Recent Progress in Assessment of Resource Efficiency and Environmental Impacts Embodied in Trade

An Introduction to this Special Issue

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Summary

This paper serves as an introduction to this special issue on the use of multiregional input-output modeling in assessments of natural resource use and resource use efficiency. Due to globalization, growth in trade has outpaced growth in global gross domestic product (GDP). As a consequence, impacts of consumption of a country increasingly take place abroad. Various methods have been developed to perform so-called footprint analyses. We argue that global multiregional input-output (GMRIO) analysis has the largest potential to provide a consistent accounting framework to calculate a variety of different footprint indicators. The state of the art in GMRIO has, however, various shortcomings, such as limited sector and regional detail and incomplete extensions. The work presented in this special issue addresses a number of such problems and how to possibly overcome them, focusing on the construction of a new GMRIO database (EXIOBASE V3). This database includes long time series in both current and constant prices, a high level of product and sector detail, a physical representation of the world economy, and allows analyzing which footprints out of the many possible indicators provide most information for policy making. Various options for empirical analyses are presented in this special issue. Finally, we analyze how GMRIOs can be further standardized and gradually moved from the scientific to the official statistical domain.

Introduction

Over the last few decades, growth in trade has generally outpaced growth in gross domestic product (GDP) (Peters et al. 2011a). Further, due to ongoing offshoring and globalization, value chains of most products now span various countries. As a result, traditional territorial accounting approaches, that measure environmental pressures and resource extraction within the borders of a country, have become insufficient to understand, how consumption of products in a country drives environmental impacts globally (e.g., Peters et al. 2011a; Ahmad and Ribarsky 2014).

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This poses national statistical institutes (NSIs) and supranational institutes like the Organization for Economic Cooperation and Development (OECD), the European Environment Agency and Eurostat, with the problem of how to compile indicators that take a consumption-based perspective into account. Robust databases, models, and indicators that allow assessing *pollution and resources embodied in trade* are therefore under increasing demand by both academia and policy makers. Countries can ensure that high-quality statistical data for their own territory are available. It is much more difficult to ensure such data from trade partners is available. As a consequence, various *footprint* databases and methods have been developed by academia, statistical offices, and international organizations, which are adapted to the specific needs and constraints of each group of actors (Feng et al. 2011; Lutter et al. 2016; Weinzettel et al. 2014).

More than six large European and international research projects aimed at further developing these methods in the academic sphere. This Special Issue is dedicated to illustrating the results of one of the main projects in this area in the past few years, the European Union's (EU) Seventh Framework Programme project DESIRE (Development of a System of Indicators for a Resource efficient Europe). In the DESIRE project, a new database for assessing the global environmental implications related to the consumption of Europe and other countries was developed, including time-series data and a high level of product and sector detail as well as a physical representation of the world economy.

In this introduction to this special issue, we will discuss the work performed within the DESIRE project to assess natural resource use and pollution embodied in trade. We then shortly review some databases that can be used for this purpose and their pros and cons. After this, we will present recent progress in this field, exemplified by results achieved in the DESIRE project, and summarizing the papers in this special issue. The paper ends with conclusions.

Methods for Assessing Pollution and Resources Embodied in Trade

In general, the following methods can be discerned to assess pollution embodied in trade of countries and related footprints (e.g., Kanemoto et al. 2012; Tukker et al. 2013a; Bruckner et al. 2015; Eisenmenger et al. 2016):

1. Using emission and resource use coefficients for foreign countries derived with life cycle inventories (LCIs) in combination with trade data on imported products (e.g., Schoer et al. 2013).
2. Applying the domestic technology assumption (DTA), that is, assuming that imported products are produced with the same technologies as domestically produced products (e.g., Wood and Dey 2009).
3. Applying the DTA corrected for purchasing power parities, or relative prices of imports compared to European production (e.g., Tukker et al. 2013a).
4. Using emission and resource coefficients for foreign countries derived with environmentally extended input-output (EE IO) data for these countries, taking into account bilateral trade only (e.g., Lenzen et al. 2004).
5. Using an available environmental global multiregional input-output (GMRIO) databases at face value, and calculating footprints of a country with such a GMRIO (e.g., Tukker et al. 2016).
6. As per item 5, using official data for a specific country for which environmental footprints need to be calculated, and adjusting and rebalancing an existing GMRIO by implementing that data in it. This is also called a single-country national accounts consistent (SNAC) footprint (e.g., Edens et al. 2015).
7. As per item 6, using official data for a specific country for which footprints are calculated but using the full environmental GMRIO model only to calculate pollution and resources in imports rather than creating a new GMRIO adjusted to this specific country.

Bruckner and colleagues (2015) discuss further a hybrid approach for land use that combines the high level of detail of physical data from FAOSTAT and land use coefficients (item 1) with the value chain perspective of environmental GMRIO (items 5 to 7). Such detailed combined hybrid databases currently are not yet available, so for that reason we do not take this into account in this analysis[1]. The various approaches mentioned above will now be discussed in more detail[2].

