The Ecological Cost Of Consumption

Isaac Peterson (✉ isaac.peterson@helsinki.fi)

The University of Helsinki

Matthew Selinske

Royal Melbourne Institute of Technology

Manfred Lenzen

The University of Sydney <https://orcid.org/0000-0002-0828-5288>

Atte Moilanen

University of Helsinki

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Abstract

The link between global ecosystem decline, trade, and human consumption suggests that trade-based biodiversity footprints should be regarded as a critical indicator of planetary impacts. Here we integrate a global input-output economic framework that encompasses global trade between 15909 sectors, with range and impact data on 10518 terrestrial plant, 17234 terrestrial animal, 6101 freshwater and 5059 marine species, to specify the biodiversity footprints associated with global trade and consumption across domestic and international supply chains. Our framework characterises global species loss as driven by domestic trade in emerging market economies including China, Brazil, Mexico, India, and Ecuador, and exacerbated by consumption in high-income countries, especially those in the G7, that are driving species loss in emerging markets and low-income nations. We attribute the largest sector-scope footprints to construction in China, Colombia, and India, agriculture commodity trade in Madagascar, Mexico, Tanzania, and Peru, and food manufacture in Mexico, Germany and France.

Introduction

Consumption, commerce, and the global supply chains that produce and deliver commodities and services to consumers, are causing over-exploitation of planetary resources, land use change, human-induced climate change, and pollution, resulting in fundamental disruptions to planetary biophysical systems, and global biodiversity loss and decline^{1–7}. The consumers and trade-sectors that ultimately drive these processes are increasingly geographically, socio-economically, and psychologically distanced from the impacts associated with resource acquisition and commodity production⁸. Hence, it has been proposed that conservation interventions need to be directed toward influencing entire supply chains, including the stages of commodity production, distribution and consumption, rather than singularly focussing on interventions at the locations of biodiversity loss.

Many studies have linked resource intensive industry with direct impacts on biodiversity, with examples ranging from the deforestation associated with the production of soy beans⁹, palm oil^{10,11}, cacao¹², and rubber¹³, impacts associated with mining¹⁴, and marine life depletion associated with industrialised fishing^{15,16}. However, the widespread adoption of a framework that can determine the responsibility for the biodiversity “footprint” associated with each commodity or service, i.e. the resource requirements and/or impacts that are associated with commodity acquisition, production and distribution, is yet to be realised. The need to assess the footprint associated with commodity production, trade, and distribution has promoted the development of various life cycle assessment (LSA) and input-output frameworks^{17,18} aimed at estimating the total amount of embodied carbon per commodity or service^{18–20}, and, more recently, to encompass environmental pressures facilitated by globalised trade such as water, energy, land use change, and primary productivity [^{21–25}]. While these applications typically use relatively simple, fungible, and widely accepted metrics in the impact and footprint estimates (for example CO₂, H₂O, NO₃), consensus on a metric (or surrogate) that can adequately capture impacts on “biodiversity”, and subsequently, the estimation of embodied impacts on biodiversity, is yet to be achieved, with footprints

expressed in terms of displaced bird ranges²⁶, pressure on biodiversity exerted by CO₂ emissions and beef²⁷, or the extinction risk threat intensity^{28,29}.

In this paper we extend and adapt the footprint calculation framework proposed by Lenzen et al.²⁸, linking a global economic framework³⁰ with data on species range and extinction risk provided by the International Union of Conservation for Nature (IUCN), to estimate the biodiversity impacts associated with commodity production and service provision, and consequently the biodiversity footprints at the stages of commodity trade, and consumption, for 15909 commodity and service sectors operating in 187 major global economic zones, across all international and domestic supply chains. We assess the international and domestic supply chain footprints at the scopes pertaining to individual supply chain inputs, over all domestic and international supply chains per nation, and, in an important development, over all of the supply chain inputs required to produce and distribute each commodity and provision of service. We use the species range data to determine the impacts, and consequently the footprints, in terms of impacts on the range size rarity³¹ (RSR), a species range-based metric that accounts for species endemism. In doing so, we identify and address several critical biases relating to the treatment of species range and impact intensity that were present in previous studies^{28,29}, and can result in a fundamentally skewed footprint analysis that (among other biases) can vastly overestimate the impacts on species with multi-national ranges while relatively underestimating the impacts on endemic species. We greatly extend the taxonomic scope of previous biodiversity-based footprint analyses^{21,26,28,29}, assessing the trade-driven impacts on species in marine ecosystems (5059 species), freshwater ecosystems (6101 species), and terrestrial ecosystems (27752 species), where the latter category is partitioned into impacts on terrestrial animals (17234 species), and, for the first time, terrestrial plants (10518 species). The inclusion of plants in our broad-scale assessment is especially important as plants act as a proxy for larger scale impacts on ecosystem functioning³². Using this framework, we specify the nations that are most affected by trade-based biodiversity loss, trading their natural resources for economic gains, identifying the supply chain footprints of the countries where these commodities and services are ultimately consumed, as well as the footprint of the sectors and countries that are fundamentally integrated in the trade network as intermediate traders and distributors.

