Going global to local: achieving agri-food sustainability from a spatially explicit input-output analysis perspective

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Chapter 4.
Land use in key biodiversity areas disproportionately threatens global biodiversity

4 Land use in key biodiversity areas disproportionately threatens global biodiversity[3]

Abstract

Key Biodiversity Areas (KBAs) are critical regions in efforts to preserve global biodiversity. KBAs are identified by their importance to biodiversity rather than their naturalness or legal status. As such, KBAs are often under pressure from human activities. KBAs can encompass many different land use types (e.g. cropland, pastures) and land use intensities. Here we combine a global economic model with spatial mapping to estimate the biodiversity impact of human land use in KBAs. We find that global human land use within KBAs causes disproportionate biodiversity losses. While land use within KBAs accounts for only 7% of total land use, it causes 16% of global plant loss and 12% of global vertebrate loss. The consumption of animal products accounts for more than half of biodiversity loss within KBAs, with housing the second largest at around 10%. Bovine meat is the largest single contributor to this loss at around 31% of total biodiversity loss. In terms of land use, lightly grazed pasture contributes most, accounting for around half of all species loss. This loss is concentrated mainly in middle- and low-income regions with rich biodiversity. International trade is an important driver of loss, accounting for 22-29% of total plant and vertebrate loss. Our comprehensive global, trade-linked analysis provides insights into maintaining the integrity of KBAs and global biodiversity.

Significance

Global land use threatens biodiversity within Key Biodiversity Areas (KBAs). In an interconnected world, the consumption of products such as food in one region can drive biodiversity loss in other, producing regions via the international supply chain. We linked high-resolution global land use and land-use intensity maps with detailed environmental-economic databases to trace biodiversity loss due to land use with different intensities within KBAs. We find a much higher proportional level of biodiversity loss within KBAs than in other areas. In terms of products, animal-based foods drive over half the total biodiversity loss. With respect to land use, pasture with light intensity accounts for half of the total loss. The findings can help to better target KBA conservation efforts.

Keywords

Biodiversity loss, countryside species-area relationship, multi-regional input-output analysis, land use intensity

4.1 Introduction

Biodiversity loss severely alters and threatens ecosystem functioning, and human-driven land use is the largest threat to terrestrial biodiversity [278,279]. This land use has led to a rapid acceleration in the rate of species extinction, far exceeding estimated planetary boundaries [280–282]. The urgency for biodiversity protection is reflected in international agreements, for instance in Sustainable Development Goals (SDGs) 14 and 15 [283] and the elapsed 2020 Aichi Biodiversity Targets [284]. Recent developments in biodiversity protection include the identification of Key Biodiversity Areas (KBAs), sites that significantly contribute to the global persistence of biodiversity [285]. KBAs reflect an increasing appreciation of the complexities required to maintain biodiversity and are identified on the basis of 11 globally standardized threshold-based criteria within five categories: threatened biodiversity, geographically restricted biodiversity, ecological integrity, biological processes, and irreplaceability. Around

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16,000 KBAs have been identified as of 2020 [286] and they are likely to take a more central role in the main framework for identifying future conservation priorities [287–289]. This approach contrasts with other methods that generally address one biome or a group of species, leading to the omission of important biodiversity integrity [290]. Even though KBAs play an important role in biodiversity protection, little is known about the biodiversity loss driven by land use within KBAs.

KBAs encompass regions of human activities and land use. However, it is not only the amount of land use that drives biodiversity loss, but also the intensity of that land use [291,292]. To investigate land use impacts on biodiversity, researchers have used characterization factors (CFs) derived from the countryside Species–Area Relationship (SAR) (see methods) [291,292]. These CFs estimate the potential species extinctions driven by a unit of land use if it remains in its current state over the long term [291,292]. Although land use is a local phenomenon, these CFs also evaluate if a species faces the potential for loss globally and will therefore go extinct [292]. Here we refer to global species-equivalents potentially lost over the long term as *species lost* and use this approach in our analysis [292].

Further, due to increasing levels of globalization, local human land use is often driven by global demand, which enhances the geographic disconnection between producers and consumers as supply chains grow in complexity. For example, biofuels consumed in the EU can drive loss in Indonesia when these fuels are derived from palm oil [293]. Previous estimates have concluded that 25% of global species lost [291] and 30% [294] of global species threats are driven by international trade, a larger proportion than for estimates of several other trade-based displacements such as carbon emissions [295]. The displacement of biodiversity loss is generally from high-income to middle- and low-income nations [296]. As such, assessments of the responsibility for land use in KBAs benefit from taking both a production-based (responsibility is shouldered by the producing nation) and consumption-based (responsibility is shouldered by consumers of products all along the value chain) perspectives.

A previous analysis found that global cropland, even inside protected areas, has large impacts on vertebrate species, but did not include the role of other land uses, impacts on other species or the responsibility of international trade [297]. There have been efforts to map biodiversity loss in trade, for instance Moran et al. (2017) mapped consumption-based global biodiversity loss hotspots, but did not identify biodiversity loss due to a specific driver (e.g. land use) and used highly aggregated sectors for the economic activities driving this loss [296]. Other studies have traced biodiversity loss along the global supply chain for some products back to specific production locations (e.g. the Brazilian Cerrado) but have not examined the global picture [298]. Here we provide a global, trade-linked assessment of biodiversity loss within Key Biodiversity Areas (KBAs). We examine potential global loss of terrestrial species driven by domestic and teleconnected land use both within and outside KBAs (to provide a comparison of activities within and outside KBAs). We do this by building a hybrid model using physical and monetary input-output databases, spatially explicit land use maps, and characterization factors (CFs) of biodiversity loss (see methods for further details).