Description of Methods

Applying Life Cycle Inventory Data for Imports

A practitioner may use LCI databases to estimate the impacts in the life cycle of imported products (Eurostat 2012). For material footprints, following this approach, so-called raw material equivalents (RMEs) are calculated that identify for imported products how much primary materials have been extracted for producing them. LCI data are often limited in the sense that they are mostly available for European, U.S., and Japanese processes. This could lead to similar errors as in the method for DTA (see below), due to the fact that the LCI data for developed countries may not apply well to countries from which a product is imported. At best, one can expect some differentiation by country on the use of energy carriers and electricity sources in life cycle assessments (LCAs) for products made abroad. A further problem is that LCI data cover unit processes in great detail. Scaling up from specific product LCAs to, for example, 60 broad product categories of imports can lead to further errors. Further, RMEs have only been calculated for Europe (Schoer et al. 2012, 2013). Two fundamental problems, however, are the following:

- An environmental GMRIO approach merely redistributes the global extraction of resources and global emissions to final demand. The pollution and extractions embodied in final demand is hence by nature identical to global pollution and extractions, as they should be.

When LCI data are used for imports, and combined with domestic extraction and emission data, the resources and emissions embodied in imports will be based on a different data set. Inevitably, once aggregated to the global level, the pollution and resource extraction embodied in final demand will hence differ from the world-wide resource extraction and emissions.

- An environmental GMRIO approach truly follows value chains through the global economy. The LCI/coefficient-based approach assumes that an imported product is made in full in the country of exports. In practice, components of the imported products are made in third countries, and elements of these components again in other countries, etc. Giljum and colleagues (2016) found that such fragmentation of supply chains has become more important over time.

Some authors have argued that, particularly for water and land footprints related to agriculture, the detail that can be achieved by coefficient-based approaches is a decisive advantage (e.g., Weinzettel et al. 2014). Other authors, however, have shown that the drawbacks identified above can lead to miscalculations of water and land footprints when coefficient approaches are used (e.g., Feng et al. 2011; Hubaceck and Feng 2016). Creating more detail in GMRIOs or applying hybrid approaches is now widely seen as the best way forward (compare Lutter et al. 2016; Weinzettel et al. 2014; Tukker et al. 2016).

Domestic Technology Assumption

The DTA has been used in a large number of studies. DTA is simple to apply and before GMRIOs were available, it was one of the few practical ways available to calculate impacts embodied in imports. It assumes that imports are made with domestic technology. It hence just needs data on imports from the supply and use table (SUT) or input-output table (IOT) to make an estimate. However, this method can lead to erroneous results since impact intensities of imported goods can differ from those produced domestically (Peters and Hertwich 2006a, 2006b; Weber and Matthews 2007; Ghertner and Fripp 2007; Andrews et al. 2009; Peters et al. 2011a). The DTA as derived by Tukker and colleagues (2013a) for Eurostat suggested that the carbgon dioxide emissions in imports and exports of the EU27 are similar (respectively 1.7 vs. 1.6 metric tons per capita), which does not correspond to multiregional input-output (MRIO) or more detailed assessments. Studies calculating impacts of imports using specific data for non-EU countries showed major differences, up to 3 metric tons per capita (e.g., Bruckner et al. 2010; Davis and Caldeira 2010; Tukker et al. 2016). All this is not surprising. Countries can have a fundamentally different production structure as the countries from which they import. Such limitations imply that the DTA can, at best, be used as a *last resort method* in cases where no other information is available.

Price-Adjusted Domestic Technology Assumption

Tukker and colleagues proposed an alternative for the DTA. They considered that there can be three main reasons why the DTA may not give correct results, taking the European situation as an example:

a) For the same industry and product, the direct pollution per unit of production abroad is higher as in Europe (i.e., there is a difference in emission coefficients in the producing industries);
b) For the same industry and product, the intermediate inputs and/or the pollution related to production of intermediate inputs per unit of production is higher as in Europe (i.e., there is a difference in the technical [input] coefficients in the producing industries, and/or higher emission coefficients in the downstream industries); and
c) For the same product, one Euro of imports represents a larger amount of physical imports as one Euro of production in Europe (i.e., countries abroad area able to produce more amounts for less money).

This leads to a simple possibility to improve the DTA with statistical data available from NSIs only. NSIs and organizations such as Eurostat usually have already available environmentally extended (EE) SUT/IOTs with an export vector, for EUROSTAT typically at the level of 60 product categories. NSIs have, however, also insight into trade flows. Eurostat's COMEXT database, for instance, contains both data on the economic value as well as the physical quantity of imported and exported products. COMEXT's detailed trade data can easily be aggregated to the 60 product categories in EU EE SUT/IOTs. With both economic value as well as physical quantity known, an average price per product group can be calculated for imports and exports. Assuming price homogeneity in the EE SUT/IOT, the price of the exports equals the price of domestic production. The ratio of domestic (= export) price and import price now can be used to adjust impacts per imported product group calculated via the DTA. This factor corrects, in essence, how much more physical imports takes place per Euro spent compared to physical output per Euro production in Europe.

