Towards Robust, Authoritative Assessments of Environmental Impacts Embodied in Trade

Current State and Recommendations

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Summary

Global multiregional input-output databases (GMRIOs) became the standard tool for tracking environmental impacts through global supply chains. To date, several GMRIOs are available, but the numerical results differ. This paper considers how GMRIOs can be made more robust and authoritative. We show that GMRIOs need detail in environmentally relevant sectors. On the basis of a review of earlier work, we conclude that the highest uncertainty in footprint analyses is caused by the environmental data used in a GMRIO, followed by the size of country measured in gross domestic product (GDP) as fraction of the global total, the structure of the national table, and only at the end the structure of trade. We suggest the following to enhance robustness of results. In the short term, we recommend using the Single country National Accounts Consistent footprint approach, that uses official data for extensions and the national table for the country in question, combined with embodiments in imports calculated using a GMRIO. In a time period of 2 to 3 years, we propose work on harmonized environmental data for water, carbon, materials, and land, and use the aggregated Organization for Economic Cooperation and Development (OECD) Inter-Country Input-Output GMRIO as default in combination with detailing procedures developed in, for example, the EXIOBASE and Eora projects. In the long term, solutions should be coordinated by the international organizations such as the United Nations (UN) Statistical Division, OECD, and Eurostat. This could ensure that when input-output tables and trade data of individual countries are combined, that the global totals are consistent and that bilateral trade asymmetries are resolved.

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Introduction

In general, growth in trade has outpaced growth in gross domestic product (GDP) in the last few decades (e.g., Peters et al. 2011; see also Tukker et al. 2018). As a result of globalization processes, environmental impacts embodied in trade now constitute a significant share in the life cycle impacts of consumption of a country (Wood et al. 2018). The traditional territorial monitoring of emissions and resource extraction is therefore insufficient and must be complemented with information on natural resources and pollution embodied in trade in order to assess the environmental impacts of consumption in a country. Hence, national and supranational environmental and statistical agencies (like Eurostat and the European Environment Agency) are interested in calculating the *footprint* of final consumption in their country/region, including emissions and resource extraction abroad. However, calculating such footprints poses a significant challenge for national statistical institutes (NSIs), who have no mandate to gather data outside their country borders and hence have no means to calculate footprints embodied in trade with officially sourced data.[1]

As discussed in Tukker and colleagues (2018), global multiregional input-output (GMRIO) approaches are the most promising way forward to create a globally consistent environmental and economic accounting system that captures a broad set of environmental problems, through both the territorial as well as the consumption-based perspective (cf. UN 2013). The first paper in this special issue discerns three approaches for using GMRIOs for calculating environmental footprints (Tukker et al. 2018):

1. GMRIO at face value: Using an available environmental global multiregional input-output (GMRIO) database at face value, and calculating footprints of a country with such an GMRIO (e.g., Peters et al. 2011; Wiedmann et al. 2015; Tukker et al. 2016).
2. SNAC: Applying the Single-country National Accounts Consistent (SNAC) footprint (e.g., Edens et al. 2015). SNAC uses official input-output (I-O) and environment data for a specific country for which environmental footprints need to be calculated. These data are implemented in an existing GMRIO, creating a slightly adjusted GMRIO in which the specific country data are fixed. Edens and colleagues suggested that the SNAC approach is particularly useful for countries with out-of-the-ordinary trade patterns such as the Netherlands, having a high level of transit trade which makes the trade shares from databases such as COMTRADE poor proxies for the real trade shares.
3. Simplified SNAC (Tukker et al. 2018): This approach uses again the method under item 2, with official data for a specific country. However, it uses the full environmental GMRIO model just to calculate pollution and resources in imports rather than creating a new GMRIO adjusted to this specific country. A drawback is that the official export statistics from this specific country are not included in the GRMIO analysis. This can lead to inconsistencies if the export of components by that country is reimported, after traveling through product value chains.

Creating GMRIOs requires a laborious and complicated harmonization and consolidation process, even with the recent progress in automating their construction (Wood et al. 2015) or the use of a virtual laboratory environment (Lenzen et al. 2014). This construction process, by nature, alters the national I-O tables (IOTs). Single-country IOTs, published by NSIs, can have very different formats.[2] Trade data further differ from import and exports as given in IOTs. Trade data between countries have asymmetries. The results are imbalances in trade at global level, where the global sum of exports exceeds the global sum of imports. This is a phenomenon which *The Economist* jokingly referred to as "Exports to Mars" (Economist 2011). Further, with the exception of the highly aggregated Inter-Country Input Output (ICIO) table of the Organization for Economic Cooperation and Development (OECD), all existing GMRIOs were constructed by academic researchers (see table 1).

These factors imply that existing GMRIOs are not part of "official statistics"[3] and face questions about credibility. The future of footprint analysis will be greatly improved if a strategy can be elaborated in which (1) the calculation of country footprints can be simplified while at the same time being made more robust and (2) existing GMRIO databases can be harmonized and aligned and gain, at least partly, an official or semiofficial "statistical stamp." This paper develops such a strategy by answering the following research questions in the next three sections, via a review of recent literature, and the proposed strategy is presented in the concluding section of this paper:

Simplification of footprint calculations (section *Factors Affecting the Potential for Simplification of Footprint Calculations*)

a. There is already one GMRIO from a recognized international organization available, the ICIO of OECD. This GMRIO, however, is highly aggregated (34 sectors/products). A first question is hence: *How acceptable is a high level of aggregation in GMRIO for calculating environmental and other footprints?*
b. The simplified SNAC approach as suggested above neglects feedback embodied impacts. A second question is hence: *How important are feedback embodied impacts in calculating environmental footprints of a country?*

Enhancement or robustness and acceptance of GMRIO (section *Factors Affecting Robustness of Footprints Calculated with Global Multiregional Input-Output Databases*)

c. Several studies are available that have analyzed the factors that contributed most to differences in footprint calculations done between GMRIOs. A third question is hence: *What factors contribute most to uncertainty in GMRIOs and are a priority for harmonization efforts?*

Implications for footprint calculations and GMRIO development in the future (section *Reflection and Implications*)

Table 1 Characteristics of existing GMRIOs (Tukker and Dietzenbacher 2013)

