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Identifying species threat hotspots from global supply chains

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Identifying hotspots of species threat has been a successful approach for setting conservation priorities. One important challenge in conservation is that, in many hotspots, export industries continue to drive overexploitation. Conservation measures must consider not just the point of impact, but also the consumer demand that ultimately drives resource use. To understand which species threat hotspots are driven by which consumers, we have developed a new approach to link a set of biodiversity footprint accounts to the hotspots of threatened species on the IUCN Red List of Threatened Species. The result is a map connecting consumption to spatially explicit hotspots driven by production on a global scale. Locating biodiversity threat hotspots driven by consumption of goods and services can help to connect conservationists, consumers, companies and governments in order to better target conservation actions.

Human-induced biodiversity threats, such as from deforestation, overfishing, overhunting and climate change, often arise from incursion into natural ecosystems in search of food and resources. One of the main drivers of this incursion is the production of goods for export. Lenzen and colleagues suggested that at least one-third of biodiversity threats worldwide are linked to production for international trade[1,2]. Understanding market forces and using effective spatial targeting are key to efficient protection[3,4]. To expedite remedial actions, however, the threat causes must be located more specifically. Previous work has linked consumption and supply chains to biodiversity impacts, but only at the country level[1]. Biodiversity threats are often highly localized. Knowing that a given consumption demand drives a biodiversity threat somewhere within a country is not enough information to act upon. Here we present a new approach to making the inshore and terrestrial biodiversity footprint spatially explicit at a subnational level.

Results

As described in the Methods, we built a map of threat hotspots by combining extent-of-occurrence (EOO) maps for a range of threatened species. We attributed each anthropogenic species threat to one or more industries, then traced the commodities involved to final consumers worldwide.

With the complete spatial footprint accounts in hand, we may ask which countries, and which consumption categories, threaten habitat at various hotspots. Figure 1 presents the map of biodiversity threats driven by US consumption.

For marine species, southeast Asia is the overwhelmingly dominant global hotspot area, with the United States and European Union both exerting many threats there, primarily owing to fishing, pollution and aquaculture. The United States has additional marine hotspots off the Caribbean coast of Costa Rica and Nicaragua, and at the mouth of the Orinoco around Trinidad and Tobago (Fig. 2a). The European Union drives threat hotspots outside southeast Asia in the islands around Madagascar: Réunion, Mauritius and the Seychelles.

The US footprint on terrestrial species provides some notable findings. While the hotspots in southeast Asia and Madagascar are perhaps expected, we also observe hotspots in southern Europe, the Sahel, the east and west coast of southern Mexico, throughout Central America, and in Central Asia and southern Canada. Despite much attention given to the Amazon rainforest, the US footprint in Brazil is, in fact, greater in southern Brazil (in the Brazilian Highlands where agriculture and grazing are extensive) than inside the Amazon basin, although impacts along the Amazon river itself are high. The high US biodiversity footprint in southern Spain and Portugal — linked to impacts on a number of threatened fish and bird species — is also noteworthy, given that these countries are rarely perceived as threat hotspots.

We find that the biodiversity footprint is concentrated: for threats driven by US consumption, the 5% of land area that is most intensively affected covers 23.6% of its total impact on species, and at sea the most intensively affected 5% of marine area includes 60.7% of threatened species habitats.

It is possible to view the threat hotspots for various major consumer countries and zoom in on particular regions affected by their consumption. The enlargements in Fig. 2 focus on threat hotspots in South America driven by US consumption (Fig. 2a); in Africa driven by EU consumption (Fig. 2b); and in southeast Asia driven by Japanese consumption (Fig. 2c). EU consumption drives threat hotspots in Morocco, all along the coast of the Horn of Africa from Libya to Cameroon, in Ethiopia, Madagascar, throughout Zimbabwe, and at Lake Malawi and Lake Victoria. We also note the heavy EU footprint in Turkey and Central Asia, regions perhaps not known for their charismatic species but nevertheless important areas of EU-driven biodiversity impact.

