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Estimating Raw Material Equivalents on a Macro-Level: Comparison of Multi-Regional Input−Output Analysis and Hybrid LCI-IO

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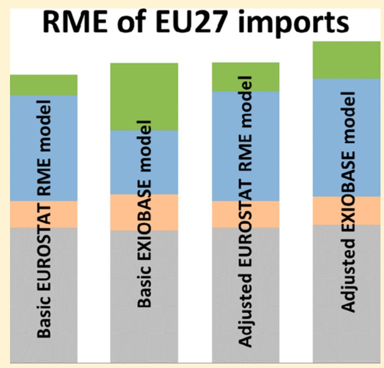
S *Supporting Information*

ABSTRACT: The mass of material consumed by a population has become a useful proxy for measuring environmental pressure. The "raw material equivalents" (RME) metric of material consumption addresses the issue of including the full supply chain (including imports) when calculating national or product level material impacts. The RME calculation suffers from data availability, however, as quantitative data on production practices along the full supply chain (in different regions) is required. Hence, the RME is currently being estimated by three main approaches: (1) assuming domestic technology in foreign economies, (2) utilizing region-specific life-cycle inventories (in a hybrid framework), and (3) utilizing multi-regional input−output (MRIO) analysis to explicitly cover all regions of the supply chain. While the first approach has been shown to give inaccurate results, this paper focuses on the benefits and costs of the latter two approaches. We analyze results from two key (MRIO and hybrid) projects modeling raw material equivalents, adjusting the models in a stepwise manner in order to quantify the effects of individual conceptual elements. We attempt to isolate the MRIO gap, which denotes the quantitative impact of calculating the RME of imports by an MRIO approach instead of the hybrid model, focusing on the RME of EU external trade imports. While, the models give quantitatively similar results, differences become more pronounced when tracking more detailed material flows. We assess the advantages and disadvantages of the two approaches and look forward to ways to further harmonize data and approaches.



INTRODUCTION

On the basis of the Thematic Strategy on the Sustainable Use of Natural Resources and the sixth Environmental Action Programme, the European Union Commission decided to provide policy makers and other stakeholders with a framework of information about the use of resources and products. In order to meet data requirements of that resource policy, EUROSTAT has developed an environmentally extended input−output (IO) model for converting product flows, including import and export flows, into raw material equivalents (RME). In parallel, a number of multi-regional IO (MRIO) models have been developed by different institutions that can also serve the purpose of estimating the RME. The purpose of this paper is to compare the EUROSTAT model with the MRIO approach in order to assess the quality of both approaches with respect to policy application.

IO methods have been widely used for assessing the use of resources (e.g., land, raw materials, or water) and the generation of pollution (e.g., greenhouse gases) in relation to consumption and trade activities. In the case of raw materials, there are three main IO approaches for the calculation of the RME: (a) an approach working with the "domestic technology assumption" (DTA), (b) a hybrid life-cycle inventory IO (LCI-IO), and (c) an approach that applies a MRIO table.[1]

Models based on the DTA are used when the data availability is restricted to the IO tables of the country analyzed, and as a consequence, there is no information on the technology used for producing the goods in other countries, which is necessary for calculating the RME of imported goods. In such a case, it is assumed that imported products are manufactured with the identical technology as it is used for manufacturing of the same product category in the domestic economy (i.e., the DTA) (see Muñoz et al.[2]) This method was proved to be inappropriate for estimating the RME of international trade by Weinzettel and Kovanda,[3] who applied a hybrid LCI-IO method for estimating the RME.[3,4]

The hybrid LCI-IO method is represented by the EUROSTAT model applied by Schoer et al.,[5] which is based on the DTA but applies additional multi-regional information from

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Table 1. Conceptual and Data-Related Differences between the EXIOBASE and EUROSTAT Approaches

no.	description	EXIOBASE v1 model[10]	EUROSTAT model[5]
1	regional disaggregation of the IOT model	multi-regional model (44 regions)	DTA model amended by external multi-regional regional information
2	sectoral disaggregation of the IOT model	129 product groups	166 product groups (with specific focus on raw material flows)
3	hybridization of IOT	full monetary IOT	Hybrid IOT (mixed physical and monetary sales structures)
4	classification for DEU	EXIOBASE classification (48 raw material categories), linked to SERI classification.	Expanded EUROSTAT EW-MFA classification (52 raw material categories)
5	data IOT matrix	based on individual country SUTs	based on official EUROSTAT 60 × 60 IOT
6	data domestic extraction used (DEU)	SERI database, nonrevised	EUROSTAT EW-MFA database
7	external trade data	multi-regional trade matrix based on UN trade data but adapted/reconciled	based on official EUROSTAT 60 × 60 IOT, disaggregation by COMEXT

life-cycle inventories for imported products without appropriate domestic representation.