No.	*Name*	*References and characteristics*
1	Eora	Lenzen et al. (2012a., 2012b, 2013); sector detail varying from 25 to 500; about 180 countries
2	EXIOBASE	Tukker et al. (2009, 2013); Wood et al. (2014 and 2015); Stadler et al. (2018); 200 products, 160 industries, 48 countries/regions
3	WIOD	Dietzenbacher et al. (2013); 35 sectors, 40 countries plus one Rest of World
4	GTAP-MRIO	Peters et al. (2011); 57 sectors, 140 countries/regions
5	ICIO (Inter-Country Input Output table)	OECD (2015); 34 sectors, 64 countries/regions. Previously, researchers used OECD I-O data to build an early GMRIO called GRAM (Bruckner et al. 2012; Wiebe et al. 2012a, 2012b); 48 sectors, 53 countries/region

Note: GMRIOs = global multiregional input-outputs; WIOD = World Input-Output Database; GTAP = Global Trade Analysis Project Database; MRIO = multiregional input-output; OECD = Organization for Economic Cooperation and Development; I-O = input-output.

d. On the basis of the answer of the former questions a strategy is proposed. The fourth question is hence: *What strategies can be followed to make footprint analyses and GMRIOs more robust and accepted in the short, medium, and long term?*

Factors Affecting the Potential for Simplification of Footprint Calculations

Required Level of Disaggregation

In order to assess the feasibility of using aggregated economic and environmental data for footprint calculations, de Koning and colleagues (2015) investigated the relevance of aggregation for the calculation results. While this issue has already been discussed by other authors, with particular focus on carbon emissions (Lenzen 2011; Steen-Olsen et al. 2014), these studies were the first to consider a broad range of footprints. The assessments were based on version 2 of EXIOBASE with as base year 2007 and analyzed the impact of aggregation of extensions, industry sectors, and countries on country footprints. The differences in the results are hence solely aggregation effects, thus excluding differences caused by the use of different, underlying data.

Figure 1 shows the impact of the reduction of the product and sector resolution from 200 to 60 products on the country material footprints (de Koning et al. 2015). In this aggregation, we moved from, for example, the detailed agricultural, mining, and energy production sectors in EXIOBASE v2 to single agricultural, mining, and energy production sectors that can be found in aggregated GMRIOs such as World Input-Output Database (WIOD) or ICIO. Changes in observed country footprints are typically in the 2% to 10% range, with occasional higher numbers for smaller countries such as the Netherlands and Belgium. Figure 2 shows differences in country footprints for carbon, water, land, and materials when the resolution in EXIOBASE is reduced from 200 to 60, 31, and 17 products, respectively (de Koning et al. in preparation). Here, we see that the differences rise substantially when product resolution is reduced to 31 and further to 17 product groups, and that the differences are consistently more accentuated for the land, water, and material footprint than for the carbon footprint. The reduced sensitivity of carbon to aggregation effects was also found by Stadler and Wood (2014) and is explained by the wider distribution of carbon emissions across sectors, while material extraction, water, and land use is concentrated in fewer sectors of the economy. Differences are low for value added embodied in final demand, regardless of the aggregation level. This is due to the fact that any economic sector will have a certain level of profits, wages, depreciation, etc., and differences in the share of value added in gross production between sectors are quite limited compared to large differences in the carbon, water, land, and material intensity per sector.

All the findings above relate to assessments of footprints at country level. At this level, uncertainties in footprints of individual final demand categories cancel one another out to some extent. Footprinting applications, with a focus on specific sectors, products, etc., obviously also benefit from a higher sector and product resolution (de Koning et al. 2015). However top-down models such as GMRIOs will probably always have trouble in reflecting the subtleties of individual sectors, products, and transactions. Hybrid life cycle assessment (LCA) approaches may be the optimal solution here, allowing an integration of sector- and product-level LCA results to be integrated into a background GMRIO (Lutter et al. 2016). An alternative is to provide per-element reliability estimates. The Eora database gives some initial attempts in this direction (e.g., Lenzen et al. 2013).

In conclusion, our analysis shows that when calculating water, material, or land footprints, a high level of disaggregation of particularly the agricultural, forestry, and mining sector and related processing sectors is essential. A typical 30- or 60-sector GMRIO aggregates these environmentally sensitive sectors to just one agricultural, forestry, and mining sector, and this leads to clear changes in country footprints. While uncertainty may be higher at the level of the individual sectors and products,

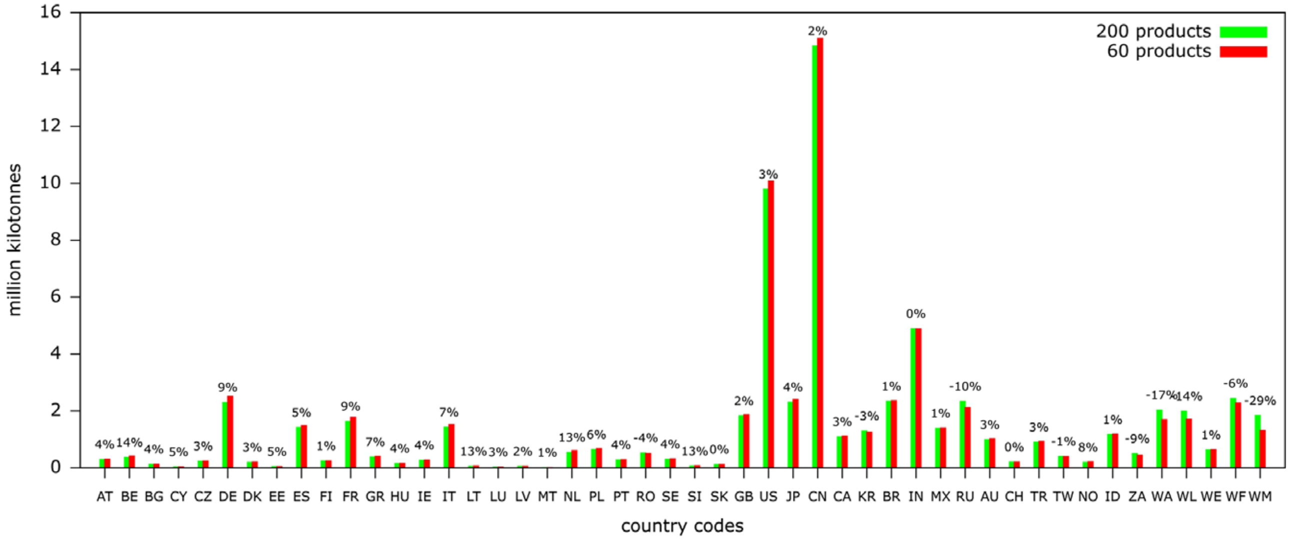

Figure 1 (de Koning et al. 2015): Product aggregation scenario: effect of reducing the product resolution from 200 to 60 products on the material footprint of countries. The percentage at the top indicates the change from the default scenario (green bar) to the product aggregation scenario (red bar). Data for 2007. Countries identified by the ISO Alpha 2 code (see www.nationsonline.org/oneworld/country_code_list.htm [accessed 15 September 2017]; see also Wood et al. [2015]).

