregion of each taxonomic group (giving equal weight to each taxonomic group, SI section C6). Alternatively, CFs could be simply summed across the taxonomic group (giving equal weight to each species). Although the reversible occupation and transformation impacts can be aggregated, adding permanent impacts requires a weighting between regional and global species loss, which can be performed by adapting the time horizon (t_m in eq 9) considered for permanent impacts.

Implications. In this paper, we present an approach to derive globally applicable CFs of land use using a species-extinction model. Our approach allows an assessment of the impacts of land use in LCA that is more complete than previous methods. We provide global CFs for occupation and, for the first time, transformation and permanent impacts, including uncertainties for nearly all world regions for five taxonomic groups and four broad land use types. These three types of impacts provide decision-makers with information on the effects of actual land use, land use changes, and the risk of irreversible damage. The approach also aims to improve the environmental relevance of land use LCIA results: We regionalize the CFs to the ecologically relevant scales of ecoregions and calculate the impacts at the regional scale instead of the local scale,²⁶ which is relevant for assessing species extinction risk. Finally, with the unit potential regional loss of species, we propose an absolute instead of a relative measure for biodiversity loss in LCA. This facilitates the comparison with absolutely measured land use impact on ecosystem services.^{2,14–16} The currently prevalent unit in LCA, potentially disappeared fraction of species (PDF), has been criticized for its lacking definition of the scale of impacts, conflating both local, regional, and global losses.¹⁰ This unclear definition results in a misleading aggregation of impacts on biodiversity of different impact pathways (e.g., land use, climate change, and eutrophication) modeled at different spatial scales.¹⁰ A reevaluation of meaningful and readily under-

standable end point units for measuring biodiversity loss in LCA is thus desirable, considering both scientific rigor and practicality.

■ ASSOCIATED CONTENT

● Supporting Information

Additional results and method descriptions are provided in SI1. Spreadsheets containing all characterization factors and uncertainties are provided in SI2. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

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