3. Results

Footprint characteristics

The footprints presented here were calculated at three fundamental scopes for all international and domestic supply chains: (i) the footprint per supply chain input, as per Lenzen et al.²⁸, e.g. a portion of the impact of forestry in China is attributed to the construction sectors in China, (ii) the footprint per supply chain, aggregated over all supply chain inputs - we consider this as the true measure of the footprint per commodity or service, e.g. a portion of the impacts associated with all supply chains leading to construction in China, inclusive of forestry and mining commodities from China, forestry commodities from Indonesia, etc., is attributed to the footprint for construction in China, (iii) the consumption-based

footprint per nation, aggregated over all supply chains inputs, considered for individual sectors and all sectors per economic zone.

i. Supply chain input footprints per commodity and service sector

The greatest footprints per supply chain input are shown in Fig. 1, all of which were attributed to low income and emerging markets. The majority of the large footprints per supply chain input were associated with the sale of crops, livestock, and fish to domestic trade sectors, the sale of these commodities to the food manufacture sectors, as well as the sale of forestry commodities to forestry trade sectors and construction sectors. Terrestrial industries had the greatest impacts on terrestrial plants and animals, fisheries had the greatest impacts on marine species, and freshwater species were affected by both terrestrial industry pressure (largely agricultural) and fisheries. A comprehensive list of the footprints per supply chain input is provided in Table S1a, with a full taxonomic description of the species impacted by each of the 10 greatest supply chain inputs provided in Tables S1b:S1k.

The greatest footprint per supply chain input was attributed to the agriculture trade sectors in Madagascar (1731.9 wRSR, impacting 2112 species, 1662 endemic) and is shown in Fig. 2. The sale of agricultural commodities from Madagascar to the food manufacture sectors in France (248.7 wRSR, 100% imported) and Germany (220.4 wRSR, 100% imported), ranked as the two highest footprints per supply chain input associated with international trade. The footprint for food manufacture in France can be interpreted as the attribution of the entire pressure on at least 248 species in Madagascar, assuming endemic species classified as LC, or at least 27 species in Madagascar, assuming endemic species classified as CR. The agriculture commodity trade sectors in Tanzania, Mexico, and Peru, were all ranked among the 5 greatest single input footprints (Fig. 1). Fisheries were associated with large scale impacts on both marine and freshwater species, especially in Indonesia (349.8 wRSR, 100% domestic, impacting 1966 species, 191 endemic), India (288.1 wRSR, 100% domestic, impacting 1663 species, 285 endemic), and China (268.2 wRSR, 100% domestic, impacting 1577 species, 317 endemic).

The sale of agricultural commodities to the food manufacture sectors resulted in large footprints per supply chain input attributed to the sale of livestock to the food manufacture sectors in Mexico, Ecuador, and Colombia, the sale of livestock and crops to the food manufacture sectors in Tanzania and Cameroon, and the sale of crops to the food manufacture sectors in Mexico (Fig. 1). Other large agriculture-based footprints were attributed to the sale of crops to the grain milling sectors in Indonesia (338.6 wRSR, 100% domestic, impacting 2252 species, 628 endemic), the sale of bananas, coffee and cocoa cultivated in Ecuador (263.4 wRSR, 100% domestic, impacting 1333 species, 715 endemic), and the sale of sugar and brown sugar cultivated in Colombia (256.6 wRSR, 100% domestic, impacting 1352 species, 466 endemic).

The forestry trade sectors were attributed large footprints in Malaysia (Fig. 1), Mexico (351.8 wRSR, 100% domestic, impacting 1125 species, 589 endemic), and India (271.3 wRSR, 100% domestic, impacting 1312 species, 543 endemic). Construction, closely tied to forestry, was attributed large footprints for civil

construction in Colombia (Fig. 1), and in China, for the supply of forestry commodities to the construction sectors in China (Fig. 1), and also due to the direct impacts from the construction industry itself (Fig. 1). The remaining outsized footprints per supply chain input were attributed and to transport, especially to truck transport in the United States (351.9 wRSR, 100% domestic, impacting 2098 species, 1201 endemic), and the transport sectors in Ecuador (309.5 wRSR, 100% domestic, impacting 917 species, 421 endemic).

ii. Total supply chain footprints per commodity and service sector

Figure 3 shows the greatest commodity and service sector footprints, aggregated over all supply chain inputs, the majority of which were attributed to low-income and emerging markets. The aggregation over all supply chain inputs resulted in a major increase in the size of the footprints for the construction sectors in emerging market economies, the food manufacture sectors in high income countries, and the hospitality sectors in all countries. The agriculture and fishery sectors with exceptionally large individual supply chain input footprints retained a relatively high ranking. A comprehensive list of the total supply chain footprints is provided in Table S2a, with a decomposition of each footprint provided in Table S2b.

Construction was identified as a major driver of biodiversity loss, especially in emerging markets, with construction in China (Fig. 4) attributed the greatest footprint of any sector, globally. Other large construction-based footprints were attributed to construction in Colombia (Fig. 3), India (Fig. 3), Ecuador (411 wRSR, 100% domestic, impacting 1533 species, 814 endemic), Mexico (409.8 wRSR, 98% domestic, impacting 6139 species, 4515 endemic), and Brazil (354.82 wRSR, 98% domestic, impacting 3704 species, 2391 endemic). In high income countries our framework assesses many sub categories of the construction sectors (see Table S2c for details on the 10 greatest footprints attributed to construction sectors, inclusive of each of the aforementioned construction sectors, and, in addition, the United States, Japan, and Spain), with especially large footprints attributed to residential construction in the United States (293.7 wRSR, 69% domestic, impacting 15771 species, 11110 endemic), residential construction in Spain (206.1 wRSR, 90% domestic, impacting 6105 species, 4359 endemic), and wooden residential construction in Japan (200.7 wRSR, 13% domestic, impacting 10893 species, 7153 endemic). The majority of the footprint for wooden residential construction in Japan was attributed to purchases from the forestry sectors in Papua New Guinea (64.3 wRSR, impacting 785 species, 258 endemic), Malaysia (23.2 wRSR, impacting 900 species, 201 endemic), Indonesia (22.6 wRSR, impacting 1395 species, 612 endemic), and the Philippines (17.4 wRSR, impacting 545 species, 443 endemic).