This method hence corrects for point c above. However, no insight is provided into points a and b above, whereas like the DTA also no insight into the full value chains across countries is provided. It is hence not possible to assess how imports drive emissions and resource extractions abroad per country, as only the total emission and resource extraction abroad are estimated.

Including Bilateral Trade Based on National Environmentally Extended Input-Output Tables

A practitioner may identify the main trading partners of a central country for which environmental footprints need to be calculated, make available EE IOTs for these countries or country groups, and calculate the embedded pollution and resource use in bilateral trade (see, e.g., Lenzen et al. 2004; Peters and Hertwich [2006b; Norway], Nijdam et al. [2005; the Netherlands], Weber and Matthews [2007, United States], and Norman et al. (2007; Canadian-U.S. trade]).

National EE IOTs by country usually only give an aggregated import vector and do not specify the countries of origin. Usually, auxiliary trade data (e.g., from COMEXT or UN COMTRADE) are used to calculate import shares to split up the import vector to countries of origin.

Using then any EE IOT available from these exporting countries, the resources and pollution embodied in imports are calculated. The main drawback of this method is obvious—again, the full value chains are not followed and it is assumed that pollution embodied in trade is only related to production of the full product in the country of exports. Trade between countries other than the central country is ignored.

Using a Global Multiregional Input-Output Database

Another option is to use an environmental GMRIO like Eora (Lenzen et al. 2013), World Input-Output Database (WIOD) (Dietzenbacher et al. 2013), EXIOBASE (Tukker et al. 2013b), Global Trade Analysis Project (GTAP) (e.g., Peters et al. 2011b), or others (see, for an overview, Tukker and Dietzenbacher [2013]) as such. In this case, the practitioner simply uses one of these global multiregional (MR) EE input-outputs (I-Os) to calculate footprints of emissions and resource use per country (as, e.g., illustrated by Tukker et al. [2014, 2016]) for EXIOBASE.

The advantage is that with a ready-to-use GMRIO, the analysis is relatively straightforward and quick. The disadvantage, as indicated, is that virtually all GMRIOs have to adjust national SUT and IOTs to arrive at a global MR EE SUT in which trade is balanced. For NSIs, it is often difficult to accept the use of national SUTs and IOTs derived from GMRIOs that differ from their own published data.

Single-Country National Accounts Consistent Footprint

Edens and colleagues (2015) proposed a method for calculating a footprint that is consistent with national economic (in their case: Dutch) and environmental accounts called a SNAC footprint, using the WIOD database in their example. Simply said, they rely for a country for which they want to assess environmental footprints entirely on data from the country's NSI. The country data in the GMRIO are replaced by these NSI data—since these data slightly differ, usually resulting in an imbalanced global table. Edens and colleagues (2015) hence replaced the Dutch data in WIOD by their superior NSI data. Particularly for the Netherlands transit trade and re-export data need to be properly accounted for, a task for which an NSI is better placed compared to research teams producing GMRIOs such as WIOD. Then, trade linking with the countries in the WIOD database was performed—but then under the constraint that the Dutch data (the country central in the analysis) could not change. This resulted hence in a new version of WIOD, in which the Dutch data exactly matched national statistics. A team at Leeds University used a similar approach using official UK statistics in combination with the Eora database to calculate UK carbon footprints.

The advantage is that official statistics are used for the country central in the analysis and for which a footprint is calculated. The disadvantage is that the data available in an existing GMRIO cannot be used directly, but that the MR EE I-O has to be reconstructed with as a constraint that the SUTs of IOTs of the country central in the analysis cannot be adjusted. If for all 40 countries covered by WIOD this procedure would be applied, one would end up with 40 slightly different versions of WIOD, with each version a different country for which data are fixed consistent with national accounts. The underlying problem, that in the end all officially published SUTs and IOTs by NSIs lead to an imbalance in global trade, is not addressed, but hidden.

Single-Country National Accounts Consistent Footprints with Imports from Global Multiregional Input-Output

An alternative to the approach discussed in the former section is a *simplified SNAC*. In the SNAC approach described above, NSI data for a specific country and a GMRIO are combined into a new, balanced GMRIO in which the NSI data for that specific country are not changed. An alternative is to use NSI data for the specific country SUT and calculate the pollution and resource extraction embodied in imports to that country with an existing GMRIO model. This approach hence avoids that the specific country SUT/IOT has to be embedded in the GMRIO database that is chosen for the analysis, which would require doing the job of rebalancing the GMRIO. There is just one drawback. In principle, exports from the specific country for which footprints are calculated are not included in the GMRIO analysis anymore, which can lead to errors if the export of components by that country is likely to show up, after traveling through the value chains, in the imports of that country. As shown by Moran and colleagues (2018), this problem is more significant for big economies compared to small ones.