4.2 Results

4.2.1 A global picture of biodiversity loss from land use within KBAs

Overall, we find that human land use within KBAs leads to a total potential loss of 781 terrestrial plant species (hereafter referred to as plants) and 208 terrestrial vertebrate species, including mammals, birds, amphibians, and reptiles (hereafter referred to as vertebrates) (Figure 4.1). The loss accounts for 0.3% of global plant species and 0.7% of global vertebrate species. To put this in perspective, our results suggest that total land use (inside and outside KBAs) causes a potential loss of 5038 plant species and 1765 vertebrate species (Figure S 8.13). While land use within KBAs only accounts for 7% of total land use, it drives 16% of global plant loss and 12% of global vertebrate loss compared to total land use. The biodiversity loss due to land use differs among regions (Figure S 8.14), since different regions have different mixes of land use types, varying land use intensities (we cover minimal, light, and intensive land use patterns here), consume different goods, and have different levels of biodiversity. Light use of pasture within KBAs is the primary driver of biodiversity loss, accounting for a loss of 382 plant species (49% of losses), and 91 vertebrate species (44% of losses). This is because pasture with light use accounts for the largest proportion (50%) of land use within KBAs (Figure S 8.14). Pasture also sometimes displaces species-rich natural ecosystems, such as tropical forests in Latin America [299], thereby causing severe biodiversity loss. The exact mechanism by which cattle grazing influences biodiversity varies depending on location and management practices, but in general, biomass removal, trampling and destruction of root systems, and competition between livestock and wildlife have the largest impacts on reducing biodiversity [299,300].

At a regional level, there are several distinct biodiversity-loss hotspots. Plant loss is highly concentrated across Mexico, the nations of Central America, the Caribbean, Colombia, Venezuela, Madagascar, Southern Europe, South Africa, the south of India, the southwest of China, Southeast Asia, and the southwest and southeast of Australia (Figure 4.1). Vertebrate loss from land use within KBAs is also mainly located in Mexico, the nations of Central America, the Caribbean, Colombia, Venezuela, Madagascar, southern India, and Southeast Asia (Figure 4.1).

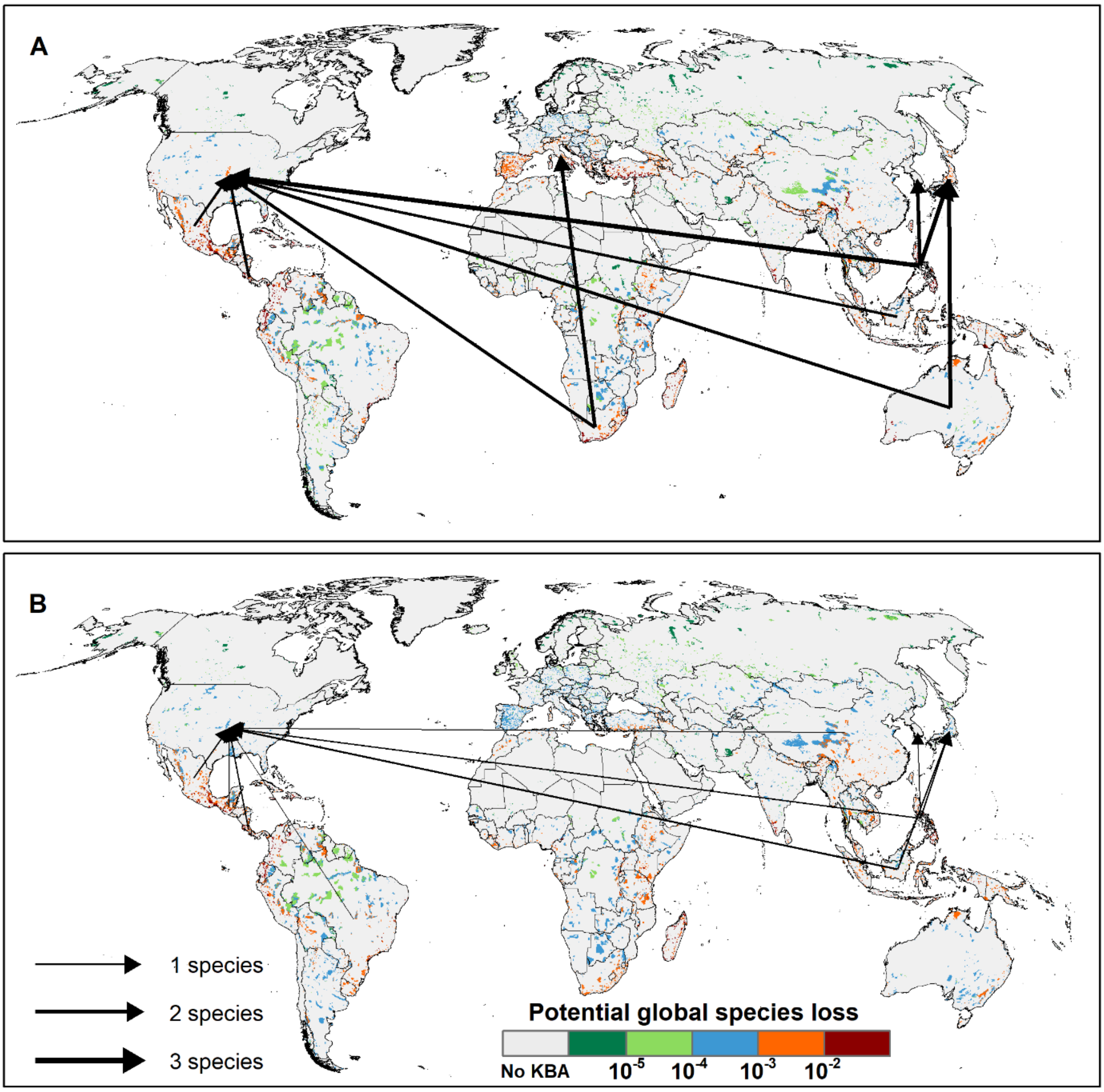

Figure 4.1. Potential global species loss driven by land use within KBAs for A) plants and B) vertebrates (mammals, birds, amphibians, and reptiles). Arrows indicate the top 10 flows of potential global species loss from nations where biodiversity loss occurs (tail of arrow) to final consumers (head of arrow). The width of arrows reflects the value of potential global species loss.

