EXIOBASE 3

Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables

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Summary

Environmentally extended multiregional input-output (EE MRIO) tables have emerged as a key framework to provide a comprehensive description of the global economy and analyze its effects on the environment. Of the available EE MRIO databases, EXIOBASE stands out as a database compatible with the System of Environmental-Economic Accounting (SEEA) with a high sectorial detail matched with multiple social and environmental satellite accounts. In this paper, we present the latest developments realized with EXIOBASE 3—a time series of EE MRIO tables ranging from 1995 to 2011 for 44 countries (28 EU member plus 16 major economies) and five rest of the world regions. EXIOBASE 3 builds upon the previous versions of EXIOBASE by using rectangular supply-use tables (SUTs) in a 163 industry by 200 products classification as the main building blocks. In order to capture structural changes, economic developments, as reported by national statistical agencies, were imposed on the available, disaggregated SUTs from EXIOBASE 2. These initial estimates were further refined by incorporating detailed data on energy, agricultural production, resource extraction, and bilateral trade. EXIOBASE 3 inherits the high level of environmental stressor detail from its precursor, with further improvement in the level of detail for resource extraction. To account for the expansion of the European Union (EU), EXIOBASE 3 was developed with the full EU28 country set (including the new member state Croatia). EXIOBASE 3 provides a unique tool for analyzing the dynamics of environmental pressures of economic activities over time.

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Introduction

To enable the decoupling of the socioeconomic metabolism from its current levels of environmental impacts, in-depth insights on how and where resources are used and emissions are discharged are required as a basis for the design of effective policy strategies. To that end, countries have commonly monitored domestic environmental pressures arising from production and consumption processes within their own territory. In the past 15 years, however, liberalization of international trade, economic specialization, and the increasing importance of emerging economies led to a reorganization of supply chains at the global level. As a consequence, consumption in one country causes environmental impacts in multiple other countries in multifaced ways rendering territorial resource extraction and emissions monitoring insufficient for the evaluation of environmental impacts driven by final consumption (Davis et al. 2011; Ivanova et al. 2016; Tukker et al. 2016; Verones et al. 2017). Hence, there is a need for environmental accounting systems which enable the analysis of interrelations between global production and consumption processes.

Environmentally extended multi-regional input-output (EE MRIO) tables contain data that describe the complex net of global economic relationships and their environmental consequences. Presenting economic and environmental data in an EE MRIO format is consistent with the recommended accounting systems proposed by the United Nations (UN) System of Environmental-Economic Accounting (SEEA) (European Commission et al. 2012), allowing for international comparisons across countries and regions. Up until 2010, a number of EE MRIO databases were already available, but they all had significant drawbacks for environmental analysis: The IDE-JETRO (Meng et al. 2012) database goes back to the 1970s, but covers mainly Asian countries and is hence not suitable for global, MRIO-based, assessments. The Global Trade Analysis Project (GTAP) (Narayanan and Walmsley 2008) provides a database of harmonized input-output (I-O) tables (IOTs) and trade data which can be used to construct MRIO tables (Peters et al. 2011). While providing a very good country coverage, the GTAP-based MRIO consist of only 57 sectors, which hampers adequate assessments of, for example, material footprints. A similar drawback of limited sector detail exists for Organization for Economic Cooperation and Development (OECD) Inter-Country Input-Output Database (ICIO) (Wiebe and Yamano 2016) and the related Global Resource Accounting Model (GRAM) global EE MRIO model (Wiebe et al. 2012). None of these databases currently have consistent time series on a yearly basis.

To overcome these drawbacks, from around 2010 onward, new EE MRIO databases have been set up (for a full review on databases and methodology, we refer to Tukker and Dietzenbacher [2013]; Inomata and Owen [2014]). The World Input-Output Database (WIOD) project (Timmer et al. 2012) developed the first global database with long time series (1995–2009) in both constant and current prices, but still has a limited sector detail (35), making it mainly suitable for economic assessments (e.g., trade in value added, labor embodied in trade). The Eora database was the first project that used all available country supply-use tables (SUTs) and IOTs in its original form, using a sophisticated and fully automated procedure to calculate highly detailed global MRIO tables discerning around 180 countries with time series in current prices from 1970 to 2013 (Lenzen et al. 2012). Eora has a highly variable sector detail (ranging from 26 to over 400 sectors) which impedes cross-country comparisons for specific sectors.