In contrast to DTA models, MRIO models allow a detailed assessment of the RME of countries by taking into account the different production technologies across regions. These models cover a set of countries or regions—with their own IO structures—interlinked via trade flows. The MRIO approach was applied for example by Arto et al.[6] using the WIOD database, Bruckner et al. [7] using the OECD database, and Moran et al. [8]and Wiedmann et al. [9] using the EORA database. However, in this comparison, the MRIO approach is represented by the MRIO model developed in EXIOPOL (hereafter "EXIOBASE" version 1 is used,[10] referring to the environmentally extended MRIO part of EXIOPOL) due to a more detailed sector resolution, especially for material extraction and first processing.

The objective of this paper is to compare the hybrid LCI-IO and the MRIO and more specifically the EUROSTAT model and the EXIOBASE model. These two representations have been chosen because they seem to be well suited for estimating the RME of international trade due to the high level of detail of relevant sectors and materials. The conceptual and quantitative differences between both models are analyzed and suggestions for improving both models are put forward.

The advantage of the EXIOBASE/MRIO-type model is an application of country of origin production technology on all imported products, while the EUROSTAT model (developed specifically for the EU-27) assumes that the imported products (except for imported products denoted as LCI products) are manufactured with the production technology of the country of destination, particularly in this case EU-27. The LCI products (mainly metal ores and basic metals) are assumed to be produced by technology derived from the so-called metal model, which refers to a large number of individual mine reports and to life-cycle inventories. The EUROSTAT model was especially designed for estimating the RME for EU-27 imports and final demand. Therefore, it is more specific regarding sectors of material extraction and primary processing and applies physical units on selected product flows. It has advantages in terms of resource requirement, data quality, and flexibility. As less data is needed, the data is derived from reliable sources, and the model can be more easily adjusted according to the to the specified scope.

There are number of reasons why simple DTA provides inaccurate results and underestimates or overestimates the RME of international trade; for example, the composition of products within one product group, as well as the price of products, production technology (due to different geographical, climate, and economic conditions), or the imported product is simply not produced within the domestic economy.[5]

Compared to a multi-regional approach, the standard DTA approach with monetary sales structures has the principal shortcoming that differences in raw material intensities between domestic and imported products and differences in prices for domestic and imported products are not taken into account.[11−14] The monetary MRIO model has the shortcoming of assuming the same price of products for domestic consumption and international trade (a general assumption of monetary input−output analysis that one price is valid for all users).

Much work has been done on analyzing the differences between results generated by the DTA compared to a MRIO (for examples, see refs 11, 15−17). These papers (generally focusing on greenhouse gases) make it clear that the DTA needs refining in order to give accurate results but also find that a proxy (such as price adjustments) for an MRIO can suffice.[12]

We seek to develop this direction further. In order to quantify the effects of individual conceptual elements, we adjust the models in a stepwise approach with an aim to improve the EUROSTAT model by taking more multi-regional features on board by a simplified and manageable approach. This comparison is focused on the RME of EU external trade imports because the EUROSTAT model was developed for the EU as one region, and the main conceptual differences between the two approaches predominantly have an impact on the estimates of the RME of imports.

In the first step, we isolate the MRIO gap, which denotes the quantitative impact of calculating the RME of imports by the EXIOBASE-based MRIO approach instead of the specific DTA approach of the EUROSTAT model. For quantifying the influence of applying a MRIO model, all other conceptual differences and differences regarding auxiliary data have to be removed as much as possible. Therefore, the EXIOBASE model was widely adjusted to the conceptual and data framework of the EUROSTAT approach.

The following comparison refers to the year 2000 as the reference year of EXIOBASE and to EU27, for which the EUROSTAT model was developed.