4.2.2 **Biodiversity loss from different land use types with three intensities**

We focus on the results for 15 countries with the largest consumption-based or production-based biodiversity loss from KBAs (Figure 4.2). These top 15 countries account for 62%-73% of total plant or vertebrate loss from either a production or consumption perspective. Consumption-based biodiversity loss from land use within KBAs ranks highest in biodiverse regions, such as South Africa and Madagascar (i.e. mainly as a result of domestic consumption) as well as in areas that import large amounts of loss via trade (e.g. the US). For plant species, South Africa sees the largest loss from a consumption- and production-based perspective (149 and 168 species lost from land use within KBAs, respectively). Pasture with light use is the primary land-use driver in South Africa, contributing to 82% and 80% of consumption- and production-based plant loss, respectively.

São Tomé and Príncipe sees the largest per-capita plant loss from a consumption- and production-based perspective (both 135 × 10^{-6} per-capita species lost from land use within KBAs). This is almost entirely due to land used for crops at a minimal use intensity. Such a large result is driven by São Tomé and Príncipe's position as an important region for endemic species – 30% of its mammals are endemic – and more than half of its land area being covered by KBAs, a higher share than any other country [301,302]. There is a large drop in per-capita plant loss in the next most prominent country, South Africa, at 3 × 10^{-6} and 5 × 10^{-6} per-capita consumption- and production-based species loss, respectively.

Focusing on vertebrate loss, Colombia's teleconnected land use within KBAs drives the largest consumption-based loss (13 species lost), where pasture contributes to 89% of the loss. In contrast, Indonesia sees the largest production-based impacts, with 14 species lost from land use within KBAs. Here, managed and planted forests are the main driver, contributing 61% of the loss. When looking at land use also outside KBAs, Brazil and the US surpass Indonesia and China, causing the largest production- and consumption-based total vertebrate species loss, respectively (Figure S 8.14). Among the top countries (Figure 4.2), Ecuador sees the largest per-capita consumption-based and production-based vertebrate loss (0.7 × 10^{-6} and 0.8 × 10^{-6} species lost from land use within KBAs), where pasture with light use accounts for 80% and 79%, respectively.

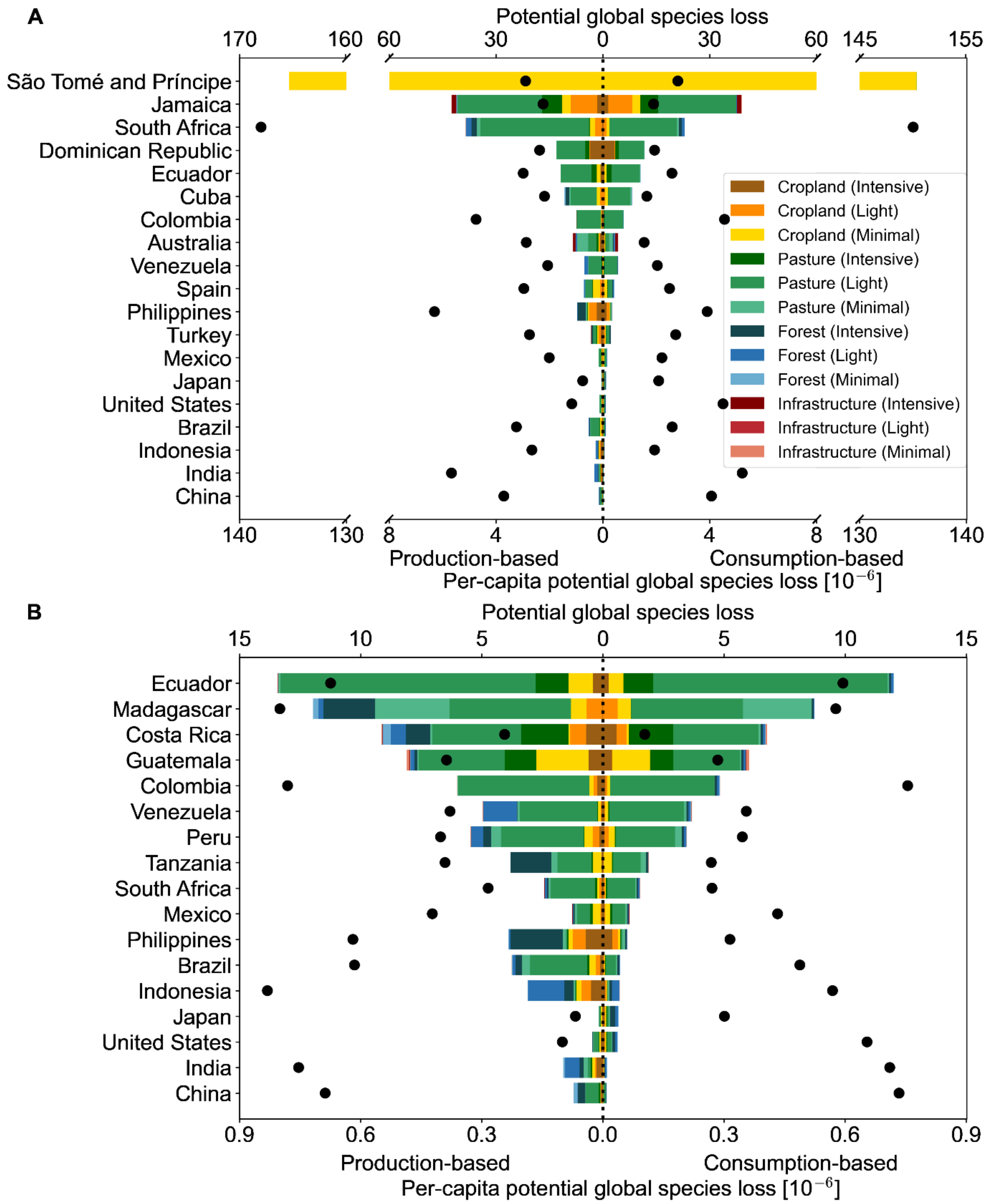

Figure 4.2. Potential global species loss from land use within KBAs for A) plants and B) vertebrates (mammals, birds, amphibians, and reptiles). On each x-axis (bottom and top of figures), the production-based perspective is shown to the left of zero and the consumption-based perspective to the right. The y-axis lists the top 15 countries/regions with the largest consumption-based or production-based biodiversity loss from land use within KBAs at the national level. The bar shows the per-capita value of biodiversity loss within KBAs per land type and land use intensity. The circles show the total national biodiversity loss with a value shown by the upper x-axes on the top of each plot. Forest includes managed and planted forest.