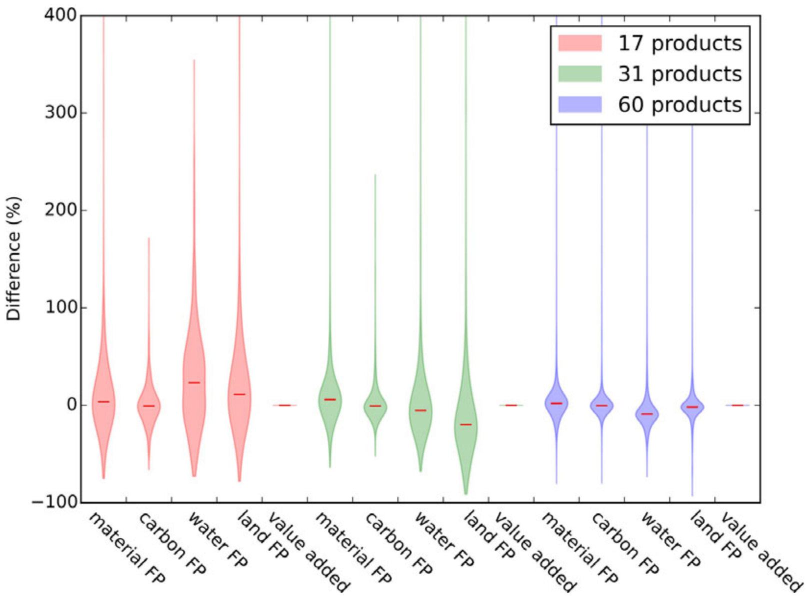

Figure 2 (de Koning et al. in preparation): Box and whisker plot of the differences between country footprints (FP) calculated with the default scenario (detail of 200 products) and the product aggregation scenarios. Data for 2007.

Lenzen (2011) showed that the country footprints based on higher resolution tables will be more reliable. If one wants to look even deeper, for example, at the level of the environmental footprint of specific product groups, detail certainly is essential. We conclude that the comprehensive assessment of environmental footprints of nations that include emissions, water, land, and resources requires a GMRIO with a high level of detail in the related environmentally relevant sectors: agriculture, forestry, mining, and related processing sectors. This rules out aggregated databases such as WIOD and the ICIO database for this kind of analysis. Global Trade Analysis Project Database (GTAP) has a disaggregated agricultural sector which helps land and water footprinting, but has too limited detail in the mining and energy sectors, which hampers material and energy footprinting. For carbon footprints and particularly value added, this sector resolution is less relevant.

Importance of Feedback Embodied Impacts

GMRIOs account for the bilateral trade relationships between countries. In principle, the exports of a country (particularly in the form of primary materials and intermediate products)

Table 2 Feedback embodied impacts (fraction of the embodied impacts in imports originally emitted in the country, i.e., exports feeding back into imports) as calculated with EXIOBASE v3, for carbon emissions in 2012 (Moran et al. 2018)

Country	*Feedback emissions*	*Country/region*	*Feedback emissions*
Austria	0.2%	Slovenia	<0.1%
Belgium	0.3%	Slovakia	0.2%
Bulgaria	0.4%	United Kingdom	0.5%
Cyprus	<0.1%	United States	4.2%
Czech Republic	0.6%	Japan	0.8%
Germany	1.7%	China	6.1%
Denmark	0.4%	Canada	1.1%
Estonia	0.6%	South Korea	0.6%
Spain	0.4%	Brazil	0.8%
Finland	0.1%	India	0.9%
France	0.5%	Mexico	0.8%
Greece	0.2%	Russia	3.0%
Croatia	0.1%	Australia	0.5%
Hungary	0.1%	Switzerland	0.1%
Ireland	0.1%	Turkey	0.2%
Italy	0.3%	Taiwan	0.4%
Lithuania	0.1%	Norway	0.4%
Luxembourg	<0.1%	Indonesia	0.7%
Latvia	0.1%	South Africa	0.8%
Malta	0.0%	RoW Asia and Pacific	2.5%
Netherlands	0.3%	RoW America	1.1%
Poland	0.4%	RoW Europe	0.9%
Portugal	0.1%	RoW Africa	1.1%
Romania	0.3%	RoW Middle East	3.5%
Sweden	0.2%		

Note: RoW = Rest of World.

may be used to make finished products in other countries in the value chain, which then return to the original country as part of a finished product, etc. So, it is possible that the embodied emissions and resource uses in the exports of country A, to some extent, return in the form of imports to this country A.

In another publication in this Special Issue, Moran and colleagues (2018) performed an assessment of such feedback embodied impacts of carbon emissions per country, using EXIOBASE v3 for 2011. The results are presented in table 2 below. The results are illuminating. For virtually all individual countries, the "feedback emissions" are 1.5% or less. The exceptions are Germany (1.7%), Russia (3%), China (6.1 %), and the United States (4.2%). So, only for a small number of large economies the feedback loops caused by their exports may lead to relevant errors in assessing the footprints of their imports. For the vast majority of the countries, it hence seems feasible to apply what we called the "Simplified SNAC" procedure in the *Introduction*: using SNAC information for the national economic structure and environmental pressures including import volumes, and calculate the environmental impacts of these imports with a suitable GMRIO. Note further that in this approach, even for large countries such as the United States and

China, the feedback emissions are not missing, but merely estimated on the emissions and export data as contained the GMRIO (instead of the SNAC information).