■ ALTERNATE MODEL SPECIFICATIONS

Conceptual and Data-Related Differences between the EXIOBASE and EUROSTAT Approaches. The model formulations EU-1, EU-2, EX-1, EX-2, EX-3, and EX-4 in the following sections attempt to isolate and quantify the difference between the MRIO approach and the modified DTA approach by adjusting for all other conceptual and data-related differences that are listed in the Table 1. Focus is put on comparing the RME of imports for total EU-27. As EU-27 is referred to as one region, the trade flows within EU are regarded as internal flows, and imports and exports in this paper reflect only the trade flows between EU and the rest of the world (external trade).

For more details regarding the two data sets, please see the referenced documents.[5,10] A list of EUROSTAT model product groups is available in the Supporting Information.

The technical differences in the approaches for calculating the RME (Table 1) are explained below.

In the rest of this paper, we seek to compare the data quality of several model variants ranging from a modified DTA through to a full MRIO. We start from the basis of the EUROSTAT model for RME, which in essence is a DTA modified to give realistic approximations for the production technology of imports. We explore six options for creating hybrid RME models as described below.

Option EU-1: Basic EUROSTAT (Hybrid LCI-IO) Approach. In the published EUROSTAT basic model,[5] an attempt was made to compensate for some major deficiencies in the DTA in comparison to a full multi-regional approach as represented by the EXIOBASE model. The results on the RME, which are published by EUROSTAT, are generated with a hybrid LCI-IO model based on the DTA. That model goes beyond a standard DTA by using a hybrid LCI-IO based on a hybrid unit product by product IOT matrix and includes a sectoral disaggregation of 166 product groups (HIOT166), estimated by disaggregating the official EUROSTAT monetary IOT, which has the format of 60 × 60 product groups (MIOT60) by utilizing a set of structural information (for more a detailed description, see ref 18). The specific model of option EU-1 differs from the standard monetary IOT 60 × 60 with DTA, based on official statistical data by the following features.

Disaggregation of the IOT matrix to the format 166 × 166 product groups: The principal idea was to improve the tracking of the 52 raw material categories by establishing a product group for extraction of almost each of the raw material categories and to depict the first processing of raw materials in a disaggregated manner.

Hybrid unit IOT: The monetary IOT is converted into a hybrid IOT (HIOT166) with physical sales structures for 70 product groups. Physical sales structures are applied for all raw materials, basic metals, and energy carriers. Physical sales structures for those selected product groups are considered to be superior to monetary relationships for depicting the flow of raw materials.

Hybrid LCI-IO: Instead of pure DTA, for selected product groups, (metals ores and basic metals, oil and gas) external information is applied for estimating the RME of imports. Those estimates are based on the so-called EUROSTAT "metal model",[18] which is combined with further information from LCI. The metal model is based on multi-regional information. It is considered that the external information is able to provide more accurate results in the case of the selected product groups compared to those of the DTA.

The calculation for the hybrid LCI-IO is based on regionalized information on the imports of oil, gas, metal ores, basic metal ("metal model"), and energy carriers. The so-called metal model uses regionalized information on ore grades for metals (gross ore per metal content). The flows of all other raw products (biomass, nonmetallic minerals) are expressed in the model in physical units. All together, 70 out of 166 sales structures are expressed in physical units. It can be considered that the physical product flows are closely related to the embodied raw materials in the case of those products. The effect of differences in prices for domestic compared to imported products on the RME estimates with monetary relationships can be neutralized by applying physical sales structures.

The RME of imported oil, gas, metal ores, and basic metals alone are accounting for nearly 60% of all RME of imports. For the purpose of the EUROSTAT model, the domestic extraction used (DEU) is broken down by 52 material categories (expanded EW-MFA classification).

Re-exports are taken out of the version of the EUROSTAT model, which is presented in this paper. It is considered that including re-exports would not add any useful information for analyzing RME flows as the same material impact is embodied in both imports and exports, giving no net effect on the raw material consumption (RMC). Re-exports account for roughly 100 million tons (1 ton = 10^6 grams) of RME, which amounts to about 3% of the total RME of imports (3100 million tons) and 1% of the total RMC.

Imports at basic prices of country of destination: Compared to the current published version of the EUROSTAT calculation model, the model that is presented in this paper was amended by converting the monetary parts of the import vector of the IOT matrix from the CIF concept to FOB concept at basic prices. According to the standard IOT, the value of exports is measured at the customs border of the country of origin at basic prices. That is, the trade and transport costs that accrue between the place of production and the customs border are excluded from the value of the exported product. In turn, those costs are regarded as exports by a separate service flow. Compared to that, the value of the imports is measured at the customs border of the country of destination. That is, the value of the imports includes the trade and transport margin within the country of origin as well as the costs for the transports of the goods between the country of origin and the country of destination.