4.2.3 **Biodiversity loss embodied in international trade**

International trade is a major driver of biodiversity loss, contributing around a third of global vertebrate loss and a quarter of plant loss within KBAs (Figure 4.3). To illustrate flows from regions where biodiversity loss occurs to regions which consume the goods produced, we aggregate countries/regions into seven world regions. Western Europe and North America drive the largest biodiversity loss embodied in international trade (Figure 4.3). For instance, 79% of consumption-based plant loss in North America is driven through international markets, mainly from Central and South America (37%), and Asia and Pacific (30%) (Figure 4.3). Similarly, 82% of consumption-based vertebrate loss in Western Europe is embodied in international trade, mainly from Asia and Pacific (33%), Africa (26%), and Central and South America (20%) (Figure 4.3). This is similar to other studies finding that Western Europe and North America were responsible for 69% of biodiversity impacts transferred through international trade [291]. Specifically, the largest flow of plant loss via trade (excluding domestic production and consumption) is from Philippines to the US with 2.4 species lost (from land use within KBAs) (Figure 4.1). In contrast, the largest flow of vertebrate loss through trade is from Indonesia to the US with 1 species lost (Figure 4.1). The US is involved in 7 and 6 of the top 10 trade flows for vertebrates and plants, respectively.

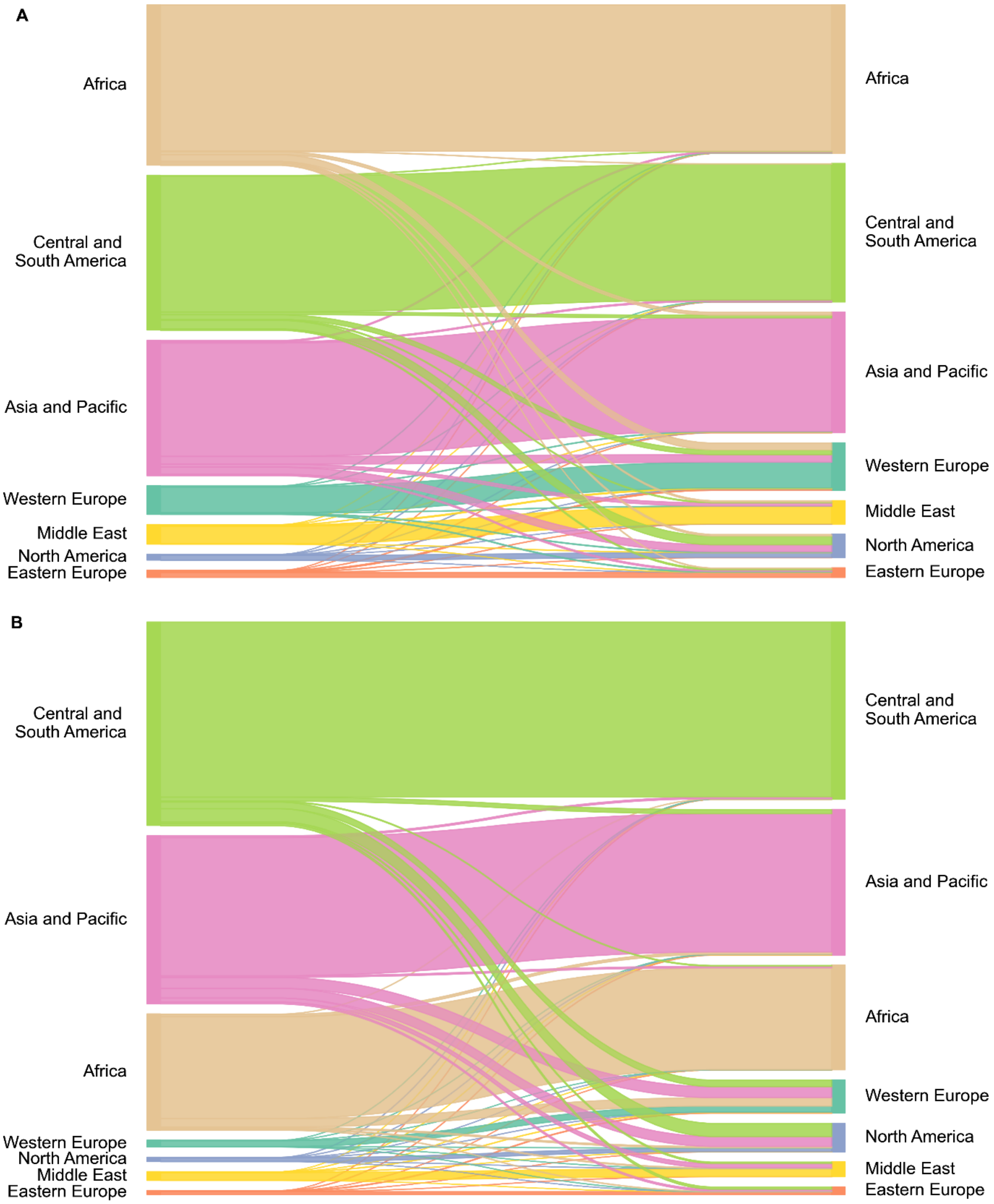

Figure 4.3. Embodied biodiversity loss flows for A) plants, and B) vertebrates (mammals, birds, amphibians, and reptiles) from land use within KBAs. Producing regions are on the left of the figure, consuming regions on the right. Regions are ordered by the magnitude of loss in the consuming region. The width of the flows are proportional to the magnitude of the potential global species loss.