Factors Affecting Robustness of Footprints Calculated with Global Multiregional Input-Output Databases

Most of the GMRIO databases presented in the *Introduction* section have been constructed in the last 5 years. And it is only recently that in-depth comparisons have been performed between different GMRIO databases, with the goal to identify the main factors for uncertainty and differences in environmental footprints. Most of this work until now concentrated on uncertainty in carbon dioxide (CO_2) footprints at country level. GMRIO databases—and hence the footprints calculated using them—can differ for a number of reasons (Hoekstra et al. 2014). First, the allocation principles implicitly or explicitly used in the footprint calculation may differ. Second, the source data for stressors may differ. Third, the structure of the global IOT may differ, in part depending on the approaches that the scientists have taken to deal with missing or conflicting data and to ensure that the rows and columns balance. We discuss these topics in the following sections while reviewing the factors that dominate uncertainty and their implications in two final sections (sections *Reflection and Implications* and *Conclusions and Recommendations*).[4]

Differences in Allocation Principles

Peters and colleagues (2012) highlighted a number of factors relating to which allocation principle is used:

(a) Fundamental differences in allocation of emissions and resource uses. In a true GMRIO approach, exports from country A to B will embody emissions/resource uses from earlier in the value chain (i.e., the imports of country A). But, for instance, coefficient approaches (see Tukker et al. 2018) often used in land and water footprinting analysis, however, assume that the full embodied emissions in the exports from country A to B are caused by country A.[5] Since we want to allocate emissions and resource uses embodied in trade flows to the country where these are taking place, a GMRIO approach is the way forward.

(b) Using the territorial principle rather than the residential principle (Usubiaga and Acosta-Fernandez 2015). A simple example: Petrol is cheap in Luxembourg, so many people from neighboring countries buy petrol in Luxembourg. A territorial approach would see this as consumption in Luxembourg. A residential approach would allocate this consumption and related emissions to the countries whose citizens buy this petrol. For footprint analyses, related to final consumption of (citizens of) countries, we would argue that a residential approach is to be followed, consistent with the System of Environmental and Economic Accounts (UN DESA 2015).

(c) Misallocation (and even neglecting) of bunker fuels and related emissions. For international shipping and aviation transports, companies buy so-called bunker fuels in various countries. Ideally, these bunker fuels are first allocated to the country in which a shipping company and airline is based (residential principle), and then further allocated to the countries who make use of the shipping and airline services. Due to the complications of such allocation methods, short cuts may be applied in this allocation, or sometimes bunker fuels even are neglected. This leads to misallocations or under-representation of carbon emissions and the like in the calculations.

Differences in Definitions and Data for Environmental Extensions

Different databases obviously use different source data. This is true for emission, land use, water use, and resource extraction data and their allocation to individual sectors.

From empirical work of various authors, we see that particularly differences in such extension data have a major influence on footprint results calculated with different GMRIOs.

First, we see that different studies and databases use a different scope for the included emissions. Some studies use a definition of the carbon footprint that include land use and land use change and forestry while others do not. Some studies simply neglect difficulties regarding data handling. An example is only including energy-related emissions in cement productions while neglecting the CO_2 emissions from the decomposition of calcium carbonate. Another example is the aforementioned omission related to bunker fuels since their allocation is so complicated (e.g., Davis and Caldeira 2010). By such neglect, studies can miss significant carbon emissions (Peters et al. 2012).

Second, we see that studies use different data sets for emissions and resource use. This appears to dominate differences in calculated footprints for different GMRIOs. Eisenmenger and colleagues (2016) found that differences in domestic resource extraction for Austria between different GMRIO databases, with obvious implications for differences in the calculated material footprints. Owen and colleagues (2014), building upon earlier work with others (Steen-Olsen et al. 2014), showed in a pair-wise comparison of carbon footprints of nations—one with WIOD, Eora, and GTAP—that differences in production emission data alone could explain around 50% of the differences in the carbon footprints of countries. Moran and Wood (2014) later came to similar conclusions. They found that overall there are differences of up to 10% to 20% for major economies, with the degree of agreement/disagreement varying depending on the country in focus and on which models are compared. Part of this was due to the aforementioned definition and scoping differences of the environmental stressor used, but that even after harmonizing the stressor, the difference between model results is, in many cases, still larger than 1 standard deviation. Hence, the remaining disagreement is due to the different descriptions of the economic structure as well as the differences in the value and composition of final demand (as discussed below). These differences require more collaboration and standardization of approaches for multiregional input-output (MRIO) accounting.

Differences in Input-Output Structures

Source Data

With regard to economic data, various sources can be used for trade data, country-level I-O, or supply and Use data, and for the conversion to a common currency. In part, this leads to data conflicts (such as the aforementioned "trade with aliens" issue). But there is also a rather simple, yet relevant, implication: In different GMRIO databases, due to the use of different data source and currency exchange rates, different countries make up a different percentage of the global GDP. Since GDP equals final demand, this obviously leads to different allocations of production impacts to consumption footprints. When analyzing the most important factor for differences in national carbon footprints, Owen and colleagues (2014, 2016) found that after differences in extension data, the second-most important factor was consumption by country.

Supply and Use Table or Input-Output Table and the Transformation from Supply and Use Table to Input-Output Table

Another important element is the principal decision to construct the database as a supply-use table (SUT) (as is the case with EXIOBASE), which can be converted via various techniques into a GMRIO (with again implications for calculated footprints), or directly available as a GMRIO (e.g., GTAP, WIOD, or ICIO). It can be expected that country-level footprints vary as a function of the model that is used to construct the IOT from the SUT (e.g., the industry or product technology assumption, and others; see Eurostat [2008]; Rueda Cantuche and ten Raa [2009, 2013]).

Reconciliation and Balancing

Finally, in all construction procedures, GMRIO compilers have to deal with data conflicts and imbalances. Trade data from commodity trade databases like COMTRADE (UN undated) do not match trade data in IOTs. COMTRADE itself is incomplete or inconsistent (e.g., exports to country B reported by country A do not match imports from country A reported by country B). Data on bilateral trade in services are coarse and need estimations. Country IOTs can be differently structured, and, apart from Eora, all other GMRIOs harmonize the tables, while some (EXIOBASE) disaggregate them. Currently, all GMRIO tables are expressed in economic terms, implicitly assuming that a doubling of economic volume represents a doubling of physical volume, which can be erroneous if large price fluctuations are at stake (such as can be the case with electricity imports and exports; Owen et al. [2016]). GMRIO compilers all have developed their own reconciliation and balancing approaches, some using implicit or explicit knowledge on uncertainty in specific data points (Eora), some first harmonizing the trade blocks and imposing these imports and exports on country SUT or IOT (GTAP, EXIOBASE), and some first harmonizing country data and then trying to find the best trade fit (WIOD). This results in different structures for the domestic, import, and export block in the economic matrix of GMRIOs (Tukker and Dietzenbacher 2013).