Assessment of Advantages and Disadvantages

A robust methodology to assess environmental impacts embodied in traded products needs to fulfill a number of criteria related to the system boundaries of the calculation approach, quality of the underlying data, as well as technical feasibility for broad application (see Giljum et al. 2011; Lutter et al. 2016). For the assessment of the pros and cons of each method as illustrated below, we condense the existing sets of criteria to the following four headings:

a) Ease of assessment;
b) Fit with official national statistics;
c) Theoretical reliability; and
d) Other advantages and drawbacks.

The assessment is summarized in table 1. The table suggests that methods like the DTA and price-corrected DTA should not be applied, as results lack robustness due to the insufficient reflection of differences in production structures and environmental intensities between countries. Coefficient approaches have the significant drawback that the global footprint of consumption calculated in this way is not equal to the territorial global emissions and resource extraction. They further cannot be used for analyses along the full value chain. This drawback is valid for bilateral trade approaches, too.

Table 1 Pros and cons of various ways of dealing with pollution and resources embodied in imports

	Ease of use	*Fit with official national statistics*	*Theoretical reliability*	*Remark*
Coefficient approaches	Medium	Good	Unknown. Will cause difference between global extraction/emissions and footprints, which by definition must be equal	High-detail assessments can be performed, but coefficients are only available for a limited number of products. Cannot identify which part of value chains are located in which country
DTA	Easy	Good	Low	Assumption that production abroad is equal to domestic production has been shown empirically to be flawed
Price-corrected DTA	Medium	Good	Medium	Misses value-chain perspective, and differences in production efficiency and emission intensities abroad
Bilateral trade	Medium	Good	Medium	Misses value-chain perspective; assumes products made in full in country of exports
GMRIO	Easy	Variable	Good, covers full value chain	Country SUT/IOT in GMRIO may differ from official statistics. High level of sector/product aggregation can lead to distortions of results.
SNAC-GMRIO	Difficult	Good	Good, has as advantage official statistics for country central in the analysis is used	GMRIO must be rebuilt with official statistics for one country
SNAC with imports from GMRIO (simplified SNAC)	Easy	Good	"Feedback emissions" are not corrected (see remark)	If exports of the country central in the analysis end up in its imports, theoretically this approach has an internal inconsistency (albeit in practice, these effects are currently minor).

Note: DTA = domestic technology assumption; GMRIO = global multiregional input-output; IOT = input-output table; SNAC = single-country national accounts consistent; SUT = supply and use table.

This leaves the approaches discussed in last three subsections above: GMRIO, SNAC, and simplified SNAC. Using a GMRIO at face value, once it is constructed, is relatively easy. The disadvantage is that since a GMRIO must be balanced, and national SUT/IOT do not add up to a consistent balanced data set at global level, a GMRIO inevitably will contain for each country economic data that slightly deviate from official NSI data. Using one of the two SNAC approaches overcomes this, but the SNAC approach as proposed by Edens and colleagues (2015) has as a disadvantage that de facto a new GMRIO has to be rebuilt using individual country data underlying the GMRIO with national statistics (here dubbed: SNAC-GMRIO). A simplified SNAC approach that simply uses pollution and resources embodied in imports is easy to implement, but has as a theoretical drawback that pollution and resources embodied in exports that come back to a country via imports is neglected. The conclusion is hence that applying a GMRIO or a SNAC-GMRIO is the best available option, depending on the research question. If one is interested in obtaining the most precise indicators of one single country, one of the two SNAC approaches are the best way forward. If one, however, wants to deliver a comparison between footprints of different countries, using one consistent GMRIO without further adjustments seems the most robust and feasible approach.

Approaches Based on Global Multiregional Input-Output Analysis

The second section of this paper clearly suggests that approaches using GMRIOs have important advantages over coefficient-based approaches, just taking into account of bilateral trade, or variants of the DTA.

A practical limitation to the acceptance of the GMRIO approach, however, is that most GMRIOs available have been produced in the scientific arena. Currently, there is no GMRIO available covering the full globe that has commonly accepted authoritative position or is backed by an authoritative international agency. The exception is the recently developed and highly aggregated Inter-Country Input-Output table (ICIO) of the OECD. As described by, for example, Tukker and

Dietzenbacher (2013), currently around four to five global MRIOs are available with quite varying characteristics. They include Eora (Lenzen et al. 2012a, 2012b, 2013; sector detail varying from 25 to 500; about 180 countries), EXIOBASE (Tukker et al. 2009, 2013b; Wood et al. 2014, 2015; 163 sectors, 48 countries/regions), WIOD (Dietzenbacher et al. 2013; 35 sectors, 40 countries), GTAP-MRIO (Peters et al. 2011b; 57 sectors, >120 countries/regions), and the OECD's ICIO database (34 sectors, up to 70 regions [OECD 2015]). Table 2 summarizes the characteristics of these databases. These existing databases have a number of weaknesses, which we will discuss in the next section. After this, we then summarize the improvements to which the papers in this special issue have contributed.