If physical relationships are used for the RME calculation, that conceptual difference is not relevant for goods. But if the RME of imports are estimated by a DTA approach by applying monetary values, the imports have to be conceptually adjusted to the demarcation of the exports (or domestic products). That is, trade and transport costs within the country of origin and the cost for international transports have to be deducted from the value at the customs border of the country of destination. On the other hand, those costs have to be added to the imports of trade and transport services as a counter entry. It has to be noted that also in the case of applying physical sales structures that the counter entry still has to be regarded.

For estimating those costs, a "trade and transport model" was developed by using among others regionalized information of transport distances, quantities, and average freight rates.

Option EX-1: Basic EXIOBASE Approach. The **basic version** of the EXIOBASE model is a multi-regional world input−output model with the following features: a monetary product by product IOT matrix with a regional disaggregation by 44 countries/regions (17 countries regions outside EU-27) and a sectoral disaggregation by 129 product groups.

The data for domestic extraction used (DEU) are taken from SERI database.[19] The classification for DEU represents a breakdown by 48 raw material categories (EXIOBASE classification).

Compared to earlier versions of the EXIOBASE basic approach some changes were introduced: (1) The product by product IOT was utilized alongside the EXIOBASE industry classification of material extraction. While materials were reported by industry in EXIOBASE, the data actually referred to the principal product of that industry and ignored coproduction. (2) Assignment of "other construction materials" to the construction branch, i.e., it was assumed that "other construction materials" are directly extracted by the construction industry rather than a generic mining industry. (3) Correction of data for uranium (especially for the rest of world countries). Both monetary and physical estimates of Uranium in EXIOBASE mismatched official statistics. Further, the monetary sales structure of uranium is poorly represented in IO tables because of the structure of the industry and confidentiality of information.

Option EX-2: 3-Region EXIOBASE Approach. As explained above, in the following calculation steps, the EXIOBASE model will be adjusted to the conceptual and data-related framework of the EUROSTAT model. However, that effort could only be kept manageable by reducing the regional resolution of the EXIOBASE model. Therefore, option EX-2 represents a regionally aggregated version of the EXIOBASE basic model. The 44 region MRIO data set of option EX-1 was aggregated into a 3-region data set, distinguishing EU-27 as one region; major non-European OECD countries, Australia, Canada, Japan, South Korea, Mexico, Turkey, and the United States into one region; and a rest of the world region comprised of all other countries.

For the purpose of this article, option EX-2 is used as the reference approach for determining the so-called MRIO gap for two reasons. Beside the manageability problem of applying the below adjustment procedure to option EX-1, it also had to be regarded that the interpretation of the quantitative difference between options EX-1 and EX-2 is not straightforward and needs further investigation (see the Results section).

Option EX-3: Conceptual and Data-Related Adjustment of the EXIOBASE Model. While the MRIO model represented by EXIOBASE includes quite some detail on material categories and products, it still lacks the full detail of the EUROSTAT model at the material and product level. Option EX-3, hence, includes greater detail than the EXIOBASE model on certain products, coming at the expense of the regional disaggregation; modifications here are only done at the 3-region level of EX-2. The following conceptual and data-related adjustments are included compared to option EX-2. (1) **Sectoral disaggregation**: Conversion of the EXIOBASE sectoral disaggregation (129 product groups) into the EUROSTAT sectoral disaggregation (166 product groups). (2) **DEU classification**: Replacement of EXIOBASE classification (48 raw material categories) for domestic extraction used by expanding the EW-MFA classification (52 raw material categories). (3) **Data IOT matrix**: Correction of implausible sales structures for agriculture ("Cultivation of crops n.e.c."), forestry, metals, sand and stone, and adjustment of data on output of gold. (4) **Data for DEU**: Introduction of revised SERI data for DEU (as of October 2012) and replacement of SERI DEU data for EU-27 by EW-MFA data and fossil energy carriers (based on IEA energy balance). (5) **Hybridization of the IOT matrix**: Application of physical sales structures for most products groups that are represented in physical units within the EUROSTAT model.