The food manufacture sectors operating in high-income economies drove global species loss through many international supply chain inputs, with especially large footprints attributed to the food manufacture sectors in Germany and France (Fig. 3). The footprint for the food manufacture sectors in Germany was almost entirely comprised of impacts attributed to international supply chains (95% due to imports), driving large impacts on species in low-income countries through the purchase of agriculture commodities from Madagascar (220.1 wRSR), Tanzania (32.1 wRSR), and Papua New Guinea (29.4

wRSR, impacting 694 species, 258 endemic), where food consumption in Germany was potentially attributed the entire global pressure on at least one species in 50 countries, assuming endemic species classified as LC, and 17 countries, for endemic species classified as CR. In low-income and emerging markets, food manufacture was reliant on a smaller number of domestic supply chain inputs compared the food manufacture sectors in high-income countries, largely from impacts attributed to the domestic purchase of livestock and crops, with the greatest footprint attributed to the food manufacture sectors in Mexico (Fig. 3), largely from domestic livestock production (572.5 wRSR, impacting 1430 species, 713 endemic) and domestic crops (408.4 wRSR, impacting 1715 species, 881 endemic), and also in Ecuador (Fig. 3), largely from domestic livestock production (564.5 wRSR, impacting 1627 species, 1009 endemic), and grain cultivation (82.9 wRSR, impacting 1730 species, 1138 endemic), and Tanzania (Fig. 3).

The remaining large footprints were attributed to the service sectors, in particular the state and local government service in the United States (Fig. 3), and the hospitality sectors in both emerging markets and high-income countries, driving impacts on domestic species from purchases of crops and especially for livestock, and impacts attributed to the international supply of agriculture commodities and fish, especially for high-income economies. The footprint for the state and government services in the United States, was comprised of impacts attributed to many supply chain inputs, with over 78 supply chain inputs attributed a footprint greater than 1 wRSR, largely from impacts attributed to governmental services, inclusive of municipality impacts from parks etc. (104.6 wRSR, impacting 872 species, 396 endemic), truck transportation (40.3 wRSR impacting 1707 species, 1137 endemic), and the supply of food-stuffs to governmental sectors. The latter sector was comprised of impacts associated with the supply of agricultural commodities from Madagascar (36.5 wRSR), and domestic impacts associated with domestic milk and butter manufacture, meat production (44.92 wRSR collectively, impacting 1448 species, 981 endemic), and waste management (16.0 wRSR, impacting 229 species, 129 endemic).

The greatest footprints attributed to the hospitality sectors occurred in the United States (513.7 wRSR, 48% domestic, impacting 23201 species, 15255 endemic), Brazil (380.6 wRSR, 98% domestic, impacting 3056 species, 1622 endemic), and Japan (335.9 wRSR, 82% imported, impacting 20380 species, 13266 endemic). The footprint for the hospitality sectors in the United States associated with domestic trade was primarily due to direct impacts attributed to the hospitality industry, contributing 35% of the footprint (91.9 wRSR, impacting 1065 species, 495 endemic), truck transport (19.0 wRSR), and domestic impacts attributed to domestic livestock and dairy industries (34.0 wRSR, 1448 species, 981 endemic). International supply chains contributed 54% of the total footprint, with 46 international supply chains attributed a footprint of greater than 1 wRSR. The greatest impacts associated with international supply chains attributed to agriculture in Madagascar (42.5 wRSR) and Jamaica (19.4 wRSR, impacting 160 species, 137 endemic). The fish-based portion of the footprint for the hospitality sectors in the United States (18.5% collectively) was almost entirely associated with international trade, with impacts driven by fisheries in Panama (10.8 wRSR, impacting 430 species, 30 endemic), Tanzania (9.7 wRSR, impacting 674 species, 109 endemic), and Fiji (7.7 wRSR, impacting 224 species, 95 endemic), while only 1% of the

footprint for the hospitality sectors in the United States was associated with impacts on domestic species attributed to domestic fisheries.

iii. Consumption-stage footprints

The supply chain footprints evaluated at the stage of consumption were specified according to each economic zone, for 187 countries and territories, as distinct from the impacts and footprints at the stages of production and trade, which were specified according to the commodities or industries defined in the Eora database³⁰. The commodities or services that were consumed in the same country as the stage of final trade (98 of the 100 greatest consumption-stage footprints meet this criterion), resulted in the attribution of the entire footprint evaluated at the stage of final trade to the footprint evaluated at the stage of consumption. In the case where an exported commodity was consumed in multiple countries (e.g. the consumption in France, Germany, and the United States of agricultural commodities exported from Madagascar), the footprint size was partitioned according to the commodity purchase, retaining an otherwise identical set of species impact characteristics (identical impact taxonomies, relative threats per taxonomy etc.). Hence, due to the similarity in the characteristics of the high-ranked footprints evaluated at the stages of final trade and consumption, the supply chain footprints evaluated at the stage of consumption are provided in Table S3a. For the remainder of this paper, the impacts associated with primary production, and the footprints evaluated at the stages of final trade and the stage of consumption are presented per economic zone.

The greatest total footprints per nation, aggregated over all domestic and international supply chains domestic are shown in Fig. 5, attributed to the United States, with large-impacts associated with both domestic and international supply chains, followed by China, Brazil, Mexico, India, Indonesia, Ecuador, and Colombia, all of which are emerging markets that drive large-scale impacts on domestic species by domestic trade (Fig. 5), and Japan, largely due to its' exceptionally large international supply chain footprint (especially when considered on a per capita basis). A comprehensive list of the footprints due to domestic and international trade is provided in Table S3b.