Strengths and Weaknesses of Current Global Multi-Regional Input-Output Databases and Related Indicators

When we look at the GMRIO databases available per mid-2016, before the release of EXIOBASE V3 as constructed in the DESIRE project, we can see that they have different strengths and weaknesses. Some important features of the available GMRIOs include (compare Tukker and Dietzenbacher 2013; Tukker et al. 2016):

Sector and product detail:

- WIOD and the OECD ICIO database have a rather aggregated industry classification, in particular for the agriculture, mining, and energy-producing sectors. For economic-oriented applications of these databases, this poses not a major problem, since, for example, the number of jobs and added value in these sectors is just a limited part of country totals, and do not differ highly per unit turnover per subsector (e.g., Tukker and Dietzenbacher 2013; Dietzenbacher et al. 2013; Tukker et al. 2016). For environmental assessments, this is, however, the opposite. Agriculture and power generation are among the most environmentally intensive sectors, and subsectors (e.g., wind vs. coal power or animal husbandry vs. grain production) can have highly different emission intensities. A high level of detail in such sectors is hence highly relevant for environmental assessments (e.g., Lenzen 2011; Wood et al. 2014; de Koning et al. 2015a).
- Overall, Eora splits up the global economy in most products and sectors. Yet, Eora has a varying sector and product detail. Some countries such as Japan and the United States have a highly detailed representation of 500 sectors, where the vast majority of the countries in Eora has a sector and product detail of well below 100, many of them just 25—often not based on actual country I-O source data, but modeled by combining macroeconomic statistics of a country with a template I-O structure.
- EXIOBASE has the highest level of consistent sector detail (of 163 sectors and 200 product groups for all included countries/regions). Detail has been particularly created in environmentally intensive sectors such as agriculture, mining, and power generation. As indicated, this is essential for environmental footprint analyses.

Country detail:

- Eora and GTAP discern considerably more countries specifically than ICIO, and particularly WIOD and EXIOBASE which focus on Europe. As we concluded earlier in Tukker and Dietzenbacher (2013), this has important advantages in assessing impacts of final consumption that take place in relatively poor countries with a low gross domestic product (GDP) not covered in other databases (Lenzen et al. 2012) and is also important to attribute impacts to individual countries (as opposed to a large aggregated Rest of World [RoW]).

Time series and constant versus current prices:

- Eora and WIOD are the only databases with time series. WIOD was recently the only of the two that is available in both current and previous year prices; until very recently, these were interpolated for Eora using U.S. price indices (see Lan et al. 2016). Such price-corrected data are highly relevant to understand the underlying drivers of, for instance, changes in environmental footprints of countries: changes in consumption patterns; the intermediate production structure; emissions factors; or trade relations. Structural decomposition analysis is a very powerful tool to uncover such drivers, but needs to be applied to time-series tables at constant prices (cf. Dietzenbacher and Los 1998; Hoekstra and van den Bergh 2002; Wood 2009).

Timeliness

- IOTs published by statistical institutes often have a time lag of several years, making the possibility to create updated GMRIO databases very difficult. Eora currently has time series to 2013. WIOD has full time series to 2009, and updated IOTs and socioeconomic accounts to 2011, but lacks updated environmental accounts beyond 2009. The OECD ICIO and GTAP database currently covers years to 2011. Most policy analysts want to know either current or previous year results, and struggle to accept 5-year-old data, so a number of methods have been introduced to extrapolate forward (Peters et al. 2012).

Representing the economy in economic rather than physical units:

- All databases are in monetary units. Particularly for transactions of which the value per physical unit varies highly, or this value is zero or negative, monetary data are an inappropriate representation of physical data. For this reason, unless hybrid physical-economic tables are constructed, economic IOTs are notoriously weak in representing particularly the waste management system (compare Nakamura et al. 2007; Weisz and Duchin 2006).

Table 2 Review of the main global multiregional input output (GMRIO) databases in 2016 (updated from Tukker and Dietzenbacher 2013)

Database name	*Countries*	*Type*	*Detail (ixp)**	*Time*	*Extensions*	*Approach*
GTAP-MRIO	World (140)	MR IOT	57 × 57	1990, 1992, 1995, 1997, 2001, 2004, 2007,2011	5 (GWP), land use (18 AEZ), energy volumes, migration	Trade data are balanced first. Trade is imposed on IOTS. IOTs are balanced with trade and macroeconomic data
ICIO	World (70)	MR IOT	34 × 34	1995–2011	Various	The harmonized OECD IOTs are used as a basis. The OECD bilateral trade database, which is consistent with the IOTS, is used for trade linking.
WIOD	World (40+RoW)	MR SUT	35 × 59	1995–2011, annually	Detailed socio economic and environmental satellite accounts	SUTs are harmonized first. The use table is split in domestic and import use. Bilateral trade databases are created for goods and services using international statistics. Trade shares from this trade database are used to estimate the countries of origin of the import use. The Rest of World (RoW) is used to reconcile bilateral trade shares. Extensions are added.
Eora	World (around 190)	MR SUT/ IOT	Variable (20 to 500)	1970–2013	Various	SUTs and IOTs are gathered in original formats and used to populate an initial estimate of all data points in the GMR SUT/IOT. A large set of hard and soft constraints are formulated. A routine then calculates the global MR SUT/IOT.
EXIOBASE V2	World (43+5 Rest of the world regions)	MR SUT/IOT	163 × 200	2007	26 emissions, 69 IEA energy carriers, water, land, over 40 resources	SUTs are detailed and harmonized. The use table is split in domestic and import use. Trade shares are used to estimate the countries of origin of imports, resulting in an implicit export of these countries. These implicit exports are confronted with the exports in the country SUT and with use of a balancing routine a balanced GMRIO is obtained.