4.2.4 **Biodiversity loss driven by the consumption of products**

Overall, food products contribute 74% of biodiversity loss within KBAs, with the remaining 26% driven by non-food products. Food-driven biodiversity loss is dominated by the consumption of animal products which account for more than half of total biodiversity loss within KBAs, with 408 plants (52%) and 104 vertebrates lost (50%). Within this, the consumption of bovine meat is the largest single contributor to biodiversity loss, with 241 plants lost (31%) and 63 vertebrates lost (30%). The result is consistent with Marques et al. (2019) who found that cattle farming was the largest driver of bird species loss from 2000 to 2011 [291]. Since they did not consider land use intensity, we can further clarify that this is more due to the extent of cattle farming than its intensity compared to other land uses. In addition, feeding livestock uses large areas of land. For example, 60% of land use within KBAs is pasture which is used for livestock ranching. Further, around 30% of cropland within KBAs is used to feed livestock.

The next largest product category is housing which includes all built infrastructure (e.g. roads), with 61 plants lost (8%) and 27 vertebrates lost (13%), driven mainly by “Construction work” and “Furniture” sub-categories, both of which heavily rely on forest products. Clothing contributes a further 6%, mainly driven again by pasture for animal products such as leather products. Grains contribute 5% biodiversity loss, which is proportionally much smaller than the around 16% land used as cropland within KBAs.

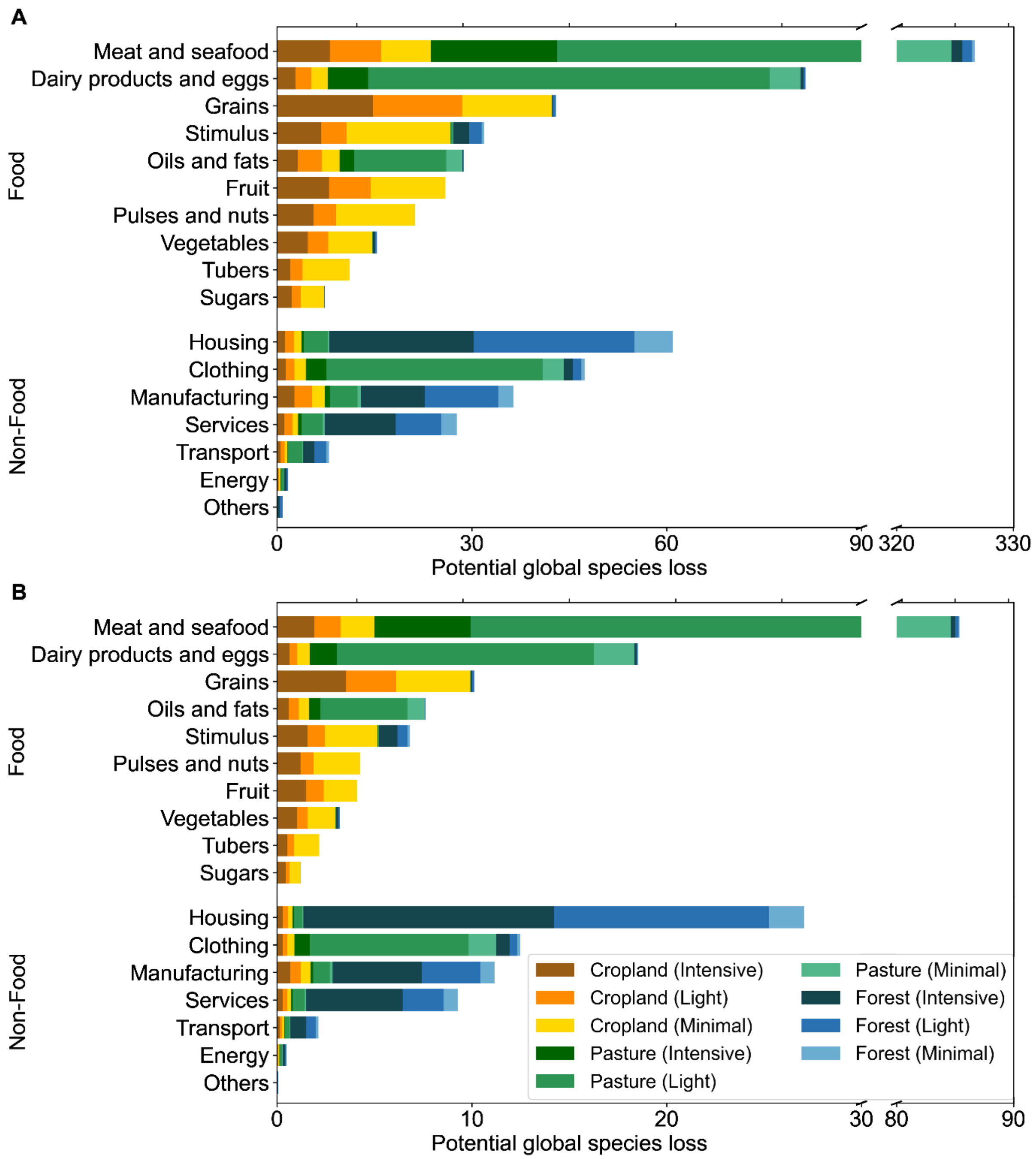

Figure 4.4. Potential global species loss due to specific product consumption from land use within KBAs for A) plants and B) vertebrates (mammals, birds, amphibians, and reptiles). Forest includes managed and planted forest.

4.3 Discussion

We provide a comprehensive overview of global, land-use driven biodiversity loss within and outside KBAs by: 1) using potential global species loss for multiple taxa rather than a single aggregated index [291,303]; 2) considering different land use intensities rather than just one [304]; and, 3) analyzing the effect of international trade on biodiversity loss rather than production-based biodiversity loss [292]. We find that pasture is the largest contributor to biodiversity loss from land use within KBAs with 58% of total plant species loss and 56% of vertebrate species loss (Table S9). Consequently, animal products are the primary drivers of biodiversity loss, in particular bovine meat. Lowering animal product consumption could reduce agricultural expansion and intensification, eventually even leading to land sparing/sharing which could potentially reverse biodiversity declines [305,306].