The Japanese-driven biodiversity impacts in southeast Asia are greatest in the Bismarck and Solomon Seas off Papua New Guinea. Terrestrial hotspots linked to Japan can be found at New Britain Island (where palm oil, cocoa, logging and coconut plantations are the dominant industries) and the eastern highlands of New Guinea; in Bornean and continental Malaysia; in Brunei (where urban and industrial areas sprawl into high-value habitat); in the Chao Phraya drainage of Thailand; in northern Vietnam; and around Colombo and southern Sri Lanka (where pressure is driven by tea, rubber, and threats linked to manufactured goods sent to Japan).

Biodiversity footprint hotspots are a function of both underlying species richness and density (as indicated by composite EOO

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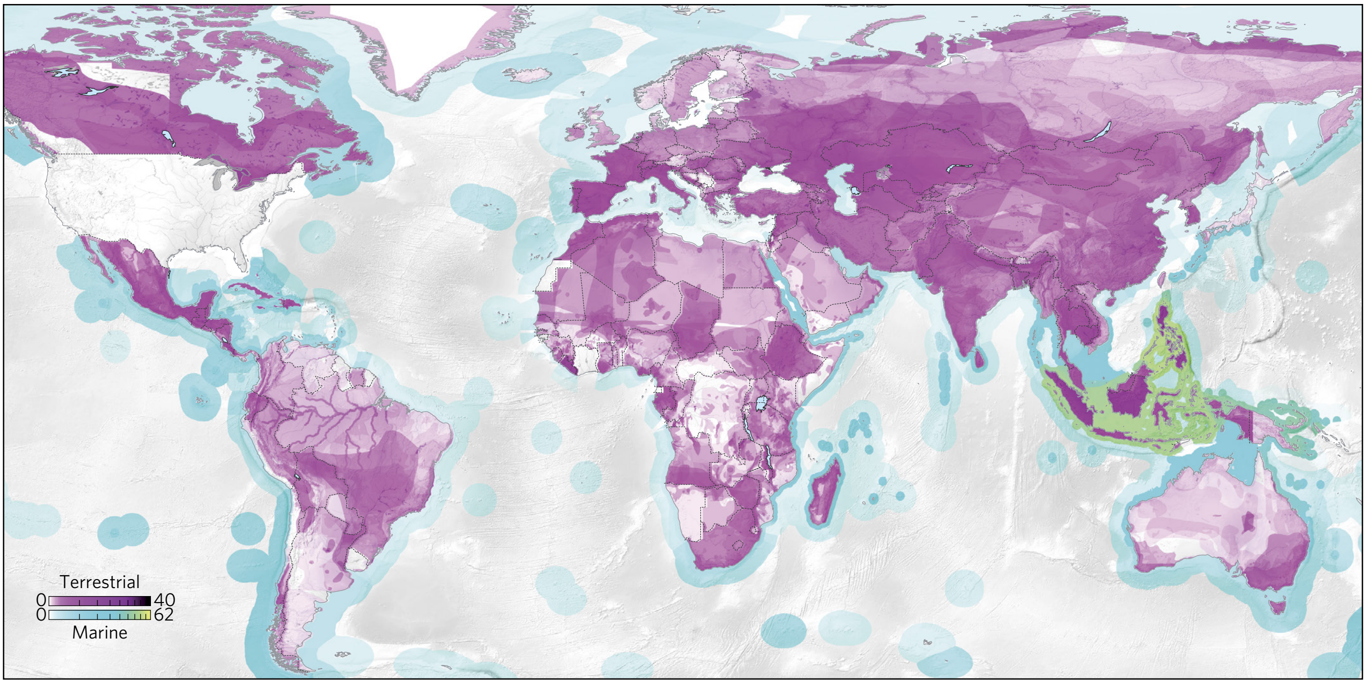

Figure 1 | Global hotspots of species threat linked to consumption in the United States. Darker areas indicate areas of threat hotspots driven by US consumption, based on the mix of threats exerted in each country and the mix of export goods sent to the United States for final consumption. Terrestrial and marine species colour bars are on log scales showing units of total species-equivalents, which is the sum over all the fraction of species threats allocated to this consumer country (see Methods).

maps), and of the level of threatening activity (that is, number of species threats attributable to implicated industries at a given location). Hotspot maps may be decomposed to view the contributing factors. Figure 3 provides a disaggregation of the US footprint in Fig. 1 by threat cause.