The majority of the total global species footprint was associated with domestic trade (73.2%), primarily attributed to emerging markets (comprising 43.0% of the global footprint attributed to domestic trade), with large domestic footprints also attributed to the United States, Spain, and Australia. The greatest marine-based footprints associated with domestic trade were attributed to Australia, Indonesia, the United States, China, and Mexico. The greatest freshwater-based and terrestrial-based footprints (both plant and animal) associated with domestic trade were attributed to emerging markets, especially Mexico, Colombia, Brazil, Indonesia, India, Ecuador, China, Peru, and Ecuador, to low-income countries including the DRC and Tanzania, and also to the United States, Spain, and Australia, each of which are distinguished as high-income countries with a particularly high aggregated wRSR.

The footprints attributed to international supply chains comprised 26.8% of the total global footprint. With the exceptions of Australia, the United States and Spain, the losses attributed to international trade were overwhelmingly associated with low-income and emerging markets, with especially great losses in

Madagascar (5291.8 wRSR, comprising 18.3% of the total impacts attributed to international trade via exports), Tanzania (2322.5 wRSR, 8.0%), and Cameroon (1313.8 wRSR, 4.1%). International trade also drove large losses in Indonesia (970.39 wRSR, 4.1%), Mexico (901.0 wRSR, 3.0%), Australia (851.5 wRSR, 2.9%), and Ecuador (748.1 wRSR, 2.6%). The largest impacts attributed to international trade on marine species occurred in a mix of high-income countries (including Australia, the United States, and New Zealand), emerging markets (including Indonesia, Argentina and Mexico), and low-income countries (including Papua New Guinea and Panama). The largest impacts on freshwater species and terrestrial species (both plant and animal) attributed to international trade occurred in lower income countries including Madagascar, Tanzania, Cameroon, Laos, and the DRC, and also to emerging markets including Indonesia, Mexico, and Ecuador. The greatest international supply chain footprints were attributed to, in decreasing order, the United States (5338.3 wRSR, with 18.4% of the globally imported footprint), China (3102.4 wRSR, 10.7%), Japan (2763.2 wRSR, 9.5%), France (1985.0 wRSR, 6.9%), Germany (1977.6 wRSR, 6.8%), the United Kingdom (963.5 wRSR, 3.3%), and Italy (916.5 wRSR, 3.2%).

Figure 6 shows a comparison of the domestic and imported footprints with the GDP per nation, partitioned into impacts on marine, freshwater, and terrestrial species. The largest deviations from linearity for the footprints associated with domestic supply chains occurred for countries with exceptionally large domestic footprints compared to their GDP, and were almost entirely attributed to emerging markets, in particular Mexico, Brazil, Indonesia, India, and Ecuador. With the notable exceptions of the United States and China, large-scale domestic impacts were associated with lower income economies and vice versa, i.e. the relationship between the GDP per nation and the domestic footprint can be characterised by an inverse relationship. The largest deviations from linearity for the footprint associated with international supply chains occurred for high-income countries with exceptionally high imported footprints compared to their GDP, with outsized footprints attributed to Japan, Germany, France and Italy, all members of the G7, and in addition Hong Kong and Spain. Although the United States and China had the largest absolute footprints attributed to international supply chains, the footprints were low relative to their GDP.

The schematic in Fig. 7 shows the impacts and footprints per economic zone associated with international supply chains, evaluated at the stages of primary production, final trade and consumption, identifying the origin of each set of impacts and the location that high-impacting commodities are ultimately consumed in. The expanding size of the nodes in Fig. 7 for high income countries (especially the G7), through each progressive stage in the trade-network, and the diminishing node size for lower income countries, indicates a fundamental imbalance in the socioeconomic status of the countries that are experiencing pressure on species from international trade, the majority of which are low-income or emerging markets, and the socioeconomic status of the countries that are driving these losses through the trade and consumption of commodities associated with large scale impacts, all of which are high-income and/or high GDP countries, with especially large losses due to international supply chains attributed the G7 and China.

4. Discussion

Building on the conceptual framework suggested by Lenzen et al.²⁸, we incorporated a highly detailed economic framework that encompasses the trade-driven impacts from 15909 industries on 38671 species in marine, freshwater, and terrestrial ecosystems in 187 economic zones, extending well beyond the taxonomic scope of previous studies on trade-based biodiversity impacts^{21,26,28,29}.

Our framework characterises global species loss as primarily driven by domestic trade in emerging market economies including China, Mexico, Brazil, India, Indonesia, Ecuador, and Colombia (all of which are among the ten greatest impacting economies globally). These losses are exacerbated by international trade between these countries and high-income nations, especially the G7, that are driving species loss and extinction in these, and lower-income nations, with especially high losses driven by international trade occurring in Madagascar, Indonesia, Mexico, and Tanzania. Overall, we estimate that 26.8% of all biodiversity impacts are due to international trade, comparing to recent estimates that link trade-driven impacts to impacts on bird ranges (23% - Kitzen et al.²⁶ ; 30% Lenzen et al.²⁸). We attribute the distinction in our findings, compared to those in latter study, i.e. our finding that domestic trade in countries with highly biodiverse regions that are undergoing rapid development is the primary driver of global species loss, to our treatment of the species range and impact intensity, where the impacts on all species, especially those that are endemic to a single nation, are weighted equivalently.