Assessment of Relative Relevance

Owen (2017) and Wieland and colleagues (2018) did a pairwise comparison of the factors that contributed most to the differences in calculated carbon footprints of nation between various GMRIOs. Both studies converted the GMRIOs into a common sector and country classification (the common classification). Since both studies used GMRIOs, the fundamental allocation principles as discussed earlier were always similar, though the different GMRIO database still may have handled bunker fuels and the resident versus territorial principle slightly differently. Owen (2017) used techniques such as difference statistics, structural decomposition analysis, and structural path decomposition analysis to highlight which part of the GMRIO matrices contributed most to differences in country footprints. Wieland and colleagues (2018) applied structural production layer decomposition for this purpose, using a harmonized environmental stressor in order to only pick up the differences due to economic data. Figures 3 and 4 show their respective results.

In Figure 3, the difference between database pairs (Eora and GTAP, Eora and WIOD, and GTAP and WIOD) is decomposed into eight contributing factors. Owen (2017) finds that the differing global emissions total (f_t) in the three MRIO databases has the most effect on the variation between Eora and GTAP. This component is also important in explaining the difference between Eora and WIOD's results and GTAP and WIOD's results. The effect of the share of emissions by country (f_c) and industry (f_b) are very small in all three pairings. The total final demand vector (y_t) is important in the variation between Eora and GTAP and also Eora and WIOD, but less so in the variation between GTAP and WIOD. The share of final demand by country and product has more of an effect that the share of emissions by country and industry.

The work of Owen and Wieland and colleagues further agree that the domestic block of the A matrix is contributing higher absolute differences in the carbon footprint compared to the trade block (see figure 4). Wieland and colleagues (2018) further revealed that for non-EU (European Union) countries, export blocks are more important compared to import blocks, whereas it is the other way around for EU countries, which show larger deviations in their import blocks. This result could be expected given that the EU countries are generally net importers of embodied GHG emissions. China stands out as the country with the strongest deviations. While Owen (2017) and Wieland and colleagues (2018) made comparisons for one base year only—that differed between studies—given the fact that their results converge, we have no reason to assume that

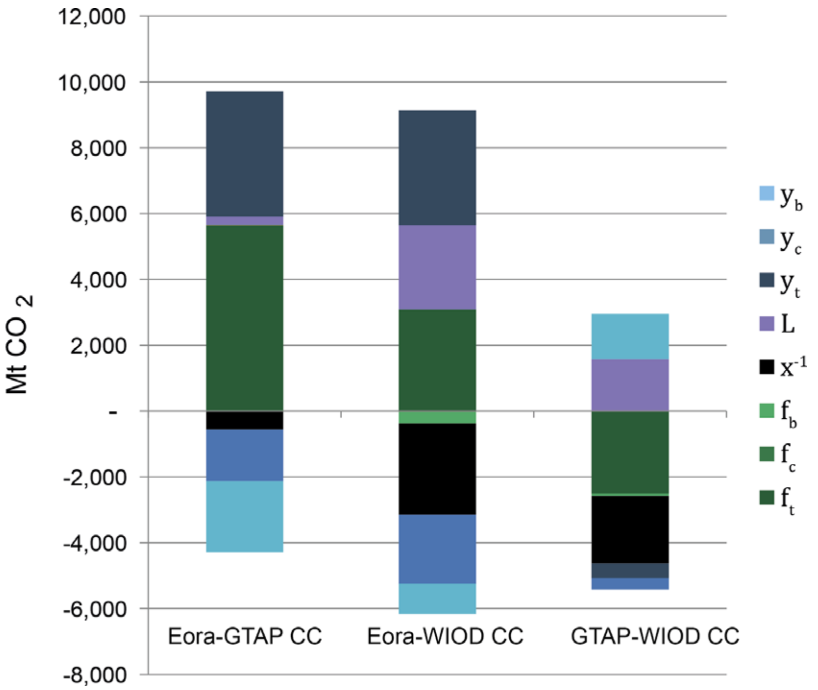

Figure 3 Decomposition of difference in global CO_2 emissions for each database pairing (from: Owen [2017]. Data for 2007).
Note: With: ft = total global industrial emissions; fc = vector or proportion of total global industrial CO_2 emissions that each country's production emissions represents; fb = vector of proportion of each country's emission that each domestic industry sector represents; x-1 = total output by region and sector; L = Leontief matrix; yb = proportion of the total region's final demand that each global product represents; yc = proportion of the region's total final demand supplied by each import country; yt = total final demand of region; CO_2 = carbon dioxide; Mt = million tonnes.

these conclusions would change if the analyses would be done for different base years.

Conclusions

An assessment of the relevance of different types of uncertainty obviously depends on the research question. A structural path analysis related to the footprint of a specific final demand category in a specific country needs a high level of certainty at the level of individual cells. Analyses focused on footprints of an entire country are more forgiving, since errors at cellular level tend to cancel one another out. When we look at the analysis from the perspective of calculating country footprints, which is currently the most common application of GMRIOs, our findings give a number of straightforward suggestions for future harmonization of GMRIO databases:

a) Ensure that basic principles with regard to allocation (true GMRIO), using a residential instead of a territorial approach, and accounting for all activities/emissions and resource uses (rather than neglecting, e.g., bunkers) are applied.
b) Harmonize the underlying databases used to compile extensions like CO_2 and other emissions, resource extractions, water use, and land use, which is likely the single biggest cause for differences in calculated country footprints.
c) Ensure further that total final demand and total product output by country form the same share of global GDP.
d) Ensure that the domestic blocks of the GMRIO are sound, that is, having an as good as possible fit with official statistics.

Particularly, points a and b are relatively easy to implement, with significant reductions in uncertainty of footprints.

Reflection and Implications

The sections *Factors Affecting the Potential for Simplification of Footprint Calculations* and *Factors Affecting Robustness of Footprints Calculated with Global Multiregional Input-Output Databases* led to the following relevant conclusions for designing a roadmap for developing robust, widely accepted footprint calculations with GMRIOs (assuming that basic allocation principles are followed such as using a true GMRIO approach and residential accounting and issues like bunker fuels are not neglected):

1. Detail in environmentally relevant sectors, such as agriculture, mining, energy production, and food processing, is essential for reliable calculations of, for example, land, water, and material footprints. Such detail is of less relevance when calculating trade in value added, and of moderate importance for calculating carbon footprints.