Discussion

Trade and responsibility attribution aside, identifying biodiversity hotspots is not trivial, and is strongly limited by data resolution. There is a need for improved models and maps locating species occurrence and biodiversity hotspots[5,6]. Since Myers and colleagues introduced the hotspot concept with 25 broad areas[7], much conservation research now relies on EOO maps[8]. Examining the overlap between EOO maps for different species[9] has limitations as a method for finding hotspots[10–14], and EOO is not the only way to identify hotspots: for birds, mapping species occupancy[15], endemism or threat reveals different hotspots[16]. Furthermore, both threat intensity and species density can vary considerably within the range[17]. Projects such as AquaMaps[18], the Global Mammal Assessment[19] and the Global Amphibian Assessment are working to generate more robust and higher-resolution maps. When a superior, globally consistent, set of species occurrence maps becomes available, it will be possible to replace the EOO maps with those.

Grenyer and colleagues[20] argued that priority areas for biodiversity conservation should be based on high-resolution range data from multiple taxa, not merely on aggregated EOO maps, since cross-taxon and rare species congruence are in fact low in such aggregate maps. Acknowledging this, the method that we use here can be used to identify the spatial biodiversity footprints at the detail of individual species. It is also possible to use the spatial footprinting method with biodiversity threat-hotspot maps generated using other approaches such as mechanistic modelling[21]. For example, Kitzes and colleagues estimated population densities based on potential net primary productivity to estimate which economic activities impact the most potentially valuable bird habitats[22]. Since EOO maps of range do not estimate actual occupancy or how the threat varies across the range, more detailed local assessments at individual hotspots will be always be needed. Nevertheless, these spatial footprint maps can be of use. For example, we can imagine that even if a company or buyer consults a spatial biodiversity footprint map that has overestimated the threat and identifies, say, three hotspots in a supplier country, even though the true hotspots will be in some subset of the identified area, this hotspot information is still more precise and actionable than simply a single total figure for impacts in that country, which has been the limit of knowledge so far.

The economic trade model is another source of uncertainty, although work continues to improve the convergence[23], reliability, and spatial[24,25] and product-level detail of multi-region input–output databases used for the trade accounting. Although alternative methods exist to calculate land footprints[26] — which is the biggest driver of the biodiversity footprint[27] — for this study an existing biodiversity footprint account was used rather than building a new one. Improved spatial data for the trade model are especially important for spatially extensive countries such as the United States, China, Russia and India, where one industry may have different impacts across its domain. With much attention on global supply chains and footprints[28], it may be expected that trade accounting and embodied resource-flow accounts will become more accurate in the future. However, it must be noted that small-scale and illegal impacts are potentially important[29] and will possibly never be covered by global-scale trade databases.

It has been estimated that 90% of the US$6 billion of annual conservation funding originates in and is spent within economically rich countries[30], yet these countries are rarely where threat hotspots lie. Directing funding back up along their supply chains, toward the original points of impact, could help to yield better conservation outcomes.