We the construction sectors in emerging market countries as a major driver of global biodiversity loss, especially for the construction sectors in China, with the greatest total supply chain footprint (greater than the entire global footprint of Germany, the United Kingdom, and Italy, and all but the top 12 greatest impacting economies). Large-scale species pressure was also attributed to the construction sectors in Colombia, India, Indonesia, Ecuador, Mexico, and Brazil. We also attributed large footprints to construction sectors in the United States, Spain, and Japan. It appears certain that unless construction is prioritized for policy-based conservation intervention, the activities and purchases of the construction sectors in high income countries, and the rapid urban and exurban expansion and development in emerging markets, and the impacts embodied in the materials employed by the construction sectors in high-income countries, will continue to drive biodiversity loss globally³³.

Our estimate of the scale of species loss driven by domestic trade (73.2% of the total global footprint), highlights an urgent need for a globally accepted set of binding policy or trade-based agreements that address losses associated with domestic supply chains, especially in biodiverse regions, the majority of which are in low-income and emerging market economies. While our results indicate an urgent requirement to address unsustainable production and consumption, competing goals that aim to increase the economic wellbeing of populations in emerging economies are likely to provide challenges to these efforts³⁴. Rather than suppressing the economic development of lower-income nations, previous work has suggested that unsustainable development should be addressed through the global establishment of sustainability agreements, especially in countries undergoing rapid expansion, in conjunction with international co-operation and agreement among industry leaders and governments,

perhaps in the return for either higher commodity prices, additional foreign aid, or the alleviation of low-income debt^{28,35,36}.

We highlighted the nations with an especially large transfer of environmental pressure via international trade, attributing disproportionately large impacts driven by international supply chains to most European nations including the Netherlands (100% imported), Belgium (100% imported), France (76.8% imported), and Germany (94.5% imported), and as well as each of the Scandinavian countries, in particular Denmark (99% imported), Finland (87% imported), Norway (87% imported), and Sweden (82.8% imported), all of which are widely celebrated for strong environmental protection. Although the United States and China were attributed the two greatest footprints of any nation, their footprints were not disproportionately large relative to their GDP. The remaining members of the G7 (i.e. excluding the United States) were characterised by disproportionately high international trade-based impacts relative to their GDP. While many high-income countries (especially those in Europe) have, or are adopting, strong conservation-based policies that govern the activity of domestic industry³⁷, the environmental protection provided by these policies does not currently encompass the impacts associated with internationally acquired resources³⁸. Rather than protecting global biodiversity, as evidenced by the large international footprints attributed to the aforementioned countries, strong domestic environmental policies can result in the exposure of biodiverse regions to over-exploitation via the transfer of environmental pressure from local, highly governed industry, to poorly governed industries, the majority of which are in low-income or emerging market countries, and can operate in, or near biodiverse regions³⁹. We also specified the sectors that, despite local industry regulation, are driving global species loss, with extraordinarily high impacts in Madagascar and Tanzania driven by the consumption of food products in Germany and France, fish depletion in Mexico, Tanzania, Panama, and Fiji driven by the supply of fish to consumers in the United States, and species loss in Papua New Guinea, Malaysia, Indonesia and the Philippines (all of which are established biodiversity hotspots) driven by Japanese demand for hardwoods.

Our focus on the externalisation of consumption-based pressure from high-income countries to biodiverse regions in low-income and emerging market countries is justified by the scale of these impacts (26.8%, for all global trade), and also under the premise that leverage from high-income countries, in the form of trade and policy regulation, can profoundly influence the activities of industries in poorly governed economic zones. Our framework is directly aligned with the implementation of Sustainable Development Goals including sustainable agriculture (SDG-2), water use (SDG-6), climate action (SDG-13), use of aquatic resources (SDG-14), and the protection of terrestrial ecosystems (SDG-15), as well as the Convention on Biodiversity current and future targets, as it provides a means to determine the compensation required by each industry or nation to protect or reverse species decline, specified at the level pertaining to individual species for many species in marine, freshwater, and terrestrial environments, across all domestic and international supply chains, globally. Despite the advances in the scope of our study, we acknowledge that the use of economic data as a proxy for the estimated impact intensity per species per industry can introduce uncertainty in the direct impact estimate and subsequently in the supply chain footprint calculations. Furthermore, it does not directly account for the terrestrial and

aquatic impacts associated with land use, deforestation rates, pollution, water consumption, or the spatial variation in these quantities. In future work, we suggest using additional human activity datasets that directly account for these impacts in conjunction with the treatment of species range and impact intensity suggested herein.

We expect that our quantification of the trade-based drivers of global species loss will be of significant interest and use to conservation bodies as a means to prioritise conservation action and intervention⁴⁰. When used in conjunction with compensatory policies, governance, and conservation interventions that aim to address industry-driven biodiversity loss, we expect our framework can inform policy-driven behaviour change at local, regional, national and global scales.

2. Methods

We provide an overview of the conceptual framework used herein, detailing the methodological distinctions, improvements, and extensions used in this paper, compared to previous work²⁸.

Conceptual framework

The impacts and footprints associated with the manufacture and distribution of commodities and services were evaluated across three fundamental stages: (i) the stage of primary production, where the resource procurement, commodity manufacture, or provided service results in a direct impact on one or more species, (ii) the stage of final production or trade, where the supply chains result in the finalised commodity or service (iii) the stage of consumption, the supply chain terminus where commodities or services are consumed. While the stages of production and trade are defined according to the specification of the commodities or industries defined in the input-output economic database, the stage of consumption is defined at the purchasing economy scale.

