

Biodiversity impacts of recent land-use change driven by increases in agri-food imports

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SI Results

Results S1. Mexico. Similar as for Brazil, Mexico's increased production of beef, dairy products, vegetables, fruits, nuts, and beverages from 1995 to 2022 surpassed the related increase in land use. This has compensated for Mexico's rise in domestic consumption, resulting in decreased consumption-based impacts through land abandonment and other forms of land conversion (Figure 5 of the main article). These decreased biodiversity impacts surpass the increased biodiversity impacts due to rising domestic consumption of dairy products (in Brazil) and other food products (in Brazil and Mexico), as shown by the difference between negative and positive values in Figures 4 and 5 for domestic consumption. Consequently, biodiversity impacts have decreased in Mexico from a consumption perspective (Figure 2d). At the same time, a net increase in land-conversion biodiversity impacts is linked to agri-food exports (Figure 4–5), reflecting the substantial increase of exported goods between 1995 and 2022.

Results S2. Biochemicals. Feedstock for biochemicals account for one-fifth of global land-use change impacts. Thereof, more than 80% are concentrated in Indonesia (23%), Australia (10%), and other Southeast Asia + Pacific (17%), Brazil (11%) and other Latin America + Caribbean (10%), and Africa (11%). Vice versa, more than half of the land-use change impacts of biochemicals are attributed to consumption by China (30%), Europe (15%), and the United States (11%).

SI Discussion

Discussion S1. Differences in land use (change) impacts for Extended Data Figures 3 and 4. Biodiversity impacts of land use are comparable to previous estimates^{4–6}, but slightly higher in Extended Data Figure 4.1 compared to Extended Data Figure 3.1, as Extended Data Figure 4.1 also includes the impacts related to forestry (Extended Data Figure 4.1a). In contrast, the cumulated land use change impacts from 1995 to 2022 are almost 40% higher in Extended Data Figure 3.2 compared to Extended Data Figure 4.2. The reason for this is that a significant portion of global land use change is related to the conversion of natural land for agriculture followed by abandonment (Extended Data Figure 5). As the increases in biodiversity impacts through natural habitat conversion exceeds the decreases in biodiversity impacts through abandonment, the net impact on biodiversity is significant. However, this is neglected when assessing net land use change impacts (Extended Data Figure 4.2), as no species loss factors exist for abandoned land (SI_CFs.xlsx).

The contribution by region of production and consumption is similar in both assessments (Extended Data Figure 3 and S4). However, land use change impacts are increasing for Europe in Extended Data Figure 3.2c, while they are slightly decreasing in Extended Data Figure 4.2c. This is attributed to reduced wood imports from tropical regions (e.g., Indonesia) which are not included in the assessment of Extended Data Figure 3. Moreover, land use change impacts are increasing for beef and dairy products in Extended Data Figure 3.2d, but are decreasing in Extended Data Figure 4.2d. The reason for this is that the net area of pastures (as considered in Extended Data Figure 4.2) has decreased in many regions (e.g., Brazil), while Extended Data Figure 3.2 includes the pattern of deforestation of pastures followed by their abandonment, as discussed for Brazil in the main article.

Discussion S2. Policy interventions. Our results underscore the critical need to implement policy measures that incentivize two primary actions: i) Biodiversity hotspot regions should be supported to halt natural habitat destruction, and ii) countries, especially China, the United States, the Middle East and Europe, should cease importing agri-food products from tropical biodiversity hotspots. For tropical regions, such policy interventions should foster the implementation of financial mechanisms that reward natural habitat conservation⁷, such as by Payments for Ecosystem Services (PES)⁸, certification schemes⁹, international grants¹⁰, debt-for-nature swaps¹¹, and ecotourism¹². For those countries importing agri-food products from tropical biodiversity hotspots, policies need to promote sustainable sourcing practices^{13,14}, such as by international agreements, encouraging corporate responsibility¹⁵, creating economic incentives¹⁶, and rising consumer awareness¹⁷. To effectively implement these policies, it is crucial to establish transparency in global supply chains by quantitatively mapping their impacts. This is essential for incentivizing consumer-facing companies to reduce their supply-chain impacts and to meet the growing consumer demand for sustainable products¹⁸.

SI Methods

Methods S1. Global potential species loss indicator. Global potential species loss (PSL_{glo}) is an indicator that assesses the proportion of species at risk of irreversible global extinction¹⁻³. Initially, ecoregion¹⁹-level extinctions are estimated using countryside species-area relationships (SAR) for five taxa (mammals, birds, reptiles, amphibians, and vascular plants)^{2,20,21} and six land use types (annual and perennial crops, pastures, intensive and extensive forestry, urban land). The number of species lost per ecoregion is then weighted with a factor between 0 and 1, which considers the range area of all species present in the ecoregion (fraction of total habitat area located in the respective ecoregion). However, regional species loss does not necessarily imply global extinction, as the species may also exist in other ecoregions. Therefore, regional species loss is multiplied by a vulnerability score ($0 \leq VS \leq 1$), which reflects the likelihood of regional loss leading to global extinction. For example, if an ecoregion harbors only endemic species, the ecoregion species loss is the same as the global species loss, while it is lower in the (usual) case that the ecoregion also harbors non-endemic species. The vulnerability score incorporates factors such as the species' range areas within the ecoregion (as a percentage of total habitat) and the IUCN red list threat level. This approach is deemed more comprehensive than solely considering endemic species loss, as it captures the escalating risks of extinction resulting from habitat reduction.