As conservation efforts must both protect critical habitat[31] and do so in an economically efficient manner[32,33], spatially explicit supply chain analysis can be a helpful tool for finding the most efficient ways to protect absolutely important areas. Given that the Aichi targets are inadequate — protecting 17% of global land area and 10%

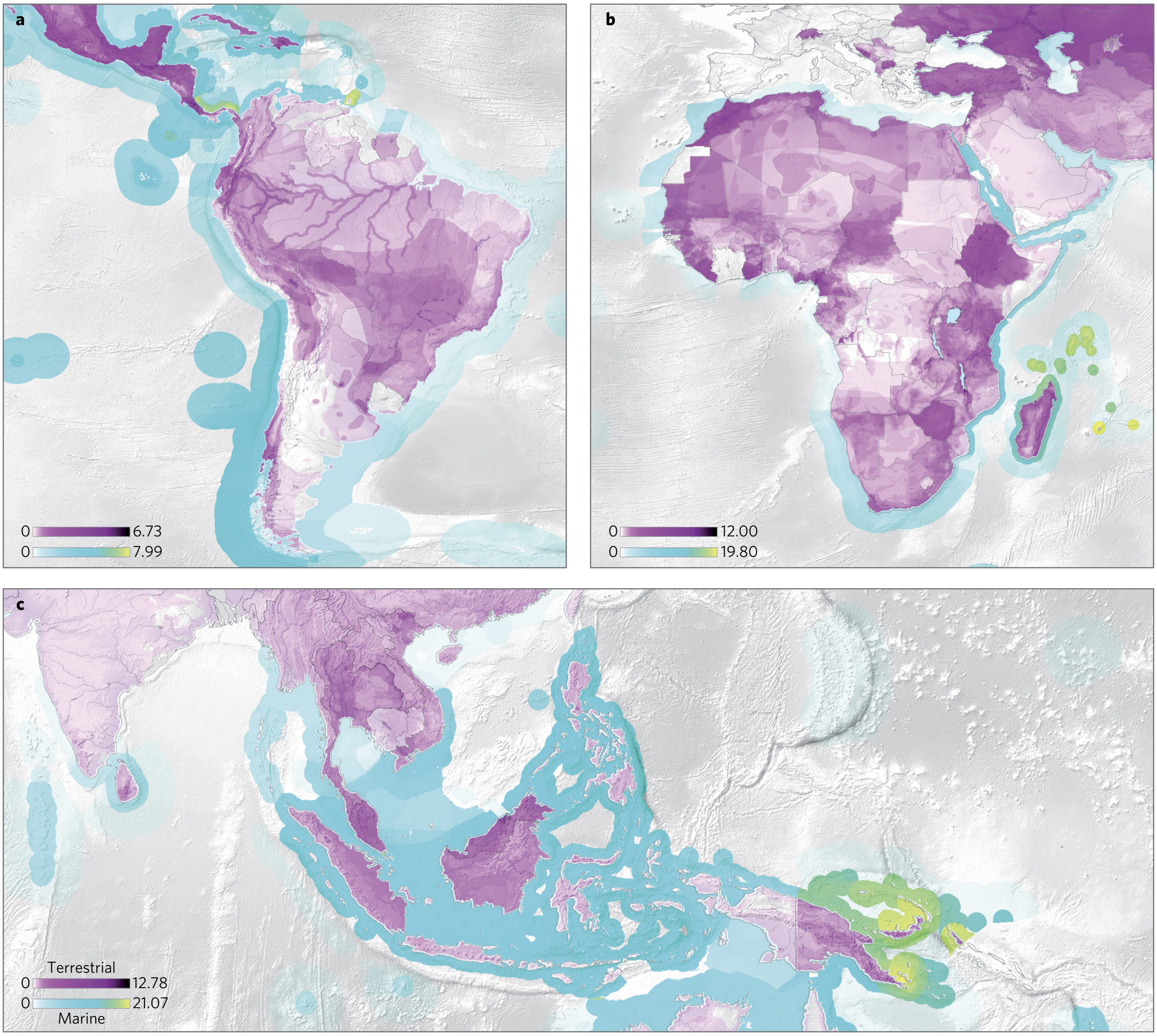

Figure 2 | Selected enlargements of threat hotspots. a–c, Enlargements are shown for hotspots in Latin America driven by US consumption (**a**); in Africa driven by European (EU27) consumption (**b**); and in Asia driven by Japanese consumption (**c**). Note that some countries (including the Solomon Islands, Guyana, French Guiana, Equatorial Guinea and Western Sahara) are not covered in the economic database.

of marine can cover at most 53.1% of the known EOO of threatened species — and that biodiversity stocks are not evenly distributed amongst countries, conservation hotspots must be prioritized (and of course, conservation efforts must not be focused on unproductive areas[34–36]).