The footprints are characterised by (i) the footprint size, measured as the estimated impact on the weighted species RSR (wRSR)⁴¹, obtained by multiplying the species RSR according to the extinction status of each species⁴² by a factor between 1 and 8, for species classified as least concern (LC) and critically endangered (CR)⁴³ respectively, (ii) the proportion of the footprint attributed domestic/international supply chains, (iii) the number of marine, freshwater, terrestrial animal, terrestrial plant, and endemic species impacted.

Supply chains are defined herein as “domestic” when commodities or services are produced, traded and consumed in the same nation, as “imported” when commodity production or trade occurs outside the nation where the commodity or service is consumed, and as “exported” when a commodity or service is traded or consumed outside the nation the resource originated from. While previous work has suggested a framework where the footprints associated with exports are subtracted from the aggregate of the domestic and imported footprints²⁸, we argue that the reduction in the calculated footprint favours countries that export commodities that are linked to large-scale local species loss rather than penalising

them. Hence, we calculate the total footprint per nation as the aggregate of the footprint associated with domestic trade and the footprint associated with imported commodities and services.

Economic data and theory fundamentals

The biodiversity footprints were determined using Leontiefs' input-output calculus¹⁷ with trade data on 187 economic regions obtained from the Eora global MRIO database³⁰. The Eora MRIO database encompasses 15909 industry sectors globally, incorporating highly detailed economic data for highly industrialised countries (as is the case for most high-income countries including the United States, the United Kingdom, Japan, and China), and lower resolution economic data otherwise.

When used in conjunction with environmental data, provided here via the IUCN Red List dataset as species extinction risk, species range, and threat cause data, Leontiefs' input-output calculus enables the determination of all supply chains and all corresponding supply chain footprints. A detailed description of the relationship between the Leontief inverse and the biodiversity footprint estimation is provided elsewhere²⁸.

Taxonomic data characteristics

The taxonomic data were obtained from the IUCN Red List dataset. The Red List is widely regarded as the most authoritative and comprehensive list of globally threatened species^{44,45} assessments of the extinction risk of each species, assessments of the likely causes of extinction pressure, and, in a large number of cases, estimates of the species range. These assessments are determined according to a set of criteria including species range and population statistics and dynamics, where the quantitative thresholds underpinning the extinction risk category are assessed against a set of common standards that provide broad consistency between criteria and to allow comparisons across taxonomic groups⁴³.

The extinction risk is classified according to the following categories: least concern (LC), lower risk (LR), near threatened (NT), endangered (EN), critically endangered (CR), and vulnerable (VU), extinct (EX), extinct in the wild (EW) and data deficient (DD), where the latter category covers the case where the species is considered at risk but there is insufficient data available. Our dataset encompassed species in all extinction risk categories aside from EX and EW. Although previous studies^{28,29} were limited to species categorised as EN, VU, and CR, (providing 5985, 7026, and 3953 species in our dataset, respectively), we argue that the additional data provided by the inclusion of species categorised as LC, LR, NT and DD, providing an additional 12862, 310, 4031, 4778, species, respectively, is justified as common species are important in ecosystem functioning⁴⁶, are facing dramatic declines of abundance⁴⁷, and may be categorised as under more serious extinction risk in the near future. It is also estimated that 60% of species categorised as DD would otherwise be categorised as EN, CR, or VU⁴⁸.

Each extinction risk assessment incorporates the attribution of one or more of 137 distinct threat types, both human induced and natural, that are considered to drive the extinction pressure on each species. These threats are defined under the broad categories: residential and commercial development,

agriculture and aquaculture, energy production and mining, transportation and service corridors, biological resource use, human intrusions and disturbance, natural system modifications, pollution, climate change and severe weather, and invasive and other problematic, genes and diseases, and geological events. Our analysis included all human-based threats with the exception of climate change and severe weather as, given the scope and importance of the impacts of climate change on biodiversity, we will treat the impacts on biodiversity attributed to embodied carbon in further work. We excluded geological events as this category is not linked to human-based pressure. The integration of the species dataset and Eora database was established through a mapping between the 137 threat types and the Eora-specified industries, associating each threat on each species with a subset of the 15909 global industries using a similar mapping to that described elsewhere²⁸. Under the assumption that the economic output per industry can be used as a proxy for the impact intensity, the impact intensity per industry per species was partitioned by the economic outputs of the set of industries that were associated with each threat on each species. A full description of this technique is provided elsewhere²⁸.

The direct impacts and embodied footprints were partitioned into impacts on marine systems (5059 species), freshwater systems (6101 species) and terrestrial systems (27752 species), with the latter category subsequently partitioned into impacts on terrestrial animals (17234 species) and terrestrial plants (10518 species), as well as the total footprint aggregated across these systems.

Methodological improvements on previous work

While previous analyses specified the footprints associated with each supply chain input^{28,29}, we assessed the entire footprint per supply chain as the aggregated footprint over all of the inputs and outputs required to produce each commodity or service. Our framework addresses the case where many small embodied impacts per supply chain input result in a significant aggregated footprint that is not captured by earlier work where the footprints per supply chain input were treated independently. The calculation of the footprint as the aggregate over all supply chain inputs also addresses the misattribution of the threat intensity of a particular input does not scale linearly with its' economic output (for example, the proportion of the economic output of lobster fisheries in Australia compared with their impact is relatively high when compared with the proportion of other fishery sectors).