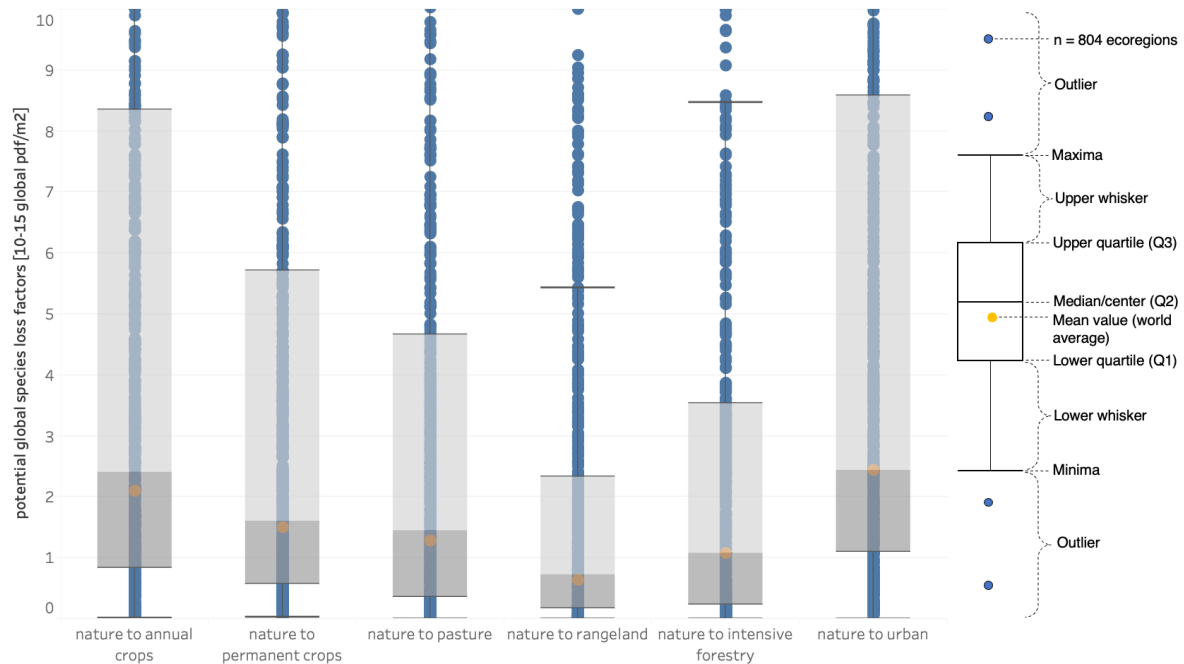


Figure S1. Global potential species loss factors¹⁻³ used in this study for six land conversion types. Each boxplot includes 804 datapoints, which refer to the 804 ecoregions¹⁹ that were distinguished in the regionalized biodiversity impact assessment. All datapoints were retrieved from UNEP-SETAC methodologies¹⁻³ and are attached to the SI (SI_CFs.xlsx, sheet: occupation CF).

Methods S2. Resolved EXIOBASE version 3 (REX3). As any MRIO database, REX3 is composed of four matrices for each year, covering the time period from 1995 to 2022. The transaction matrix (T) describes the economic flows between all sector-country combinations (163 sectors x 189 countries = 30'807 sector-country combinations), while the final demand matrix (Y) describes the final demand of each country for outputs of each sector-country combination. The satellite matrices of the economy (Q_r) and the final demand (Q_y) indicates the biodiversity impact due to land conversion for the economy (30'807 sector-country combinations) and the households (189 countries). In addition to biodiversity loss from land-use change and land occupation, REX3 also includes data on climate impacts, health impacts from particulate-matter emissions²², and water stress^{23,24}. Together with biodiversity, they are listed as key environmental concerns on the UN agenda²⁵, and were implemented following the UNEP-SETAC³ guidelines²⁶. Up to the step of adding bilateral trade flows from the BACI database²⁷, REX3 was compiled based on the constraint that if it is aggregated back the regional resolution of EXIOBASE3 (44 countries, 5 RoW regions), REX3 equals the original EXIOBASE3 database (with small deviations of $\pm 2\%$ due to numerical issues)²⁶. The integration of bilateral trade data from the BACI database²⁷ was done based on the monetary share of a bilateral trade flow of a commodity in total trade of the same commodity. For instance, if 1% of the monetary of global beef is attributed to Germany's beef imports from Brazil according to the BACI²⁷ database, this share is reflected in the REX3 database (for each year individually). Therefore, this last step slightly alters the contribution by region and sector when aggregating REX3 back to the EXIOBASE3 resolution, while the total sum of the monetary flows within the transaction and final demand matrices remained identical to the EXIOBASE3 database. Further details on the compilation of an earlier version of REX are provided in ref^{26,28}.

Methods S3. Classification by income and HDI. To assess the effect of income and development stage, we categorized the 189 countries based on income, measured by per-

capita GDP²⁹, and the human development index (HDI)³⁰. The analysis also aimed to determine the percentage of land-use change impacts shifted from higher-income regions to those with lower income. This involved creating a matrix that juxtaposed the 189 producing countries with the 189 consuming regions (*SI_Results.xlsx: trade within 189 countries*). The calculation involved aggregating all instances of land-use change impacts where the consuming region exhibited a higher per-capita income than the producing region. Moreover, we aggregated the matrix that juxtaposed the 189 producing countries with the 189 consuming regions to the income regions (4 producing income groups x 4 consuming income groups) to evaluate the link between producing and consuming income regions. The same procedure was followed for the development stage (4 producing development stages x 4 development stages). The diagonal values in these aggregated matrices refer to the impacts within a group (showed in grey in Extended Data Figures 7 and 8), while all the other values refer to trade among the income/development stages (showed in colors in Extended Data Figures 7 and 8).

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