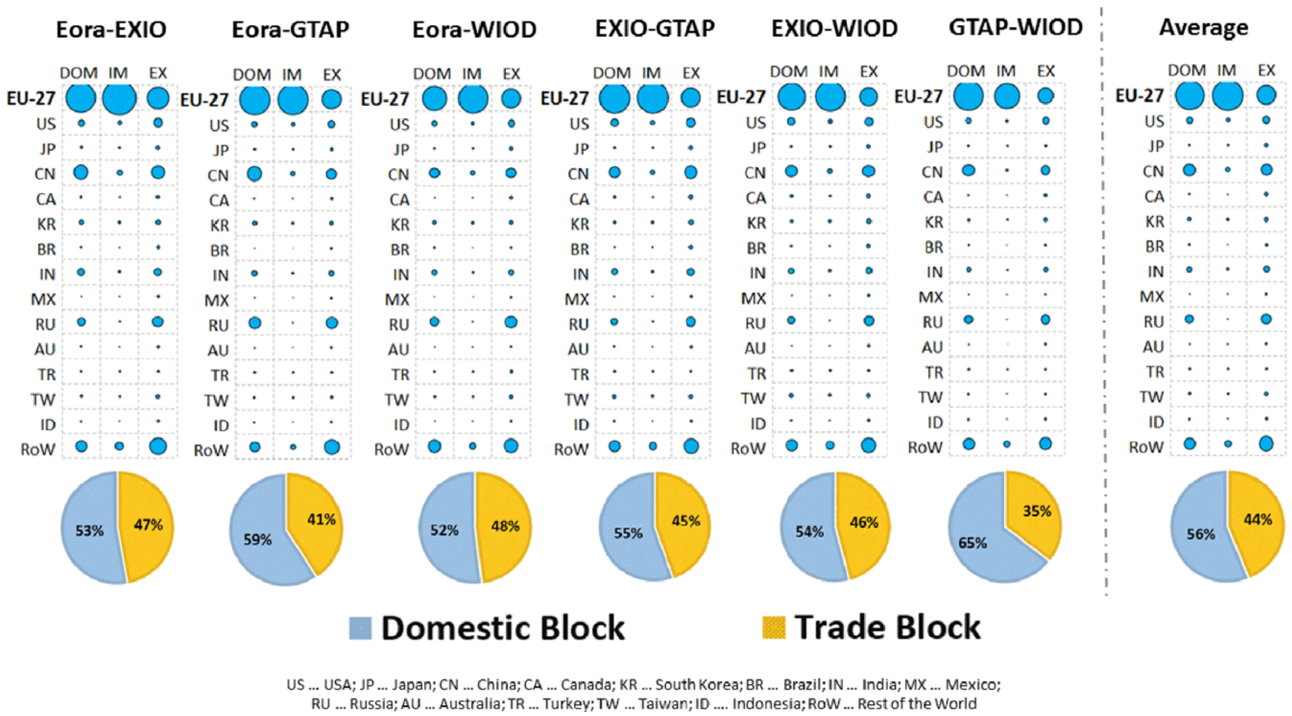

Figure 4 Effects from the domestic (DOM), import (IM), and export (EX) blocks of the A matrix on deviations of the EU carbon footprint, GMRIO model pairs, and mean across all models. Data for 2011 (adapted from Wieland et al. 2018). EU = European Union; GMRIO = Global multiregional input-output database.

2. The "feedback impacts embodied in trade," that is, the embodied impacts in exports in a country, that feedback via global value chains into the imports of this country, for most countries is negligible (<1% for most countries). The exceptions are Germany (1.7%), Russia (3%), China (6.1%), and the United States (4.2%).
3. When calculating (carbon) footprints of countries with GMRIO, the differences in results calculated with different GMRIO databases is, for over 40%, determined by the extension data used, followed by the assumed size of a country economy as percentage of the global economy, and then followed by the structure of the domestic I-O block. Differences in trade patterns between GMRIOs are least relevant.

These findings allow a strategy to be defined for improving the robustness and acceptability of footprint calculations at different time horizons. The strategy includes approaches that can be implemented almost directly; approaches that need 2 to 3 years of work; and an ideal situation that is only possible in the longer term. We will discern two situations: creating insight into the footprint of an individual country, and creating insight in comparing country footprints. While this is not the focus of the present paper, it is obvious that technical solutions that automate data reconciliation processes will facilitate practical implementation of the proposed strategies (e.g., Wood et al. 2015). More specifically, collaborative platforms such as the proposed Virtual Industrial Ecology lab can be helpful once they are fully and openly accessible for different research groups (e.g., Lenzen et al. 2014, 2017) and have already been applied to EXIOBASE (Reyes et al. 2017).

Footprint Calculations with Existing Data

If one is interested in footprint calculations for a *specific country*, the SNAC developed by Edens and colleagues (2015) is an elegant way forward to realize a high level of robustness and high level of acceptance. NSIs and similar institutes are, certainly compared to research groups, in a much better position to gather economic and environmental data for their country (Wiedmann et al. 2011), because they have access to information that is unavailable to outsiders due to firms being required by law to supply data. The SNAC approach was already briefly introduced in the *Introduction* section, and elaborated in more detail, works as follows:

1. Take an existing MRIO (e.g., EXIOBASE, ICIO, GTAP, Eora, or WIOD). The choice may be guided by the type of footprint to be calculated—for water and land, a high level of agricultural detail is required, as given by GTAP and EXIOBASE, while for carbon and value added more aggregated databases like WIOD and ICIO may be appropriate.
2. For the country for which the footprints have to be calculated, use the I-O data and extensions from existing national accounts as provided by the relevant NSI.
3. "Plug in" these national accounts data in the MRIO, fix them, and rebalance the total MRIO in such a way that,

in the resulting MRIO, the country for which footprints have to be calculated data fit precisely with national accounts.
4. Use this SNAC MRIO to calculate the footprint of consumption.