The objective of EXIOBASE (developed within the European Union [EU] projects EXIOPOL, CREEA, and DESIRE) is to provide a global EE MRIO database with high suitability for environmental analysis. Starting from the initial version, EXIOBASE aimed to be suitable for answering sustainability questions of the EU and its main trading partners as well as for major global economies. This determines the country coverage of the database, which accounts for about 90% of global gross domestic product (GDP) (Stadler et al. 2014). The design decision for the level of sector detail was based on assumptions on the required sector detail for assessments related to material, water, and land use as well as on best available data for all countries to be included. The latter was required in order to allow sector-based cross-country comparison for environmental issues. As a consequence, EXIOBASE provides a high and consistent level of sector detail for the economic activities that create high, but diverging, environmental pressures, such as agriculture, mining, and energy extraction (Tukker et al. 2009, 2013; Wood et al. 2014). This allows, for instance, discerning the environmental pressures related to a meat-rich diet and a vegetarian diet (Tukker et al. 2011).

Compared to EXIOBASE 1, the second version of EXIOBASE included a further expansion of sectorial detail, a more recent base year (from 2000 to 2007) and experimented for the first time with adding physical layers behind economic flow data in the global EE MRIO database. The domestic building blocks became rectangular SUTs, mainly to keep energy product detail while not having an artificial split of a single industry producing multiple outputs (e.g., a refinery). In addition, multiple waste processing sectors were added to the database. In terms of country coverage, the single rest of the world region of EXIOBASE 1 was split into five regions to provide a better representation of global resource extraction (Wood et al. 2015). Version 3 of EXIOBASE (developed within the EU FP7 project DESIRE) builds upon the previous EXIOBASE version with a focus on extending the time resolution to yearly MRIO tables ranging from 1995 to 2011. The sector classification follows the setup provided by EXIOBASE 2. In terms of countries, the focus remains on the EU and major economies, but with the inclusion of the new EU member state Croatia. Based on an emerging interest for coupling environmental and social sustainability analysis (Simas et al. 2014, 2015) EXIOBASE now also includes an extended set of social extensions related to gender and vulnerability aspects of labor.

This paper describes the compilation process of EXIOBASE 3, from the preparation of data sources to the final MRIO tables and their analysis (for first results based on the analysis

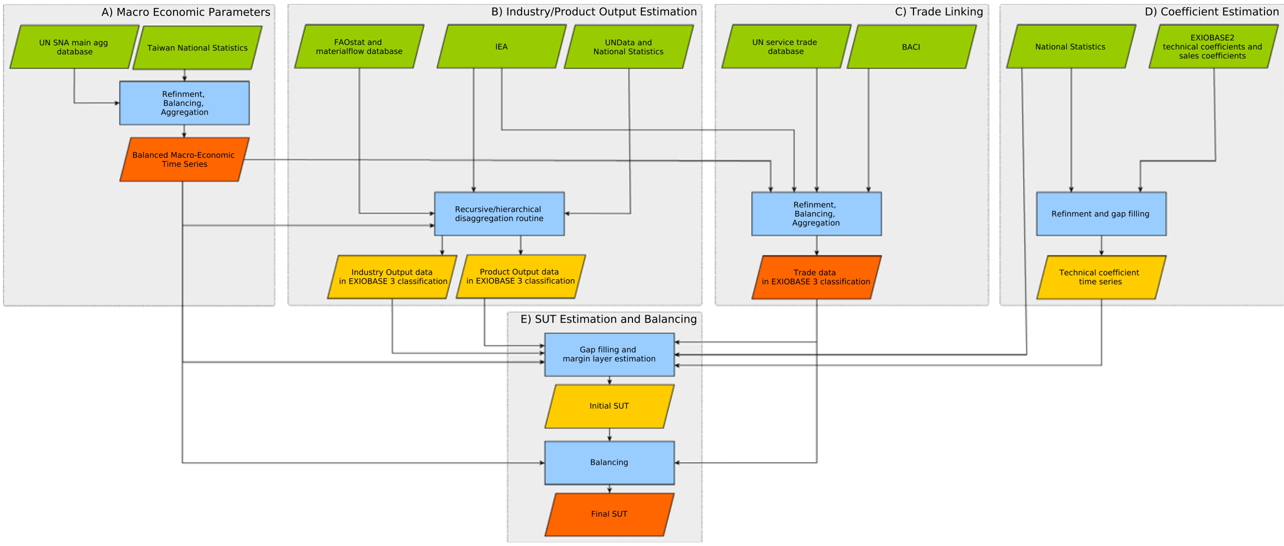

Figure 1 Compilation steps for monetary supply use tables (MSUT). Green: raw data; orange: processed data, which can change in subsequent processing/balancing steps; red: processed data, which is fixed and serves as constraint in subsequent balancing steps; blue: processing routines and algorithms. Points A to D are prerequisites for building the supply use tables (SUT) and could partially be calculated in parallel. Data output of steps A to D are time-series data for specific parameter domains. The SUT Estimation and Balancing (E) uses the output of the previous steps and calculates balanced SUT for each country and year of the time series separately. The final SUT are subsequently used for building the MSUT system (either directly for the current price time series or after conversion to constant prices). For further details, see the main text and supporting information S1 on the Web.