All these adjustments except for regional aggregation should in principal improve the results of the EXIOBASE model in comparison to version EX-1. The above adjustments are explained in detail in the Supporting Information.

Option EX-4: Adjustment for Differences in External Trade Data. Adjustment for differences in external trade data between the EXIOBASE and the EUROSTAT model was conducted in a separate adjustment step due to the specific interpretation problems that are related to that step.

The underlying external trade data on imports to EU and exports from EU differ considerably between the calculation models under consideration. The figures for the EU IOT are derived from COMEXT by applying some conceptual adjustments. The corresponding data for the EXIOBASE represent a coherent multi-regional matrix for trade flows between the individual countries. That model builds widely on national data.

However, as far as the trade flows with the EU are concerned, there are considerable differences that are most distinctive for import flows (for details, see the Supporting Information). In order to neutralize the effect of different external trade data, the EXIOBASE model was adjusted to the import and export vectors of the EUROSTAT model.

The harmonization was achieved by the following approach. Those sections of the EXIOBASE IOT matrix that refer to imports to EU and exports from EU are adjusted to the import and export values of the EUROSTAT model.

After the described adjustments option, EX-4 represents a version of the 3-region EXIOBASE model that is widely harmonized with the EUROSTAT model of option EU-1, with the exception of the multi-regional feature. Therefore, it can in principle be considered that the quantitative differences between the results of both approaches might roughly indicate the impact of using a 3-region model in comparison to the modified DTA approach of the EUROSTAT model ("MRIO gap").

Option EU-2: Integration of Further Multi-Regional Information to the EUROSTAT Model. The observed order of magnitude of the "MRIO gap" (see the Results section) indicates that option EU-1 is not capable of covering the multi-regional effect in a sufficient manner.

The objective of option EU-2 is therefore to integrate further multi-regional information into the EUROSTAT model beyond those elements that are already regarded by option EU-1.

The following issues were considered for improving the current EUROSTAT model: (a) price differences between imported and domestic products, (b) fodder intensity of animal production, and (c) recycling ratios for metals.

For more details on these issues, see the Supporting Information.

RESULTS

The aggregated calculation results are presented in Table 2, and the results for RME of EU-27 imports are highlighted in Figure 1. Generally, for any of the options under review, the results for the RME of total imports, total exports, and raw material consumption (RMC) are in a rather similar order of magnitude. However, the table shows that rather distinct differences can be observed at the level of aggregated raw material categories of imports, especially for biomass and metal ores.

The total RME of imports for external trade to the EU-27 amounted to 3100 million tons in the year 2000 according to the EU basic model (option EU-1). The RME of imports are almost double as high as the RME of total exports (1559

Table 2. Comparison of Options for Estimating RME of the EU-27 in 2000 (million metric tons)

			RME of imports								
				raw material categories				stage of production			
option	description	DEU	total	biomass	metal ores	nonmetallic minerals	fossil energy carriers	raw products	finished and semi-finished products	RME of exports	RMC
EU-1	EUROSTAT model: HIOT166 (71 physical/95 monetary), DTA with additional multi-regional information on imported oil, gas, and metals	6 544	3 100	219	1 139	284	1 457	1 481	1 619	1 559	8 085
EU-2	EUROSTAT model: HIOT166 (117 physical/49 monetary), DTA with additional multi-regional information on imported oil, gas, metals, fodder crop intensities, and metal recycling ratios	6 544	3 228	305	1 181	284	1 457	1 493	1 735	1 581	8 191
EX-1	EXIOBASE model: 44-R-MIOT129, basic approach	6 279	3 224	721	681	395	1 427	NA	NA	1 499	8 004
EX-2	EXIOBASE model: 3-R-MIOT129	6 279	3 003	616	766	336	1 284	NA	NA	1 458	7 824
EX-3	EXIOBASE model: 3-R-HIOT166, conceptual and data related adjustments to EUROSTAT model excl. adjustment to imports and exports of the EUROSTAT model	6 544	3 241	386	1 192	256	1 406	1 676	1 565	1 571	8 214
EX-4	EXIOBASE model: 3-R-HIOT166, conceptual and data related adjustments to EUROSTAT model include adjustment to imports and exports of the EUROSTAT model	6 544	3 458	398	1 270	302	1 487	1 492	1 965	1 691	8 311

million tons). In comparison, the results for total RME of imports as estimated by the EXIOBASE basic model (option EX-1, 44-region model) are with 3224 million tons RME of imports and 1499 million tons RME of exports, differing little in aggregate from the results of the EUROSTAT basic model (+124−60 million tons). The discrepancy is much more pronounced for individual aggregated raw material categories, especially for biomass (+502 million tons) and metal ores (−458 million tons).