Note: *i = number of industries; p = number of products.
MR IOT = multiregional input output table; MR SUT = multiregional supply and use table; GWP = global warming potential; AEZ = agro-ecological zone; IEA = International Energy Agency; OECD = Organization for Economic Cooperation and Development.

Ability to focus on a range of footprint indicators:

Particularly early GMRIO work focused mainly on carbon footprints (e.g., Ahmad and Wyckoff 2003; Hertwich and Peters 2009; Davis and Caldeira 2010). To most databases in Table 2, various extensions including land and water can be added, but for, as an example, WIOD and ICIO, the limited sector detail remains a drawback. Limited extensions hamper the use of these GMRIOs in addressing the agenda of Nexus issues and linking various footprints to planetary boundaries (e.g., Fang et al. 2014; Tukker et al. 2016).

It is hence desirable to have databases that do include a long list of environmental extensions, like EXIOBASE and Eora. Yet, in the practice of policy making, usually just a limited number of indicators is used. An example is the clear choice for materials, water, land, and carbon as the *dashboard of indicators* in the EU's Resource Efficiency Roadmap (EC 2011; Giljum et al. 2011). This, however, then leads to the question how to select a *best set* of indicators that represents a broad set of environmental problems, or how a meaningful aggregation of indicators can be worked out.

Ability to do both historical and forward looking (policy) analyses.

- A main application of GMRIOs has been assessment of global value-chain networks and the environmental pressures they create in the past and present (Peters et al. 2011a; Lenzen et al. 2012; Steen-Olsen et al. 2012; Tukker et al. 2016). But equally important are answering questions around what kind of policies can be applied to improve the situation, especially given the strong link between income and environmental impact (Ivanova et al. 2017; Simas et al. 2017) that gives rise to the rebound effect (Hertwich 2005). Such more forward-looking studies seem much less frequent (e.g., de Koning et al. 2015b)

Credibility for official statistical agencies:

- Finally, all these databases have the drawback that they have not been compiled by statistical agencies or supranational authorities (except the ICIO). Indeed, the construction of GMRIO databases implies harmonizing bilateral trade data—it appears that if one adds up all exports and imports in individual country IOTs, an imbalance remains. As a result, all GMRIOs to varying degrees must adjust country IOTs, and import and export data published by NSIs, to come to a balanced table at the global level. This obviously creates acceptance problems of GMRIO tables, even though the applied adjustments are unavoidable and that the imbalances encountered should be solved by a collaborative effort of NSIs. The OECD ICIO database comes closest to the ideal of a GMRIO backed by an official institution, but as indicated has the drawback of covering just 60 countries and having a limited sector resolution of 30 economic sectors.

Contributions to Improvement of the State of the Art by Papers in This Special Issue

The relevance of some of the topics discussed above for the quality of calculated footprints have been subject of some papers in a special issue of *Economic Systems Research* on the comparison of various GMRIOs (e.g., Arto et al. 2014; Geschke et al. 2014; Owen et al. 2014; Moran and Wood (2014). The last paper in this special issue (Tukker et al. 2018) uses such information and the insights obtained in this special issue to propose a strategy for creating a robust, credible GMRIO for footprint analysis. More specifically, the work done for this special issue sets out to move the state of the art on the topics above in the following ways.