of the database, see the connected paper in this special issue: Wood et al. 2018). This article is structured as follows: The *Compilation* section gives an overview on the used data sources, data preparation, and refinements for both the monetary MRIO tables and the satellite accounts. Each subsection is accompanied by detailed Supporting Information files available on the Journal's website that describe the methodology used. In the section, *EXIOBASE Structure*, we describe the database structure and compare the characteristics of EXIOBASE 3[1] with previous versions of the database. The *Discussion* section deals with potential for utilization of the database, comments on the data availability, and proposes areas for further research.

Compilation

Monetary Time Series

The compilation of the monetary supply-use tables (MSUTs) for EXIOBASE 3 follows a top-down approach reconciling technological data and national-level data to global economic estimates and aggregated official country data (see figure 1). The main principles followed were: (1) provide absolute consistency with macroeconomic data; (2) capture structural change in the economy, especially around technological improvements and shifts in sectoral composition of economies and product composition of final demand; (3) address the changing role of trade compared to national levels of production and consumption; and (4) provide consistency with international data sources as far as possible. As a result, absolute compliance to national level MSUT data was not prioritized in work efforts compared to ensuring the above principles were followed. The advantage of such an approach is that we are able to prioritize internationally and temporally consistent datasets throughout the compilation process.

At the top level, country specific macroeconomic parameters (figure 1A) in current and constant prices were obtained from the UN National Accounts Main Aggregates Database (UN 2016) and combined with additional information from the National Statistics–Republic of China (R.O.C.) (R.O.C. 2016). The final macroeconomic data set includes information on value added and (separately) taxes and subsidies per broad sector, final demand by category, and total imports and exports (both in free on board [f.o.b.] values). GDP is an aggregate of these categories. Only minimal refining steps were necessary to obtain consistent macroeconomic data, and the refined values were used as overall constraints in all subsequent processing steps. This approach ensured that the full time series is benchmarked to the macroeconomic data set. Global trade imbalances were resolved at this step using the maximum value of annual global imports versus exports, with global GDP being maintained through assigning difference to gross capital formation (which includes changes in stocks) in order to keep GDP in accordance with the official statistics. At the country level, a weighted quadratic programming approach was taken to remove minor errors (usually less than 1%) and reconcile country level to the global total. As far as possible, necessary changes were distributed to gross capital formation by applying a low penalty to the changes in those values based on the observation that inconsistent values were mostly found in gross capital formation (or its subcategories) and in order to keep domestic GDP in accordance with the reported values (supporting information S1 on the Web).

Detailed industry and product output per country data (figure 1B) were gathered from several national account databases (including the national accounts and national MSUTs) and various international databases such as the Food and Agriculture Organization statistical database (FAOSTAT) and International Energy Agency's (IEA) energy balances, (FAOSTAT 2014; IEA 2015). A list of data sources and a detailed description of the compilation can be found in supporting information S1 on the Web and supporting information S9 on the Web. The gross output per broad sector was based on the UN macroeconomic data set described above, using ratios between value added and output from that database when available, and proxy values when not. The same split by broad economic sector was applied to broad economic product group. A recursive and hierarchical disaggregation routine was utilized to add detail to the aggregate gross output values based on sequentially adding more detailed auxiliary (such as energy and agricultural) data (further explained in Wood et al. [2014]; Lenzen et al. [2017]; see also supporting information S1 on the Web). This ensures that initial product output aggregates are in accordance with established data sets, while increasing the resolution of the top-level gross output values by auxiliary data. In general, internationally consistent values were prioritized over national data, with FAO data respected in preference to the MSUT or national account data, and if a more aggregate value in the MSUT referred to two subgroups of products (e.g., electricity generation and transmission/distribution), then MSUT data would be used to do a first split before IEA values were used to split the electricity generators individually.