We estimate a quarter of global plant losses and a third of global vertebrate losses are embodied in international trade. This is slightly higher than previous estimates of 20% based on net primary productivity in biodiversity hotspots [307] and similar to a previous estimate of 25% for global endemic vertebrate loss [308] or 30% for threats to vertebrates [294]. In the international market, high-income nations can outsource land use and the associated biodiversity loss to other middle- and low-income nations that may have lower regulatory standards and higher biodiversity [291,297]. These differences partly drive leakage in biodiversity loss through international trade (analogous to carbon leakage). For example, Europe restored territorial forests by 9% (~ 13 Mha) while outsourcing 11 Mha deforestation due to crop displacement from 1990 to 2014 [17]. This deforestation occurs in many biodiversity-rich regions [17]. These dynamics may change in the future as agricultural development is projected to grow due to rapidly increasing population and per-capita income in tropical and subtropical regions which may result in higher local consumption and lower exports [305]. In addition, economic growth will threaten biodiversity loss by changing consumption patterns (e.g. increasing animal product consumption), especially in rapidly growing regions [291].

It is possible to argue that KBAs are both more and less exploited than neighboring regions. They might be more exploited because they provide more resources, such as food, timber, and fiber [309,310], but also more protected because 56% of global terrestrial KBAs are in protected areas, much higher than the global average level of protected areas (14%) [311]. Protected areas are established to prevent habitat loss and reduce biodiversity decline. Coverage of KBAs by protected areas can be used to measure the progress toward their protection [312]. However, the status of a protected area does not guarantee adequate management [289]. Some protected areas are simply "paper parks" and cover a high prevalence of habitat disturbance such as cropland, thereby, threatening biodiversity. For example, cropland within protected areas causes 18% of total species threats of global cropland [297]. In addition, protected areas can also have little biodiversity conservation value, while KBAs are important for the persistence of biodiversity [289]. Therefore, other metrics to assess progress toward reaching biodiversity protection goals within KBAs are necessary. These may include the relative change of the current value compared with a reference value for different biodiversity and habitat indicators within KBAs [289]. This reference value may be the expected biodiversity in a region if there were little or no human disturbance. These metrics need extensive data from systematic monitoring (e.g. remote sensing, in situ monitoring) and timely update across all KBAs [289].

There are a number of opportunities for future research. Given the dominance of land use for food systems, the first set of opportunities arises from improved agricultural mapping. Advances in remote sensing [313,314] and the use of crowdsourced data [315] may improve the accuracy of crop- and animal-specific maps. In terms of assessing biodiversity loss, improving the resolution of CFs can reduce uncertainties. Although other studies employ this same assumption to study biodiversity loss at a grid cell level [304], it would be an improvement to develop biodiversity CFs in line with the resolution of land use (i.e. 5 arc min in the paper). In addition, biodiversity responses are known to be scale-dependent and can be non-linear (for example, when critical thresholds are reached), making them extremely challenging to incorporate into global models [316]. Further methodological breakthroughs are needed in order to represent these dynamics. Biodiversity is itself diverse and multidimensional (involving genetic, species, ecosystem, functional, structural, cultural and behavioral diversity) [278,306,317,318]. Many species indicators, such as richness, evenness, differentiation, and abundance, have been used to assess biodiversity at multiple scales [278,306,319,320]. However, indicators going beyond the species level are usually applied in case studies and still need an impact assessment method to be developed for the global scale [318]. Even though land use change is the largest single threat to global biodiversity, other threats (e.g. climate change, invasive species, pollution, and overexploitation) can be more important locally, and will induce further global biodiversity loss via their interaction [306,321]. An ongoing challenge is to represent the interaction of these pressures in biodiversity research [306].

4.4 Conclusion

The rising salience of biodiversity loss among policy spheres has led to a deeper integration of biodiversity knowledge between science and policy, with the most prominent example being the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES) [322]. Key Biodiversity Areas (KBAs) are likely to become the main regions of focus for biodiversity conservation [289]. We globally assess biodiversity loss driven by human land use within KBAs and across nations in a spatially explicit integrated framework that retains important resolution in the food products which drive 22-29% of plant and vertebrate loss in international trade. We find that human land use within KBAs causes a proportionally high biodiversity loss (i.e. 7% of total land use caused 16% of global plant loss and 12% of global vertebrate loss), which indicates that KBAs, despite their importance, will need increasing policy protection in the future. Pasture with light use, as the most widespread land use type within KBAs, is the largest driver, accounting for around half of all species loss. Our comprehensive assessment can provide guidance for maintaining the integrity of KBAs and global biodiversity.

4.5 Materials and Methods

We assess global biodiversity loss driven by anthropogenic land use within KBAs by combining Multi-Regional Input-Output (MRIO) analysis with spatial analysis. Using MRIO analysis, we link production and associated environmental pressures to consumption anywhere in the world at the national scale. Then we allocate the consumption-based land use of a specific country into grid cells with the help of global land use maps and assign land use intensities. Different land use types and intensities determine the potential biodiversity loss at a location per area of land use, reflected by characterization factors. The biodiversity loss within the boundaries of KBAs can be delineated via this spatially explicit information. In short, we calculate biodiversity loss driven by land use both within KBAs and outside KBAs in order to provide a comparison. We focus on biodiversity loss within KBAs in the results section.

4.5.1 **Modeling framework**

The starting point for quantification of biodiversity loss within KBAs is gridded land use data (see the next section). This enables the calculation of the biodiversity loss per m^2 of land use (using characterization factors, CFs) (Figure S 8.12). While human land use is dominated by agriculture sectors, traditional global MRIO databases have highly aggregated agricultural sectors or regions. This is addressed by using the recently developed Food and Agriculture Biomass Input-Output (FABIO) table, a consistent, balanced, physical input-output database based on FAOSTAT data, covering 191 countries and 128 agriculture, food, and forestry products [323] (excluding non-agricultural sectors). To cover non-agricultural sectors, we build an integrated model framework linking FABIO and EXIOBASE (Figure S 8.12). EXIOBASE v3.6 is a highly detailed, monetary global multi-regional input-output database, including 200 products and 49 countries or regions [324]. EXIOBASE covers non-agricultural sectors in detail and by combining the two MRIO databases we can harness the advantages of both. An *other uses* matrix (A_{other}) links FABIO with EXIOBASE by providing agriculture and forestry biomass inputs in physical units for manufactured products in monetary units. We consider land use for food consumption ($\boldsymbol{y}_{FABIO}$) and non-food consumption ($\boldsymbol{y}_{EXIO}$) separately. To attribute land use to consumers across countries, we use a spatially explicit multi-regional input-output (SMRIO) model [293,325] (equations 1-2).