The total RME of imports decrease by 221 million tons (−7%) as an effect of reducing the regional disaggregation from 44 to three regions in Option EX-2. The interpretation of the quantitative effect of regional aggregation needs further investigation. Theoretically, increasing regional disaggregation should improve the accuracy of the calculation results. But in practice, the quality of the underlying data has to be considered (regarding data quality of the MRIO model, see discussion in the Supporting Information on adjusting EXIOBASE data). In cases where the data quality of highly regionalized model is impaired, aggregation of data may have the effect of compensating errors (a compensation for similar types of errors is discussed by Peters and Solli[20]). It has to be a concern that the above quantitative differences between both models are not purely reflecting the aggregation error as problems of data availability and data quality tend to increase with the level of regional disaggregation. It is not possible to analyze the true MRIO gap due to data availability and quality. Even the 44-regional model of EXIOBASE contains an aggregation of regions because it includes one single region for rest of the world, representing nearly 200 individual countries. However, we still think that it is possible to analyze at least part of the MRIO gap on a regionally more aggregated level.

Option EX-3 represents a number of conceptual and data-related adjustments toward the EUROSTAT model. A considerable combined impact of those adjustments can be stated. The total RME of imports for option EX-3 amounts to 3241 million tons (+238 million tons, + 8%) in comparison with EX-2. But the major effect of the adjustments by option EX-3 refers to the structure of aggregated raw material categories with a decrease by 230 million tons (−37%) for biomass and 81 million tons (−24%) for nonmetallic minerals and an increase in +427 million tons for metal ores (+63%) and +122 million tons (+10) for fossil energy resources. The observed changes at the level of adjusted raw material categories are significantly influenced by correcting implausible sales structures, disaggregating agricultural production, and hybridization of the IOT matrix. Disaggregation of agricultural productions refers predominantly to showing grazed biomass (nearly 40% of total biomass extraction) separately, whereas in the EXIOBASE classification, it was lumped together with other crops. The quantitative effects of the other adjustment are comparatively low.

In comparison to the EUROSTAT basic model (option EU-1), the total RME of imports of option EX-3 are 141 million tons (+5%) higher.

Option EX-4 differs from option EX-3 by applying the import and export figures of the EUROSTAT model. The RME of the total imports are increased by 217 million tons (+7%) to 3458 million tons for option EX-4 in comparison to option EX-3. The differences are rather pronounced if the results for total raw products (−184 million tons, −11%) and total finished and semi-finished products (+400 million tons, +25%) are concerned.