- *Sector and product detail:* Given the high relevance of sector and product detail in, particularly, agriculture and food production, resource extraction, and power generation for environmental analysis, EXIOBASE was used as a starting point for the work. It is the only available GMRIO database with a consistent, high level of product and sector detail for all countries covered. The work done for this special issue hence focused on mitigating the main limitations of EXIOBASE V2, as described in the former section, such as the lack of time series, timeliness, and lack of physical dimension.
- *Country detail:* This main existing limitation of EXIOBASE that was not addressed in the work done leading to this special issue. The deliberation was that issues like sector and product detail, physical tables, and constant price time series were of a higher priority. After all, EXIOBASE covers all economies in the world, albeit aggregating countries to five RoW regions. Other databases such as GTAP and Eora do provide more countries, but most of them reflect *constructed* data from a template given a lack of primary I-O source data. Given the limited relevance of these countries in the global economic systems, errors of this country aggregation are likely to be limited (cf., Stadler et al. 2014).
- *Time series and constant versus current prices:* A major improvement compared to earlier versions of EXIOBASE was the construction of long time series and tables in current and constant prices. The paper of Stadler and colleagues (2018) describes the approach to building EXIOBASE V3. Previous versions of EXIOBASE first took country SUTs and detailed them, and only then combined them via trade to construct a global MRIO. In the development of V3, trade was harmonized first, and imposed on country SUTs, while the country SUTs were made consistent with macroeconomic statistics from the United Nations (UN) as constraints. Other data sources (Food and Agricultural Organization [FAO], International Energy Agency [IEA], the WaterGAP model, the Vienna University of Economics and Business Global Material Flow Database, and International Labor Organization labor statistics) helped to add environmental extensions and create profound insights in employment

issues. Overall, EXIOBASE V3 covers 44 countries plus five RoW regions, discerns 200 products and 163 industries, has time series from 1995 to 2011, and includes 69 energy products, 222 types of resource extractions, green and blue water use, 14 types of land use, several dozens of emissions, and 14 employment categories per skill level and gender.

- *Timeliness.* As indicated, IOTs usually are published only 3 to 4 years after the year they are covering. In the context of constructing EXIOBASE V3, now-casting approaches have been developed that can estimate now-casted tables using the 2011 table in combination with much more frequent macroeconomic accounts such as industry sector output, sector value added, and GDP. An important problem that emerged is the availability of recent data sets on the full list of extensions. Extrapolating these based on, for example, GDP or industry sector output misses certain structural changes, such as the recent changes in China's electricity production that helped, for the first time in years, to stabilize their carbon emissions. Unfortunately, we were hence not able to solve this problem fully, but do provide harmonized monetary SUT data to 2015 based on available macroeconomic data. Updating the environmental extensions can then be done on an ad-hoc basis, such as when energy (currently 2014 from the IEA), emissions (2014 at national level), and material usage (currently 2013) become available.
- *Representing the economy in physical rather than economic units:* Another important advance reflected by the work presented in this special issue was creating the first ever GMRIO in physical terms, using the EXIOBASE structure. The paper of Merciai and Schmidt (2018) describes the approach to this innovation. In essence, they use all kinds of databases providing physical information on material flows (e.g., IEA, FAO, Eurostat production statistics, waste statistics, and physical trade data), estimated price data, in combination with the economic MRIO and physical mass balance constraints, to estimate the physical complement of the economic GMRIO EXIOBASE. This allowed further to enrich EXIOBASE with data on waste treatment.
- *Ability to focus on a range of footprint indicators:* The paper of Steinmann and colleagues (2017) discusses, using methods such as correlation analysis and principal component analysis, how a minimum set of representative indicators can be chosen from over 100 that can be calculated with EXIOBASE using impact assessment methods such as Ecoindicator 99, ReCiPe, etc. The study of Steinmann and colleagues shows that just using the pressure indicators of carbon/energy, land, water, and materials, that is, the indicators proposed in the resource-efficiency roadmap of the EC (2011), have a limited representation, explaining about 60% of the overall environmental variance. The study concludes that this set needs to be complemented by impact-oriented indicators, such as marine eco-toxicity, terrestrial eco-toxicity, photochemical oxidation, terrestrial acidification, and eutrophication. In essence, this conclusion shows that the EU resource efficiency indicators miss the trade-off with toxicity aspects, reflecting earlier concerns that volume-based, rather than impact-based, resource efficiency indicators may steer into a suboptimal direction (Van der Voet et al. 2004, 2009)
- *Ability to do both historical and forward-looking (policy) analyses:* The paper of Wood and colleagues (2018a) provides a number of illustrative (historical) analyses with this database, such as on embodied value added, greenhouse gas emissions, and resources in trade. They point to the increasing need to consider global supply chains, presenting results from the MRIO analysis showing that environmental pressures embodied in trade have risen considerably between 1995 and 2011, with, for instance, embodied material use in imports now 32% of total (from 23% in 1995), as opposed to just 20% for value added (up from 14% in 1995). The high sectoral detail of the database also allows describing the environmental profiles of relevant consumption clusters across countries in great detail. In this context, Usubiaga and colleagues (2018) calculate the environmental footprint of the European food system and estimate the potential savings attributable to meeting existing food waste reduction targets in the European Commission's (EC) Resource Efficiency Roadmap. Their analysis shows that compared to 2011 levels, halving consumer food waste would lead to 2% to 7% reductions of the total footprint depending on the environmental category. Finally, Wood and colleagues (2018b) propose a framework that demonstrates the usefulness of MRIO databases such as EXIOBASE V3 in assessing the impact of policy measures—both geospatially, and in terms of supply-chain impact. Such approaches can give quick estimates based on exploiting EXIOBASE V3 to give the potential savings and rebounds of a technical implementation of a policy measure, but by no means replace detailed studies.
- *Credibility for official statistical agencies:* Tukker and colleagues (2018) discuss how, based on knowledge of factors that create most uncertainty in footprint analyses, steps can be made toward constructing GMRIOs in a way that they become gradually more acceptable as a tool for use in official statistics. From the available evidence, it turns out that the environmental extensions, rather than the redistribution to final consumption via economic structure reflected by a specific GMRIO, forms the highest source of uncertainty. Creating a harmonized extension set is hence here the way forward. The next most important issue appears the differences in representation of the country SUT/IOT in GMRIOs, rather than the structure of the trade flows. Ensuring a maximum fit with country SUT/IOT, as happens in the earlier mentioned SNAC approach, is hence a good strategy to reduce uncertainty further. With Moran and colleagues (2018) showing that feedback emissions are low for most economies, the