Our framework addresses fundamental biases relating to species range and impact intensity that were present in previous work^{28,29}, and arise from the integration of the Eora economic database, a quantitative, economic dataset that is assessed at the scale pertaining to economic zones, with the IUCN Red List database, a qualitative, species extinction risk database that is assessed at the global scale, where the species ranges are provided both as non-spatial, nation-wide presence/absence data, and using species range estimates for a growing number of species. In earlier work^{28,29}, qualitative extinction risk assessment data was quantified under the assumption that each species threat is fungible, equivalent, and able to be subject to standard mathematical operations such as addition, subtraction, multiplication, and division. Without correction, this assumption, coupled with a duplication of the threat data for species that are present in more than one country introduced the following fundamental biases

in the footprint estimation: (i) the total impact on species present in more than one country is overestimated by a factor equal to the number of countries each species is extant in, relative to the total impact on species endemic to one country (ii) the total impact intensity on a particular species is determined by the number of threats attributed to that species.

The former bias (i) can vastly overestimate the impact estimate and consequently the supply chain footprint associated with species that are present in many countries (for example the majority of shore bird, marine, and common species), and also vastly overestimate the supply chain footprints for industries and countries that engage in international trade with many countries (i.e. the impacts on widespread species are falsely multiply-represented). Conversely, the supply chain footprints of industries and countries that are associated with impacts on endemic species are effectively (and falsely) suppressed. We addressed the former bias using species range data provided by the IUCN to obtain the range size rarity (RSR)⁴¹ per species. The RSR is a widely used metric that accounts for species endemism and was used as the surrogate metric in the direct impact estimation, and, consequently in the supply chain footprint analysis. Where the species range estimates were unavailable we assumed that the species range scaled linearly with the country area for the countries that each species was listed as extant in.

The latter bias overestimates the total direct impact on species with high numbers of threats (i.e. a subset of the 137 threat categories) compared to species listed with fewer threats. We illustrate this bias in Table T1, which shows all species noted on the IUCN Red List that belong to the family *Hyriidae*, inclusive of the extinct risk category, and the number of listed threats per species. In previous work (^{28,29}), the total impact intensity on *W. carteri* would be accorded 65 times the impact intensity on *C. schombergiana*, where only a single threat has been identified. A similar comparison yields *C. novaehollandiae* as having a total threat intensity at least 6 times greater than other members of the family *Hyriidae* with the same extinction risk status. We argue that the threat intensity is determined by a number of factors that are effectively summarised by the extinction risk categorisation and is not determined by the number of threats attributed to each species. We addressed the bias relating to inconsistency in the number of associated threats, by normalising the impacts on the species RSR by the inverse of the total number of threats exerted on that species, then weighting the threat intensity per species using the scheme suggested by Pouzols et. al⁴², where species classified as LC, NT, VU, EN, CR, and DD were multiplied by a factor of 1, 2, 4, 6, 8, and 2, respectively. While we acknowledge the intensity of the pressure on each species is also likely to be determined by the species population dynamics (e.g. rapidity in species decline), assessments of the population dynamics and the relative threat intensity have thus far only been performed for a small subset of the Red List species assessments. Although the proposed normalisation addresses the aforementioned threat intensity bias across the group of threats that act on each species, we acknowledge that the assumption of equal intensity per threat per species is likely to lead to the misattribution of the relative intensity per threat per species in some cases.

Table T1

The extinction risk and number of attributed threats for each member of the family *Hyriidae* that is included on the IUCN Red List.

Species	Extinction Risk Category	Number of Threats
<i>Alathyria jacksoni</i>	DD	4
<i>Castalia ambigua</i>	LC	5
<i>Castalia schombergiana</i>	DD	1
<i>Cucumerunio novaehollandiae</i>	LC	30
<i>Cucumerunio websteri</i>	DD	4
<i>Diplodon chilensis</i>	LC	4
<i>Diplodon granosus</i>	LC	4
<i>Echydella menziesii</i>	LC	4
<i>Echydella onekaka</i>	LC	4
<i>Hyridella glenelgensis</i>	CR	41
<i>Hyridella narracanensis</i>	NT	40
<i>Prisodon obliquus</i>	DD	4
<i>Prisodon syrmatophorus</i>	LC	3
<i>Velesunio moretonicus</i>	NT	22
<i>Westralunio carteri</i>	VU	65

The fungibility of the weighted RSR enables an intuitive interpretation of the aggregated footprint as the number of species that are entirely attributable to each supply chain, weighted by the IUCN status of each species. Under the assumption that the weighted RSR per species is fungible and can be aggregated, the total global impact, aggregated over all impacts on all species ranges (weighted by the IUCN extinction category of each species), and consequently the total global footprint, aggregated over all international and domestic supply chains for all 187 major economic zones, is equal to 118283.1 wRSR. The decrement between the full wRSR (132125 wRSR) and the total global impact attributed here is due to the exclusion of threats categorised as climate change and severe weather and geological events, and also to the exclusion of impacts that occur in international waters, where the latter exclusion is due to the uncertainty in the impact attribution per country in these zones.