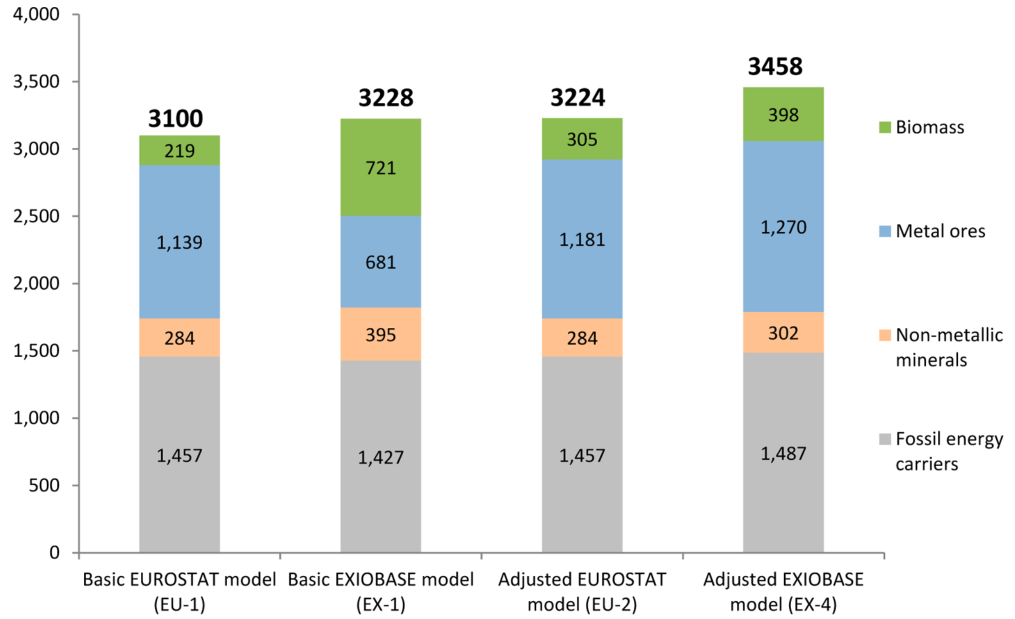

Figure 1. Comparison results, RME of EU27 imports, external trade, 2000: Comparison of the EUROSTAT and EXIOBASE models (million metric tons).

In comparison to the EUROSTAT basic model (option EU-1), the total RME of imports of option EX-4 are 358 million tons (+12%) higher. That difference could be taken as a rough indicator of the "MRIO gap" The differences for biomass account for +179 million tons (+82%). The contribution of metal ores amounts to +132 million tons (+12%). Nonmetallic minerals contribute 18 million tons (+6%), and fossil energy carriers contribute 30 million tons (+2%).

However, it has to be considered that the adjustment of import and exports figures may have given rise to some inconsistencies for the EXIOBASE model, as at the same time the corresponding output figures remain unchanged. For a given DEU, the RME of imports to EU for a product group are widely determined by the relationship between the imports to EU and the output in the country of origin. If the figures on imports are increased by the adjustment, as it was the case for most product groups, the RME of imports are growing accordingly.

Using external trade figures from the EUROSTAT model could disturb the internal consistency of sales structures, and in fact, after adjustment, dramatic increases of the import shares can be observed for many product groups, especially for the rest of world region. For example, the average share of total imported chemical products for rest of world region goes up from 4% to 10%. For the metal working industry, an average increase from 3% to 19% can be observed. As the magnitude of those changes most likely cannot be regarded as plausible, the calculation results of option EX-4 may overstate the RME of imports of EU.

That is, the calculation results for option EX-4 can at best be interpreted as an upper limit of possible realistic results but not as a rather exact value, which can be applied for precisely determining the "MRIO gap". It can still be concluded that there is a significant MRIO gap, but that gap can be considered to be roughly within the range of about 150 million tons (difference between option EU-1 and EX-2) to 350 million tons (difference between option EU-1 to EX-3).

The objective of option EU-2 is to try to bridge the "MRIO gap" by integrating further multi-regional information into the EUROSTAT model beyond those elements that have already been regarded by option EU-1.

The combined effect of introducing a set of additional multi-regional information into the EUROSTAT model by option EU-2 can be described as follows.

The total RME of imports is increased by 128 million tons (+4%); therefore, the results for raw products remain unchanged. At the level of aggregated raw material categories the following increments can be observed. (1) The results for **biomass** show an increase of 86 million tons due to taking into account the differences in fodder intensities. (2) The results for **metal ores** increased by 42 million tons as an effect of regarding differences in recycling ratios (3) The results for **nonmetallic minerals** and **fossil energy carriers** remain unchanged, as no correction factors were applied to those material categories

The match of the results of the EUROSTAT model (option EU-2) and the EXIOBASE model (option EX-4) was improved considerably by regarding the additional multi-regional information. But those adjustments are probably not sufficient for fully bridging the MRIO gap. The result for total RME of imports for option EU-2 is quite close to the result for EX-3, but if compared to EX-4, there still remains a considerable gap of more than 200 million tons.

Further, it has to be considered that within the EXIOBASE model, by shifting from the 44-region model to the 3-region model that was used for this comparison, the total RME of imports decreased by more than 200 million tons. It is not known whether a comparison between and adjusted 44-region model and an adjusted 3-region model would show a similar order of magnitude. However, as explained above, investigating that interesting issue was out of scope of this paper due to resource restrictions

For assessing the observed differences between options EU-2 and EX-4, it has to be considered that the above calculations are based on models. The results of each model are more or less influenced by underlying inaccuracies of auxiliary data and modeling assumptions. Therefore, the above comparison can only give a rough indication of whether the results of the models are fitting together, that is, the observed absolute differences between options EU-2 and EX-3 and EX-4 should not be overrated.