Product- and service-level trade data (figure 1C) were retrieved from the BACI database (balanced product trade data based on the UN Comtrade database [Gaulier and Zignago 2010]), the IEA database (IEA 2015), and the UN services trade database (UN 2015). BACI reports values in f.o.b. valuation, and we estimated international transport margins based on output from a transport model for ten product groups. The three data sources were combined. IEA data for import and export of discrete fuels were used to disaggregate the bilateral trade data of each product group. Percentage of re-export by product group was estimated based on the previous EXIOBASE 2 database (Wood et al. 2015), which uses MSUT data to explicitly split re-exports from total imports. In EXIOBASE 2, we had access to otherwise confidential data provided by EU member states that gave specific information on re-exports by product group by country and year. In EXIOBASE 3, we do not have access to these data. Instead we use publicly available data from Comtrade on either re-exports or reimports at the country level to estimate change over time in the share of re-exports in total exports from the 2007 base-year. This gives the initial estimate of the trade, split by product, exporter, importer, pricing level, and use imports used for domestic production and those for re-export. Additional information on trade partners by broad economic sectors is available (as used in Dietzenbacher et al. [2013]), but is quite aggregate and not included here.

The first estimate of the trade data set is reconciled against data constraints that ensure that country-level imports and exports including re-exports $B_{i,r,s}^{dom,0} + B_{i,s}^{re-exp}$ match the macro account, as well as constraints for product output that ensure exports (excluding re-exports) are less than total national production. A weighted least squares programming approach is used minimizing changes in the bilateral trade data with weights inversely proportional to the value of the bilateral trade flow, while obeying the aforementioned constraints. This gives a final bilateral trade database, $B_{i,r,s}$ and $B_{i,k}^{re-exp}$, that shows total bilateral trade flows by product (i), importing (r), and exporting (s) country and re-exports by product and importing/exporting country, respectively. A detailed description including mathematical formalization can be found in supporting information S1 on the Web. At this point, our database consists of internally consistent data for imports and exports by bilateral trade partner, product output, industry output, value added, taxes, and totals for categories of final demand for each year of the time series.

In order to construct time series of the actual technical relationships in the MSUTs we have collected the time series of Supply and Use tables and/or Input-Output tables from national statistical agencies (Figure 1 – D, see supporting information S1 on the Web for an overview of MSUTs/IOTs time series availability). Data originally collected from Eurostat/National Statistic Institutes suffer mainly from data gaps, changing conceptual coverage of data (e.g., how transport margins are handled) as well as changing classifications over time and changing volumes of confidential data. Therefore, MSUTs collected from the national statistical offices have rarely covered the whole period from 1995 to 2011. In case of missing years between two existing data points, the missing technical coefficients were linearly interpolated between the available data. In case of missing tail years, the missing technical coefficients were extrapolated using the average annual change in technical coefficients in the available period. The inter- and extrapolation of coefficients was done on the coefficients in the original classifications and then transferred to the EXIOBASE level. Further information on the process employed can be found in section 2.2 of supporting information S1 on the Web.

One of the major changes covered in this project was the change from the NACE1.1 to NACE2 (Statistical Classification of Economic Activities in the European Community) in the late 2000s for European countries (classification changes have also occurred in non-European data, but in most cases they came down to the change in the level of sectoral detail, which is less radical than the change in NACE). The approach taken in this project was to remap individual country MSUTs to a base-year classification (mostly 2007) and create a concordance between base-year MSUT data and final EXIOBASE classification (the concordances are available on request). For the European countries, this means that we attempted to recreate the more recent tables in NACE1 classification. To create this consistent time series, we had to convert the NACE2 tables into NACE1 tables with the help of manually created concordances and place them as the continuation of the original NACE1 tables. Since the European countries have switched from NACE1 to NACE2 quite abruptly, with only a few of the countries providing MSUTs in both classifications for the same year, we had only limited possibilities to check how well the created concordance between the two classifications works in practice. For a selected number of large countries and industries, we have performed a visual check of the resultant time series of technical coefficients. More specifically, simple time-series line graphs for largest input coefficients of specific products into specific industries have been analyzed. The graphs did not show larger changes in coefficients at the break point (year when classification changed) than in the years with official statistical data in NACE1 have been available. The results of the changing classification were most evident in the service industries, where substantial classification changes occurred. Throughout the outlined procedure, we have preferred capturing data on structural change in the economy rather than matching official statistics at the national level. Thus EXIOBASE 3 tables will not match more recent Eurostat data. This aligns with the general purpose of EXIOBASE 3 in use for analyzing change over time (resource decoupling, e.g., see Wood et al. 2018) than having an updated, benchmark table consistent with the latest national-level data. The time series of technical coefficients created covered both intermediate and primary inputs (value added), while a similar procedure was also undertaken for categories of final demand (excluding imports and exports). Further information on the process employed can be found in supporting information S1 on the Web.