SMRIO connects the economic sectors in a standard MRIO database with spatially explicit estimates of environmental pressures (e.g. land use) to track a country's final consumption to the location of the embodied environmental pressures [325]. The SMRIO in the study is used to estimate the impact of the demand of a given commodity (e.g., palm oil) in a specific region or country (e.g. the US) through land use in a region or country (e.g. Indonesia) on a species group (e.g. plants). The full model is expressed mathematically as:

$$\boldsymbol{F}^s = \sum_{i,r} R^r \frac{\boldsymbol{e}_i^r \sum_{jt} \boldsymbol{L_A}_{ij}^{rt} \boldsymbol{y}_{FABIO,j}^{ts}}{d_i^r} + \sum_{i,r} R^r \frac{\boldsymbol{e}_i^r \sum_{jt} \boldsymbol{L_B}_{ik}^{ru} \boldsymbol{y}_{EXIO,k}^{uv}}{d_i^r} + \sum_i R^s \frac{\sum_i HH_i^s}{d_i^s} \quad (1)$$

$$\boldsymbol{L} = \begin{pmatrix} (\boldsymbol{I}_{FABIO} - \boldsymbol{A}_{FABIO})^{-1} & (\boldsymbol{I}_{FABIO} - \boldsymbol{A}_{FABIO})^{-1}(\boldsymbol{0} - \boldsymbol{A}_{other})(\boldsymbol{I}_{EXIO} - \boldsymbol{A}_{EXIO})^{-1} \\ \boldsymbol{0} & (\boldsymbol{I}_{EXIO} - \boldsymbol{A}_{EXIO})^{-1} \end{pmatrix} = \begin{pmatrix} \boldsymbol{L_A} & \boldsymbol{L_B} \\ \boldsymbol{0} & \boldsymbol{L_D} \end{pmatrix} \quad (2)$$

where, $\boldsymbol{F^s}$ is the global spatial distribution of environmental impacts driven by final consumption of country *s* for both FABIO and EXIOBASE. R^r defines the spatial distribution, represented in absolute values, of land use in country *r*. e_i^r is the environmental intensity (land use area per unit of output) of product *i* in the producing country *r*. $\boldsymbol{y}^{ts}_{fabio,j}$ indicates the final consumption of FABIO product *j* in country *s* that originates from country *t*, which is the last country exporting to country *s* in FABIO (that is, in a supply chain of four countries producer A, intermediate B, intermediate C, and consumer D, this refers to country C). $\boldsymbol{y}^{uv}_{exio,k}$ indicates the final consumption of EXIOBASE product *k* in country *v* that originates from country *u*, which is the last country exporting to country *u* in the other-uses matrix (i.e. required amount of biomass inputs per Euro of manufactured product) in Fig. S1. Since EXIOBASE has a higher spatial aggregation (with five "rest of world" regions), we assume the same per-capita consumption for FABIO countries, which fall under the five "rest of world" regions in EXIOBASE (see the mapping relationship in Table S5). d^r_i expresses the total land use of product *i* in country *r*. HH^s_i is the infrastructure land which is land that is not attributed to any product of the IO model but directly to final consumption of product *i* in country *s*. Since the matrix of technical coefficients (i.e. input requirements per unit of output) is a block matrix integrating FABIO and EXIOBASE, we can derive the Leontief inverse $\boldsymbol{L}$, via a simplified equation (1) using $\boldsymbol{L_A}$, $\boldsymbol{L_B}$, $\boldsymbol{L_D}$ as the subcomponents of the inverse in equation (2). $\boldsymbol{I}_{fabio}$ is the identity matrix with the same dimension of FABIO, and $\boldsymbol{I}_{exio}$ is the identity matrix with the same dimension of EXIOBASE. $\boldsymbol{A}_{fabio}$ is the technical matrix of FABIO; $\boldsymbol{A}_{exio}$ is the technical matrix of EXIOBASE; $\boldsymbol{A}_{other}$ is the matrix of technical coefficients linking the agricultural products from FABIO to the non-agricultural products in EXIOBASE.

4.5.2 **Product groups**

There are 128 agricultural and forestry commodities in FABIO, and 172 additional product categories are provided by EXIOBASE. We reported detailed product-based biodiversity loss driven by consumption of FABIO and EXIOBASE in Tables S11 and S12 respectively. For ease of inspection, we classified 200 product categories in EXIOBASE into 8 categories (Food, Housing, Transport, Energy, Clothing, Manufacturing, Services, and Other) according to previous work [326]. Food is detailed in FABIO, therefore, we categorized food into 10 groups (Grains, Tubers, Vegetables, Fruit, Pulses and nuts, Meat and seafood, Dairy products and eggs, Oils and fats, Sugars, and Stimulus) similar to former studies [327,328]. For the detailed mapping relationship between product categories and reporting groups, see Tables S6 and S7.

4.5.3 **Land use datasets**

We choose a base year of 2005, which aligns with characterization factors we employ. To keep the geographic data consistent, we aggregate all land use maps to a common resolution of 5 arc min.