This approach uses official data for national emissions and resource extraction, and the domestic economic structure. This eliminates two factors that the section *Factors Affecting Robustness of Footprints Calculated with Global Multiregional Input-Output Databases* identified as contributing most to uncertainty. When the SNAC method is applied by NSIs themselves, they can further use insights based on underlying confidential data not accessible for outsiders, such as information on transit trade in the work of Edens and colleagues (2015). All this helps enhancing robustness and acceptance. Since we found that for most countries except China and the United States "feedback impacts embodied in trade" are minimal, and we know that few countries have large transit trade/re-export profiles, for most countries an additional simplification is possible. Instead of applying step 3 above, it is possible to simply calculate the emissions and resource use in the imports to a country directly with the GMRIO, and combine these embodiments per euro or dollar imports with the official import data in the national environmentally extended I-O. This simplified SNAC procedure eliminates hence the need for combining national I-O data with a GMRIO.

This approach can be applied almost directly for all countries that have good domestic IOTs and extension data. Even for countries with limited data, our experience is that IOTs and carbon emissions often can be estimated using secondary data, such as the International Energy Agency (IEA) database and emission factors for carbon emissions.

The SNAC and simplified SNAC approach, however, cannot help in *comparison of country footprints side-by-side*. The (simplified) SNAC method uses different data sets for the country central in the analysis compared to GMRIOs. The SNAC method as developed by Edens and colleagues (2015) indeed leads for each country calculation to a slightly different GMRIO, since data specific for one country are combined and rebalanced with an existing GMRIO. Each different country data set combined with the same GMRIO will result in a different balanced version of this GMRIO. Further, the total SNAC footprints of all countries will not equal the data for global emission and resource extraction data, which should, by definition, be identical. For global, comparative analyses, at this stage practitioners have no choice but to use one of the existing GMRIOs. The ICIO has the advantage of being produced by a supranational organization, the OECD, but is clearly too aggregated to be used for water, land, and material footprint calculations, and probably too for carbon footprint assessments.

Improved Footprint Calculations Possible in 2 to 3 Years' Time

Further refinement of footprint calculations of a *specific country* could be achieved by combining official NSI data via a (simplified) SNAC approach with a further harmonized GMRIO. *Comparative footprint calculations between countries side-by-side*, usually calculated using one consistent GMRIO, obviously also are helped by such harmonization.

The section *Factors Affecting Robustness of Footprints Calculated with Global Multiregional Input-Output Databases* shows that the single most important factor that leads to differences in footprint calculations between GMRIOs is extension data. This leads to the first, straightforward recommendation: harmonize extension data across GMRIOs. This could be done as follows:

a) Carbon emissions: agree on using data from a robust, authoritative source, such as United Nations Framework Convention on Climate Change (UNFCCC) or the Global Carbon Project.[6]
b) Materials extensions: the United Nations (UN) International Resources Panel (IRP) has published a harmonized materials extraction data set by country, combining and aligning information from research databases developed by CSIRO in Australia, and the Institute of Social Ecology at the University of Klagenfurt in Vienna, and the Vienna University of Economics and Business in Austria (UNEP 2016).
c) Water and land use: organiZe a similar process as followed by the United Nations Environment Program (UNEP) in harmonizing resource extraction databases, for other extensions such as water and land.

Another important factor, identified in the section *Importance of Feedback Embodied Impacts*, which contributes to uncertainty was the size of GDP of a country compared to the global GDP. Ensuring that all country tables in different GMRIOs are scaled to a GDP as, for example, given by the UN in the UN main aggregates, can solve another source of uncertainty.

All these suggestions do not solve the issue of acceptance. There is, however, an existing GMRIO that is produced by a supranational organization, the ICIO of OECD, to which also Eurostat contributes by providing their harmonized SUT/IOT for European countries from the Figaro project (see endnote 1). This database is, however, clearly too aggregated for most types of footprint analysis. A way forward here however could be:

1. Use the OECD ICIO database as a starting point, which provides a trade-balanced MRIO for some 60 countries at global scale.
2. Use the detailing procedures, developed for EXIOBASE and the optimization procedures developed for Eora, to disaggregate the ICIO database to a level that is appropriate for the particular research question at stake. For land and water footprint analyses, this would imply further detailing the agricultural and food processing sectors. For material footprint analysis, the materials extraction sector would need more detail. And so on. While detailing could be tailored to the research question at stake, the simplest approach would be to use the EXIOBASE/Eora

templates mentioned above to disaggregate the ICIO table in one go to some 100 to 200 industry sectors, which definitely will allow analyses for a broad set of research questions.

In this way, a database could be created that at an aggregated level has the "statistical stamp" provided by the OECD, uses extensions that are harmonized/commonly accepted, but also can provide higher level detail information (a procedure backed by a number of credible, scientific institutes). This would, for the first time, give a GMRIO that probably has a higher level of credibility as the individual scientific databases such as WIOD, EXIOBASE, GTAP, or Eora. Such a database, that holds a middle ground between official statistics and scientific work, is a good compromise MRIO database readily available for any NSI or practitioner to use.

This approach would need a project covering harmonization and some negotiations, and probably can be realized at a time horizon of 2 to 3 years.

Footprint Calculations in an Ideal Situation, Requiring 5 Years or More

Obviously, there is one route left—creating an authoritative, international GMRIO. This could be dubbed the "Royal route."

The main reason why GMRIO practitioners over-ride national statistics is due to the fact that trade data, as reported by NSIs, are in fact not mutually consistent if one looks at global scale. This problem is well known. The most prominent international trade database, COMTRADE of the UN, is known to suffer from the "mirror statistics puzzle": Imports of commodity *z* from country A reported by country B are not equal to the exports of the same commodity *z* to country B reported by country A (cf. Economist 2011). There have been efforts in the past to resolve the asymmetries (e.g., by Eurostat and OECD in collaboration with NSIs), but international organizations and NSIs at this moment have too few resources to work sufficiently on this problem. NSIs in most countries are subject to budget pressures and requests to produce statistics more efficiently. Even the crucial OECD work on the ICIO reputedly rests on time input of less than a handful of staff per year.

Having said this, the solution of this problem lies with the international organizations . The UN Statistical Division, OECD, and Eurostat are in the position to provide the institutional context in which NSIs could collaborate to ensure that the national SUT, IOT, and trade data are mutually consistent between countries.[7] Ideally, ultimately one single data set is created, that covers the national accounts data as used in the SNAC approach, but since these data for different countries would now be consistent with regard to, for example, trade, the unchanged national data sets can be used to build a GMRIO. This work on a common, global I-O data set obviously is to be complemented by work on commonly agreed upon environmental data for all countries, as already suggested in the section *Improved Footprint Calculations Possible in 2 to 3 Years' Time*. The resources for this would probably be similar to the project budget for the construction of major GMRIOs like WIOD, Eora, and EXIOBASE, that is, a few full-time staff positions per year. This clearly requires political support to enable NSIs and international organizations to make such budgets structurally available.