simplified SNAC approach is a good and less time-consuming alternative. Finally, with the ICIO now available as the first ever GMRIO produced by a supranational agency (OECD), one could consider the following: Future versions of EXIOBASE could be built with ICIO as a constraint. This would result in the best of both worlds—it uses the most authoritative GMRIO as a basis, but also provides the required detail for environmental analyses.

Conclusions

Due to the fact that globalization processes and growth in international trade has outpaced growth in global GDP, an analysis of territorial environmental impacts by country has lost a significant part of its meaning. The environmental impacts of consumption in a country are, for a large part, created outside this country, and there is a clear need to develop accounting methods that cover this life cycle perspective of the impacts of consumption.

Various such methods have been proposed, ranging from so-called coefficient approaches that combine detailed import data on products with emission or resource extraction coefficients of such products, to GMRIO approaches. The second section of this introduction argued that GMRIO-based approaches have the best potential to provide a consistent accounting framework to analyze different footprints side by side for a large number of countries. After all, GMRIOs use emission and resource extraction data per sector and country (the territorial perspective) as a basis, and use the GMRIO concept to redistribute these emissions and resource extractions to final consumption by country and per product category. The accounting system is hence inherently consistent—the global emissions and resource extraction are identical to the calculated footprint of global consumption. Coefficient approaches, that (1) do not account for full global value chains and (2) often use LCI data to estimate, for example, resource extraction, land use, and water use, mix up different data sources and allocation principles and thus lack consistency.

There is currently just a handful of GMRIOs available, and the state of the art in GMRIO has various shortcomings. An obvious one is limited sector and country detail, which is the strength of coefficient approaches. Furthermore, GMRIOs often lack time series, have either a too limited number of environmental extensions, thus failing to cover all environmental problems, or a very high number, which leads to the question how to select or aggregate indicators.

The work presented in this special issue addresses a number of such problems and illustrates how the construction of a highly detailed GMRIO (EXIOBASE V3) could help overcome the current limitations, for example, through inclusion of a long time series in both current and constant prices, a high level of product and sector detail, as well as a physical representation of the world economy. The EXIOBASE V3 database covers 44 countries plus five RoW regions, discerns 200 products and 163 industries, has time series from 1995 to 2011, and includes 69 energy products, 222 types of resource extractions, green and blue water use, 14 types of land use, several dozens of emissions, and 14 employment categories per skill level and gender. Several illustrative case studies, ranging from footprint analyses and possibilities of how to reduce food waste, illustrate the potential of this new database. The special issue further shows that the EU dashboard of indicators proposed in its resource efficiency roadmap (carbon, water, land, and materials) is able to explain around 60% of the overall environmental variation. Combined with five other impact-oriented indicators, such as terrestrial eco-toxicity or eutrophication), 95% of the overall environmental consequences can be explained.

EXIOBASE V3 still has a drawback that it shares with almost all other GMRIOs (GTAP, WIOD, and Eora): It is constructed by a team of scientists and must, by necessity, over-ride country statistics since global trade as reported by NSIs is not balanced. Hence, acceptance of such science-led GMRIOs in the statistical community is not as good as it ideally would be. As described in more detail in the contribution of Tukker and colleagues (2018), the acceptance gap can be overcome by the following. Harmonized extensions could be created. The SNAC approach could be used. And, the OECD ICIO could be the basis for constructing new, detailed GMRIO using procedures developed in the EXIOBASE and Eora projects. But, obviously, the ideal future is one where the NSIs gathered in the UN Commission on Economic and Environmental Accounts would be provided the resources to harmonize their individual import and export statistics to a globally consistent data set, next to publishing country SUTs and IOTs in a harmonized format.

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Notes

1. Authors have however used the approach to set up physical satellite accounts measuring water and/or land use related to agricultural products (see, e.g., Ewing et al. 2012; Steen-Olsen et al. 2012; Weinzettel et al. 2013, 2014).
2. The subsections on the DTA, the price-adjusted DTA, and including bilateral trade based on national EE IO tables borrow text parts of an earlier paper of the first author (see Tukker et al. 2013a).

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