Using the biodiversity hotspots method, it is possible to identify areas where the biodiversity threat is predominantly driven by a small number of countries. By identifying regions where just two or three countries are implicated in driving the pressure, it could be easier to initiate direct collaborations between producers and consumers, in parallel to existing international regimes, to mitigate biodiversity impacts at those places.

Spatially explicit impact accounting can aid improvements in sustainable production, international trade and consumption. Responsibility for environmental pressures should be shared along the supply chains, not pinned solely on primary impacting industries or exclusively on final consumers. Looking upstream, detailed information on species hotspots can be useful for companies in reducing their biodiversity impact. Downstream, accounts such as these can be of use to guide sustainable purchasing and green labelling and certification initiatives. It is possible to imagine companies comparing maps of biodiversity footprints against maps showing where their inputs are sourced. We could also foresee conservationists working to preserve affected areas using such models to help to identify the intermediate and final consumers whose purchases sustain threat-implicated industries, and looking down the supply chain to help to involve consumers in protection activities. Better targeting of spatial hotspots can assist in setting effective conservation priorities[37].

Maps of species threat hotspots can thus help all actors, from producers and conservationists to final consumers, to focus solutions on targeted biodiversity hotspots.

Methods

Using a threat hotspot map built using the composited EOO maps of multiple species from the International Union for Conservation of Nature (IUCN)[38] and BirdLife International[39]

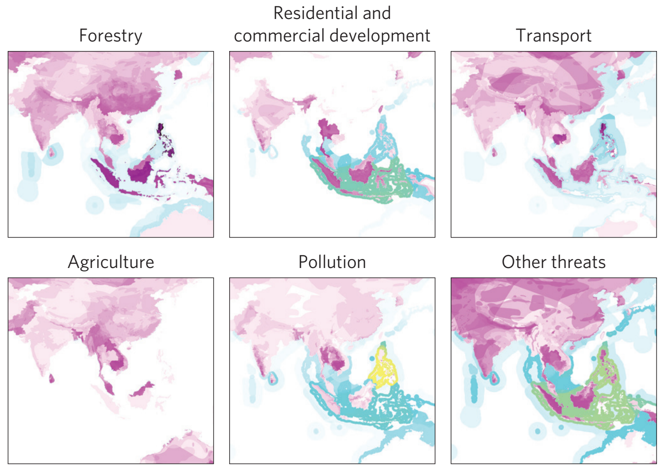

Figure 3 | Decomposition of threat hotspots linked to consumption in the United States by threat cause. Biodiversity footprint hotspots for a given country are a function of both underlying species richness and the composition and volume of threatening activity. Aggregated categories are based on 123 detailed threat causes. Note: the sub-panels are individually colour-scaled for illustrative purposes, to highlight the change in spatial pattern between threat causes, and cannot be directly compared to the other figures.

(also called distribution maps showing range boundaries), we applied the biodiversity footprint method of Lenzen *et al.*[1] to attribute each anthropogenic species threat to one or more culpable industries. We then traced the implicated commodities from 15,000 production industries worldwide to final consumers in 187 countries, by using a global trade model[40,41]. The result is an account linking production and consumption of economic sectors to spatially explicit hotspots of species threat. Spatially explicit footprints have also been calculated for air pollution[42] and greenhouse gas emissions[43], using the same method as in this study. The account only considers threats that can be attributed to industries and thus excludes threats such as change in population structure, disease or natural catastrophes (discussed further below).