DISCUSSION AND NEXT STEPS

Comparison of Results. An exact quantification of the MRIO gap has turned out not to be possible because of the lack of real references in an EXIOBASE-type model. But it can still be stated that there are significant differences between the results of a model based on domestic technology assumptions represented by the EUROSTAT basic model (option EU-1) and the adjusted EXIOBASE MRIO model. That MRIO gap can be considered to be roughly within the range of about 150 million tons to 350 million tons or roughly 5−10% of RME of imports and less than 5% of RMC.

It was shown that an improved version of the EUROSTAT model (option EU-2) is able to reduce the MRIO gap significantly by about 130 million tons. The remaining MRIO gap should be in the range of 0 million tons to about 200 million tons. That difference can be viewed as being rather moderate. However, further investigation and refinement of the improved EUROSTAT model should be considered, for example, by investigating the effect of a more differentiated regional disaggregation.

In general, the models give qualitatively similar results, even with the quantitative differences. Differences of course are less pronounced in aggregate and more pronounced when looking at relative differences of more detailed material flows.

Comparison of Data Requirement and Data Quality. The data requirement of the EUROSTAT calculation model is widely limited to data from the harmonized European Statistical system that represents a high quality data standard. An exception is the data for estimating the RME of imports of metal ores (see "metal model").[18] As far as option EU-2 is concerned, a limited amount of additional auxiliary data is taken from some centralized statistical sources as FAO and the U.S. Geological Survey in order to cope with further multi-regional effects.

Compared to that, the multi-regional EXIOBASE approach is necessarily based on national data from a vast number of countries, which are only harmonized to a limited extent with respect to concepts, classifications, and quality, as well as completeness of data.

While most focus has been on DTA versus MRIO approaches in the literature and the creation of simple DTA refinements, it is clear that a hybrid (regional) approach offers a significant advantage compared to a DTA, if high data quality can be assured.

Comparison of Resource Requirement. However, it is not only an issue of data quality. It has also to be noted that while updating the respective models in terms of establishing time series and coping for classification and other conceptual changes in the auxiliary data is important, the EXIOBASE model is much more resource consuming and less flexible than the EUROSTAT model. On the other hand, the EUROSTAT model is designed as a highly specialized approach for estimating the RME for the total EU and probably individual EU countries. Compared to that, a MRIO model allows for tracing the actual regional sources of environmental impacts (for example, if impacts occurred in China or Brazil) and can be used to calculate the RME for all regions described in the model. Furthermore, EXIOBASE was designed to calculate indicators across a broader range of environmental (or other) impacts than just material flows.

Next Steps. More experience and a longer time frame of working with the EXIOBASE data system may lead to an improvement of data quality. However, in the mean time, while calculating the RME for the EU, the EUROSTAT model tends to have advantages in terms of quantity and quality of auxiliary data and of resource requirements for running the system.

Therefore, the following suggestions are made. (1) Improve the currently existing EUROSTAT model by integrating more well-founded multi-regional information. The elements that were introduced by option EU-2 should be taken as a starting point. (2) Improve the data quality of the EXIOBASE model (for example, inclusion of latest material flow data sets; improvement of allocation to economic sectors, see steps in EX-1). (3) Further refine/detail product use and, in particular, sales structures of the EXIOBASE model for key products in the material supply chain, as per EX-3.

Already, the EXIOBASE model is being updated to a second version in the EU FP7 CREEA project, and the update will take into account the results found in this work. CREEA is focused on operationalizing the use and modeling of the System of Environmental and Economic Accounts and provides a framework for linking the type of analysis demonstrated here with statistical institutes and data.

Policy Application. A serious concern for policy application of the calculation of raw material equivalents and, more generally, other consumption-based metrics of environmental impact (such as global warming) is the uncertainty of results across a range of data and methodological approaches. While we show that there are quantifiable differences across two state of the art approaches, at the aggregate level, these differences are manageable and are in the expected range of uncertainty of the results. Furthermore, the implications of the results (direction and general magnitude) for policy formation are consistent across the approaches.

ASSOCIATED CONTENT

Supporting Information

PDF file: Further details on the conceptual and data-related adjustment of the EXIOBASE model, integration of further multi-regional information to the EUROSTAT model, comparison of import data from different sources, and basic methodology. Excel file: Detailed results and the Eurostat model product groups. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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