Cropland: For national cropland, we use the harvested area of 168 types of primary crops from FAOSTAT in 2005 [329], and aggregate them into FABIO's 62 crop sectors. For the spatial maps of cropland, we use 40 categories covering 168 types of primary crops from FAOSTAT at 5 arc min resolution in 2005, provided by the Spatial Production Allocation Model (SPAM) [330] (see Table S2 for the detailed mapping relationship between FAOSTAT, FABIO, and SPAM crop categories). Specifically, we include the original 42 categories crop maps, but since "Pearl Millet" and "Small Millet" are not split in FAOSTAT, we aggregate them into millet; similarly "Arabica Coffee" and "Robusta Coffee" are not split in FAOSTAT and we aggregate them into coffee. Since FAOSTAT does not report the physical area of crops, we use the ratio of harvested to physical area of crops from SPAM to convert the consumption-based harvested area to the physical area for impact assessment. For national cropland used to produce animal fodder, we use the harvested area derived from FABIO in 2005. However, there is no cropland map of fodder in SPAM. Therefore, we incorporate cropland used to produce animal fodder and calculated it analogously using EarthStat's aggregated fodder maps at 5 arc min resolution in 2000 [331].

Forest: Previous studies tend to overestimate forest use because they consider all reported forest areas without distinguishing between natural forests and managed or planted forests [332]. Therefore, we link our framework to the latest, global forest data at 1 km resolution in 2000 [333]. We assume there are no large changes for the forest map from 2000 to 2005. Although this assumption may not hold for some countries [334]. Overall, this may slightly underestimate the effects of forest loss on biodiversity loss. The map downscales forest areas derived from FAO's Forest Resources Assessment (FRA) into grid cells with two different levels of forest management (Level 1: primary, naturally regrown, and planted forests; Level 2: production, multiple purposes, and other purposes) [333]. First, we use 6 combinations of forest classes and forest uses as forest use for human production and consumption (Table S4) [333]. After summing the forest area used for production (derived from Schulze et al. 2019) in FABIO countries and regions, we allocate the managed and planted forest areas to the sectors "*Wood fuel*", "*Industrial roundwood, coniferous*", and "*Industrial roundwood, non-coniferous*" in FABIO. The allocation uses the share of wood produced by the different sectors in [329]. We then aggregate the forest area map to 5 arc min, which we use as the uniform spatial resolution in this paper.

Pasture: Pasture was represented by a high-resolution (30 seconds) map from 2005 [335]. We excluded non-productive areas (aboveground NPP below 20 g C m^{-2} yr^{-1}) following a previous study [291,336], and capped the pasture at 100% total land-use coverage in each grid cell.

Infrastructure: We use ESA CCI land cover maps (category Urban Areas at 300 m resolution) in 2005. We assume all infrastructure land is used in final demand (i.e., we assume all infrastructure land only takes part in domestic consumption activities and is not involved in international trade), even though some areas are used for manufacturing sectors. Previous work has outlined the challenges for including infrastructure land more comprehensively [337].

Land use intensity: For the land use intensity map, we follow the method provided by Newbold et al. (2015). They map the global land system onto five land use types (we use cropland, pasture, and urban land) with three land use intensities (minimal, light, intense). A detailed definition of land use intensity classes is given in Table S3, and detailed conversion rules between Global Land System data and land use intensity in Table S4. For the definition of forest land use intensity, see Table S4, which itself is based on [333]. The Global Land System mixes different land use types within a grid cell. For our purpose, the land use intensity at a location was judged separately for each land use type.

4.5.4 **Deriving spatially-explicit biodiversity loss related to land use**

To quantify global species loss driven by human land use at different land use intensities, we use the latest characterization factors (CFs) developed by Chaudhary & Brooks (2018). The characterization factors (CFs) allow for an estimation of global potential extinctions driven per unit of land use [292]. The CFs were derived from the countryside Species–Area Relationship (SAR) for regional species loss of 804 terrestrial ecoregions [292]. While the classic SAR approach assumes that species can only persist in their native habitat, the countryside SAR acknowledges that species can also persist to some extent in human-modified habitats. Consequently, the classic SAR overestimates species loss and the countryside SAR provides more realistic estimates [338]. Regional species loss was subsequently multiplied with a vulnerability score of species based on their geographic ranges and threat levels from the IUCN Red List to estimate global species loss [292]. The vulnerability score is 1 if all species within a region are "critically endangered", as assessed by the IUCN Red List, and have their entire range inside that region (i.e. they are strictly endemic to that region). Thus, local land use within KBAs can potentially lead to global species extinctions, especially if the species is endemic and critically endangered. The unit is *global species-equivalents potentially lost* (referred to as species lost).

The CFs consider five taxa (mammals, birds, amphibians, reptiles, and plants) and five land use types (managed forest, plantation, pasture, cropland, and urban) under three intensity levels (minimal, light, and intense) for terrestrial ecoregions [292]. Specifically, each taxon consists of numerous species, including 5,490 mammals, 6,433 amphibians, 9,084 reptiles, 10,104 birds, 321,212 plants [339]. We use average instead of marginal CFs. Marginal CFs apply to marginal changes from the current situation (e.g., one additional m^2 of land use) [339]. In this study, however, we are investigating large changes from natural habitat to the current land use pattern in KBAs or even globally. Because the CFs are at ecoregion scale, we assume that the value of CFs in each pixel is the same for all pixels situated within the ecoregion, as also assumed by Chaudhary et al. (2016). After computing the spatial distribution per unit area of each land use type at different land use intensities driven by final consumption in a given region, we multiply the corresponding CFs with consumption-based land use data to obtain consumption-based global species loss for each taxon equation (3).

$$SL^{s}_{global,g,m,n} = \mathrm{CF}_{global,g,m,n} \times \mathrm{F}^{s}_{m,n} \quad (3)$$

$SL^{s}_{global,g,m,n}$ is the potential global species loss for each taxon g for a different land use type and intensity m in each grid cell n driven by final consumption in country s. $CF_{global,g,m,n}$ is the land occupation CF (species lost per unit land use) for taxon g at a different land use type and intensity m in each grid cell n. $F^{s}_{m,n}$ is the land use for each different land use type and intensity m in each grid cell n driven by final consumption in country s. F is derived from equation 1.

After finding the global distribution of biodiversity loss driven by human consumption, we use KBA boundaries [286] to get the subset of biodiversity loss from land use within KBAs. The consumption-based biodiversity loss is the sum of agriculture related biodiversity loss (from FABIO) and non-agriculture related biodiversity loss (from EXIOBASE).