Figure 4 provides an illustration of the method. Species come under threat from a variety of causes, many of which are anthropogenic and linked to industries producing goods for consumption domestically and abroad. In Fig. 4, the EOO of *Ateles paniscus* (the red-faced spider monkey) in Brazil is shaded in a darker colour reflecting a higher fraction (2.43%) of the total anthropogenic threat to the species that can be attributed to consumption in the United States (through agriculture and logging activity in Brazil producing goods finally consumed in the United States). The range of *Atelopus spumarius* (Pebas stubfoot toad) is shown in a lighter shade because a smaller fraction (2.02%) of the total threat to that species can be attributed to final consumers in the United States, owing to the different mix of threat causes to *Atelopus* and the different mix of implicated products consumed in the United States. These impact maps are summed over all species hotspots. In the Fig. 4 example, the hotspot at the intersection of *Ateles* and *Atelopus* is shaded at the 2.43% + 2.02% = 4.45% level. The final biodiversity footprint map for a given country is thus a product both of the actual distribution of biodiversity hotspots around the world and of the unique composition of how that country's consumption affects each individual species in each partner country.

The biodiversity footprint of country s, $F_j^{(c)s}$, comprising the sum of the threat to species suffered in country r exerted directly by industry i due to consumption in country s of the good or service j, inclusive of the upstream and indirect impacts involved in provisioning j, can be expressed as

$$F_j^{(c)s} = \sum_{i,r} q_i^r \sum_t L_{ij}^{rt} y_j^{ts} \qquad (1)$$

where q is a threats coefficient, L is the Leontief inverse and y is final demand[1,44]. This trade model follows flows through multiple trade and transformation steps, even via middleman countries, to attribute impacts from production in s to consumption in r via the last supplying country t. In this study, we use the implementation of the biodiversity footprint from Lenzen *et al.* directly, which in turn uses the Eora global MRIO database[40]. The reader is referred to that paper and its supplementary information for a thorough discussion of the method, but we summarize it briefly here.

By adding spatial data, we extend the biodiversity footprint method previously produced by Lenzen and colleagues. Following that method, we consider only species that the IUCN and BirdLife International list as vulnerable, endangered or critically endangered, and we ignore threats that are not directly attributable to legal economic activities, including disease, invasive species, fires and illegal harvesting (since illegal activities are not captured in the global trade model). The IUCN documents 197 different threats, 166 of which can be attributed to human activities. Threatened species hotspots were identified by overlaying species range maps from IUCN[38] and BirdLife International[39] for $N = 6{,}803$ *Animalia* species (the combined IUCN and BirdLife databases report on 20,856 species with known threat causes; of these, 8,026 are threatened, and of those threatened, range maps are available for 6,803). Species threat records from the IUCN Red List (for example, "The vulnerable (VU) *Atelopus spumarius* in Brazil is threatened by Logging and Wood Harvesting") are mapped to economic production sectors — in this case, attributed to the forestry sector in Brazil — and the resultant products are then traced through a multi-region input–output table that documents the trade and transformation steps in the economic network consisting of 14,839 sectors/consumption categories across 187 countries. When a species faces multiple threats, all threats are given equal weight, as no relevant superior data are available. Every individual species is given equal weight, regardless of its ecological niche or threat level (vulnerable/endangered/critically endangered), and every threat cause is given equal weight.

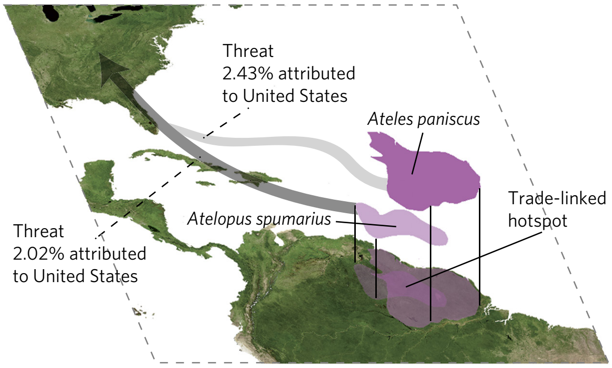

Figure 4 | Protocol illustration, for hotspot induced by consumption in the United States.