What might help in terms of arguing for extra funding is to point to the fact that GMRIOs are used for economic and environmental applications. The environmental applications have been discussed at length in this paper. However, the OECD project uses the GRMIO mainly to calculate "trade in value added" in global production chains. These types of analyses have become popular among economists in recent years. Resolving the harmonization issues in the economic data would benefit both the economic and environmental applications.

Conclusions and Recommendations

To conclude, we suggest that the most appropriate approach for the calculation of environmental footprints is to use GMRIOs. While approaches like the Domestic Technology Assumption and coefficient approaches have clear drawbacks, GMRIOs cover the full value chains through the global economy and create the required consistency between the global footprint of consumption and the total emissions and resource use of production.

The main problem is that production of GMRIOs is very labor intensive. Further, by necessity, GMRIOs over-ride the national accounts, since these national accounts for all countries together are not consistent at global level: global imports and exports do not match. We further found that particularly for calculating, for example, water, land, and materials footprint, a high level of detail of the GMRIO of 100 to 200 sectors, particularly in agriculture, energy extraction, and mining, is essential to avoid significant aggregation errors.

To overcome this situation, we recommend the following.

In the *long term*, bodies such as the UN Statistical Division (UNSD), OECD, Eurostat, and NSIs should be provided the resources to make national accounts, and particularly import and export data, consistent at the global level. Compared to researchers, NSIs have access to data of unprecedented quality and detail and, in principle, are in the best position to provide high-quality statistics that, at the same time, are consistent at global level. From the experience of compiling the existing GMRIOs, they could identify the most pressing inconsistencies at international level as input to the continuous improvement processes they already apply in their regular data inventory and reconciliation work.

In the *short term*, basic harmonization of the existing GMRIOs constructed by scientists could be realized as follows. First, a number of fairly simple agreements should be made on the basis of footprint accounting principles (i.e., using a true GMRIO approach rather than other allocation mechanisms; taking the residential principle as a starting point; and avoiding neglecting emissions or resource uses related to, e.g., international bunkers). Furthermore, harmonized databases for extensions should be developed or used, such as the resource extraction database recently developed by the UN IRP. Here, particularly work on water, land, and emission extensions remains. It is likely that such simple measures will reduce the differences in calculations of footprints of nations with different databases by over 50%.

A further step toward a higher level of credibility of GMRIO database could be made as follows: The OECD produces currently the ICIO GMRIO, which has a (too) high level of aggregation of 30 sectors for doing high-quality environmental footprint analyses. Using procedures developed for EXIOBASE and Eora, ICIO could be detailed to an appropriate level for footprint analyses and combined with the aforementioned, common environmental extension databases.[8] This would lead to a GMRIO database with an appropriate level of detail, but in which important elements (the structure at the level of 30 sectors globally, and extensions) are harmonized and endorsed by important organizations such as the OECD and UN IRP.

Finally, the problem that even such a GMRIO over-rides national accounts data can be overcome by applying the SNAC or simplified SNAC procedure described in the former section. This simplified SNAC procedure can be applied for all countries that have limited feedback emissions (i.e., emissions and resource use in their exports, that via global value chains appear also in their imports). This is the case for almost all countries except China and the United States.

With a semistandardized GMRIO available, combined with available national accounts data, in this way the calculation of country footprints should be a rather straightforward exercise.

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Notes

1. Hoekstra and colleagues (2014) review the statistical institutes which have attempted footprint calculations.
2. There are, however, regional harmonization efforts, most notably in the EU via Eurostat. Eurostat aims to produce in 2017 harmonized EU-Inter Country Supply, Use and Input-Output Tables (EU-IC-SUIOTs) in the "Full International and Global Accounts for Research in Input-Output Analysis" (FIGARO) project. See http://ec.europa.eu/eurostat/web/economic-globalisation-and-macroeconomic-statistics/multi-country-supply/figaro (accessed 6 June 2017).
3. See, for instance, guidelines such https://unstats.un.org/unsd/dnss/gp/fundprinciples.aspx and https://www.unece.org/stats/archive/docs.fp.e.html (accessed 6 June 2017), which, among others, call for international cooperation.
4. Note that the causes of differences in footprint calculations reported in literature go well beyond these construction problems with regard to GMRIO. As indicated in the *Introduction* to this Special Issue (Tukker et al. 2018), various other methods, including coefficient approaches, exist for assessing environmental footprints, and these may use quite different principles for allocating production impacts to final consumption. These obviously will lead to differently calculated consumption-based footprints (e.g., Peters et al. 2012). We here, however, focus on footprint analysis based on a true GMRIO approach and focus this section on factors that are most relevant in the uncertainty in calculating footprints with GMRIOs.
5. A similar difference is at stake with the monetary value of exports from A to B. This monetary value is usually *not* only produced country A; the monetary value consists of elements of added value created in country A and the countries from which country A imports.
6. See www.globalcarbonproject.org/ (accessed 25 January 2017). Having said this, even this is not as simple as it seems. Some databases such as EXIOBASE ensure harmonization of economic data for the use of energy carriers by economic sector, and the physical energy flow data as reported by the IEA. From this, using emission factors, CO_2 emissions can be calculated per economic sector that are consistent with the energy use in that sector. But such "energy first" calculated carbon emissions may not be consistent with reported values to, for example, UNFCCC.
7. Eurostat, the European Statistical Agency, already does a great deal of harmonization of data, both in terms of SUTs as well as environmental accounts. Given that Europe comprises about one quarter of global GDP, this contributes significantly to the overall harmonization. Both Eurostat, OECD, and the UNSD have many working groups and task forces which each help along an individual aspect of the harmonization puzzle. These activities are very important in incremental progress, but the underlying statistical work should be backed up by sufficient funding.
8. In this, we assume the ICIO database is using also harmonized data that ensure the GDP or final demand in a country is a sound representation of the % of the global GDP, another factor that can influence footprint calculations significantly (see section *Importance of Feedback Embodied Impacts*).

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