Declarations

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Figures

Figure 1

The 20 greatest footprints per supply chain input, globally. The impacts and footprints associated with the manufacture and distribution of commodities and services were evaluated across the stages of primary production (left), where the resource procurement, commodity manufacture, or provided service results in a direct impact on one or more species (shown here as the number of impacted terrestrial plant, terrestrial animal, freshwater and marine species per supply chain), and the stage of final trade (right),

where the impacts that originate with primary production are attributed to the footprint evaluated at the stage of final trade of each commodity or service, resulting in the footprints per supply chain input shown above. The sizes of the impacts and footprints are characterised by the estimated impact on the weighted species RSR (wRSR), weighted by a factor between 1 and 8, for species classified as least concern (LC) and critically endangered (CR) respectively. This metric and can be loosely understood as the total number of species attributable to each footprint, weighted by the IUCN extinction status of each species (see Methods for details). A full taxonomic description of the species impacted per supply chain is provided in Supplementary Tables S1c:S1j

Figure 2

The impacts and supply chain footprints associated with the greatest single input footprint, globally, attributed to the domestic trade of agricultural commodities in Madagascar. The taxonomies impacted by agriculture in Madagascar, partitioned into impacts on terrestrial plant, terrestrial animal, freshwater, and

marine species are shown in (a). The aggregated impact for each taxonomic category is shown in (b). The spatial distribution of the aggregated impacts over all taxonomies is shown in (c), and the supply chain input footprints are shown in (d). The export of agricultural commodities from Madagascar also resulted in the two greatest single input footprints, attributed to international trade, for the purchase of these commodities by the food manufacture sectors in France (248.7 wRSR) and Germany (220.4 wRSR). The taxonomic impacts, scaled according to the purchase quantity, are common to all industry sectors that purchase agriculture commodities from Madagascar.

Figure 3

The 10 greatest total supply chain footprints per commodity or service trade sector, globally, aggregated over all supply chain inputs. A major increase in the size of the footprints was observed for the industry sectors with many supply chain inputs, notably the construction sectors in emerging markets, especially China, Colombia, and India, and the food manufacture sectors, especially those Mexico, Germany and France, and in other high-income countries. Here we show only the 5 greatest footprints per supply chain input per sector (for supply chain input footprints > 1 wRSR), a full decomposition of the footprints per supply chain input is provided in Table S2a. Sectors with an exceptionally large single input footprint, e.g. the agriculture trade sectors in Madagascar, retained a high rank.

Figure 4

Decomposition of the footprint for construction in China. The spatial distribution of the total global footprint for construction in China is shown in (a), expressed in terms of impacts on the wRSR. The 20 greatest contributing footprints per supply chain input for construction in China are shown in (b), decomposed into impacts on species in each category, and listing the top 3 species impacts per supply chain footprint. Approximately half of the footprint for construction in China was attributed to international supply chains. The footprint for construction in China was equivalent to the entire global pressure on at least one species in 90 countries, assuming endemic species classified as LC, or at least one species in 27 countries, assuming endemic species classified as CR. The largest impacts were attributed to the supply of timber from forestry sectors in China (100% domestic, 363.3 wRSR, impacting 477 terrestrial plant, 722 terrestrial animal, 297 freshwater and 197 marine species, 565 endemic), with the largest international supply chain footprint attributed to the supply of commodities from forestry in Indonesia (100% imported, 128.8 wRSR, impacting 289 terrestrial plant, 1067 terrestrial animal, 110 freshwater, and 339 marine species, 633 endemic). A full decomposition of the footprint for construction in China is provided in Table S2a, with a list of taxonomic impacts for each of the supply chain inputs shown above provided in supplementary tables S2b:S2w.

Figure 5

The greatest footprints per economic zone, aggregated over all species are shown in (a), inclusive of the total impact per taxonomic category, aggregated over domestic and international trade, and also inclusive of the footprint attributed to exports (white). Each panel also shows the footprint characteristics of the countries that are experiencing the greatest impacts from international trade (e.g. Madagascar), trading their natural resources for economic gains. For brevity countries that fall into both categories, namely the

United States (USA), Mexico (MES), Indonesia (IDN), and Ecuador (ECU), are only shown in the section of each plot showing the greatest footprint. The footprints per taxonomic category, partitioned into the footprints associated with domestic trade (darker) and international trade (lighter) are shown in (c)-(f), inclusive of the footprint attributed to exports (white).

Figure 6

The footprints relative to GDP. The domestic and international footprints relative to the GDP per economic zone, partitioned into impacts on marine, freshwater, terrestrial animal, and terrestrial plant species, and also shown as the aggregate over all taxonomic categories, are shown in (a)-(e), and (f)-(j), respectively. A linear model identified domestic trade as a particular issue for marine species in Indonesia, Australia, Mexico, the Philippines and Brazil (i.e. the domestic footprints were high relative to the GDP). A similar comparison identified freshwater, and terrestrial plant and animal species as particularly susceptible to domestic trade in emerging markets, in particular Mexico, Colombia, Brazil, India, Indonesia, and Ecuador. With the exceptions of the United States and China, large-scale domestic impacts were associated with lower income countries and vice versa (i.e. the relationship between the GDP per nation and the domestic footprint can be generally characterised by an inverse relationship). A set of linear models identified exceptionally high footprints attributed to imports compared to their GDP for Japan, Germany, France and Italy (all of which are members of the G7) and in addition Hong Kong and Spain. Although the United States and China had the largest absolute footprints, their domestic and international footprints were not especially large compared to their GDP.

Figure 7

The impacts and footprints per economic zone attributed to international trade. The economic zones are grouped according to economic or geographic classification, where priority is given in the order G7, G20, geographic. For example, Japan (JPN) is classified as a member of the G7 rather than the G20 or under the grouping for countries in Asia. The expanding nodes through each progressive stage in the trade-network for high income countries, especially the G7, which were attributed 4.7% of the impacts associated with production, 34.6% of the footprint associated with the trade sectors, and 49.7% of the

footprint associated with consumption of internationally traded goods, and the diminishing node size for lower income countries, indicates a fundamental imbalance in the socioeconomic status of the countries that are experiencing pressure on species from international trade, the majority of which are low-income or emerging markets, and the socioeconomic status of the countries that are driving these losses through imports and consumption, all of which are high-income and/or high GDP countries, especially those in the G7 and China.

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