The hotspot maps are potentially overestimates, for several reasons. Global MRIO databases do not currently trace flows at the subnational level (that is, they do not show which cities produce or consume which goods). However, the IUCN threat maps document the mix of species threats occurring in each grid cell, and the trade model links the threats to implicated industries and traces the mix of goods and services embodied in supply chains bound for domestic or foreign final consumption. Multi-scale MRIOs combining international and subnational flows that would offer further improvements in resolution are under development[24,25,45,46]. Another cause of overestimation is that for species whose range spans multiple countries, there are no data on whether the threat or threats faced by that species occur differently in the various countries. Mathematically, our model treats country–species–threat tuples as the unique item, whereas in fact in the Red List it is only the [country–species] and [species–threat] tuples that are unique. For example, a species spanning two countries could be threatened by logging, but it may be that logging practices in one of the two countries do not threaten the species, or that one of the countries does not even have any logging industry (Chaudhary *et al.* investigate the impact of various timber practices on biodiversity[47]). But in the latter case, when one country has no logging industry or exports to the focal country, the range of the species in the innocent country will not be shaded, since the shading is a function of the unique mix of species and export of implicated goods.

Although the hotspot areas identified in this study are potentially overestimated, it is important to note that the entire analysis is based on historical records of species threats, not current or emerging threats. Threats such as invasive species, illegal activities or disease can arise very quickly, and the Red List and Eora MRIO database could be slow to identify these current issues. This delay is particularly relevant given recent indications that humanity is surpassing 'safe' limits for biodiversity loss[48].

In our study, only terrestrial and near-shore marine biodiversity are considered. Open-ocean fishing was deemed beyond the scope of this study because of challenges related to obtaining reliable data on deep-sea fishing, both for production (handling illegal and under-reported catch), and for correct allocation of catch to the producing country (foreign-flagged vessels). Additionally, instead of the IUCN EOO maps for marine species, it could be preferable to use spatialized species density models (such as the AquaMaps project) that could provide more accurate marine biodiversity hotspots. We note that marine biodiversity is higher in coastal areas than open oceans[19,49], and that jurisprudence only holds within exclusive economic zones (EEZs), these two facts partially justifying the omission of extra-EEZ threats.

In this study, we link a hotspot EOO map R (which for display we have rasterized to 0.94′, or ~3 km² grid cells at the Equator, although, as discussed, the actual accuracy of the map is less) and biodiversity footprint for each threatened species h for each country. Most threats (roughly two-thirds) are exerted domestically, so the country of export and the country of the hotspots are the same[1]. If a species is threatened by climate change (CC), the driver (exporting) country, r, and the suffering country, u, may be different. Therefore, we attribute the threat to all industries that emit carbon dioxide emissions but keep the species range map in the suffering countries. The unit of the resulting maps is number of species, also called species-equivalents. This value can be fractional, since one species can be threatened by many industries and countries. The footprint maps are defined as

$$R^{(c)s} = \sum_{r,h} R_h^r \sum_{i} q_{hi}^{r(\text{nonCC})} \sum_{j,t} L_{ij}^{rt} y_j^{ts} + \sum_{u,h} R_h^u \sum_{i,r} q_{hi}^{r(\text{CC})} \sum_{j,t} L_{ij}^{rt} y_j^{ts} \qquad (2)$$

Data availability. The results, calculated as described in the Methods, are based on the data from the IUCN, BirdLife International and Eora MRIO databases, all of which are publicly available. The results maps presented and discussed here will be available at the http://worldmrio.com website or from K.K. Maps for the United States, China, Japan and EU27 are provided in the Supplementary Information (Supplementary Figs 1–4).

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Author contributions

K.K. designed the research. D.M. and K.K. conducted the analysis. D.M. prepared the figures. D.M. and K.K. wrote the paper. Both authors contributed equally to this work.

Additional information

Supplementary information is available for this paper.

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Competing interests

The authors declare no competing interests.