In order to calculate the final domestic MSUTs (figure 1E), initial MSUTs in EXIOBASE classification were established by combining all data from the preceding processing steps (figure 1A to 1D). Total product taxes, margins, and change in inventories were obtained from national statistic SUTs or were estimated where missing (see supporting information S1 on the Web). This gave an MSUT system consisting of supply values in basic prices and a use table in purchaser prices. Import use, taxes, and transport/trade margins tables are obtained by disaggregating the yearly available total taxes, imports, and margins per product to the per industry classification used in EXOBASE based on constant 2007 shares established for EXIOBASE 2. In EXIOBASE 2, nonpublically available data on import, taxes, and margin tables (product by industry) were used in order to estimate the disaggregated tables. Such data were not available for the time series for a reasonable number of countries in EXIOBASE 3. If there is a big change in the relative share of industrial versus final consumers for these tables, then this would not be captured in our approach. Nevertheless, total import and export data are constrained, so the net effect of the assumption would be expected to be small for total footprint calculations. This then allowed for the estimation of the basic price table. The disaggregated MSUT system by domestic use, import use, transport margin, trade margin, and tax layer was then balanced in a single algorithm to match the trade and macroeconomic data sets compiled in earlier steps. A flexible mathematical programming approach, where information gain is minimized, was used subject to balancing constraints, macroeconomic parameters, and trade (see full list of constraints in supporting information S1 on the Web). To do so, a final estimate of the MSUT system $\mathbf{Z}_{m,n,k,s,t}$ was created by minimizing differences (the objective values $o(\mathbf{Z},\mathbf{Z}^0)$) from the initial MSUT system $\mathbf{Z}^0{}_{m,n,k,s,t}$

$$o\left(\mathbf{Z}_{s,t},\ \mathbf{Z}^0_{s,t}\right) = \sum_{m,n,k} \boldsymbol{SW}_{m,n,k,s,t} * \left(\mathbf{Z}_{m,n,k,s,t} - \mathbf{Z}^0_{m,n,k,s,t}\right)^2$$

with $m,\ n,\ k,\ s,\ t$ representing $m =$ rows (products i and value added), $n =$ columns (industries j and final demand), $k =$ layers (supply table in basic prices, use table basic prices domestic and import use, taxes, transport, trade margins), $s =$ region and $t =$ time period of the MSUT system (therefore, each country and year was balanced independently), and $\boldsymbol{SW}$ representing the applied weights.

A quadratic programming target function was chosen to minimize the objective value. This approach has been shown to deal with conflicting information from different data sources (Robinson et al. 2001) and allows flexibility in the estimation of inter-regional trade accounts (Canning and Wang 2005) as well as reconciling of large databases (Müller et al. 2009; Wood 2011). Weights ($\boldsymbol{SW}_{m,n,k,s,t}$) for the weighted sum of least squares (Morrison and Thumann 1980) were defined as:

$$\boldsymbol{SW}_{m,n,k,s,t} = \begin{cases} \dfrac{1}{|\mathbf{Z}^0_{m,n,k,s,t}|} & \text{if } |\mathbf{Z}^0_{m,n,k,s,t}| > 1\text{E}-3 \\ 1\text{E}3 & \text{if } |\mathbf{Z}^0_{m,n,k,s,t}| \leq 1\text{E}-3 \end{cases}$$

For details about the algorithm used and a list of constraints used, see supporting information S1 on the Web. All balancing algorithm were performed on the SUT system in unitary values. Total imports and (re-)exports per product were not allowed to deviate from the initial values, since balanced trade relationships were established during the trade linking routine earlier. The implications here are that the import and export vectors of the final 49-country/region MSUT data are already globally consistent, that is, the bilateral exports from each region match the total imports recorded in the import tables of the MSUTs (all in f.o.b. pricing). The single-region import table can then be disaggregated to point of origin assuming that each industry and final consumer purchase the same relative portion of goods from exporting countries (known as the "proportionality assumption" cf Peters et al. [2011]; Rodrigues et al. [2016]). In this procedure, re-exports are set to zero in the multiregional MSUT, and import shares calculated from $B^{dom,0}_{i,r,s}$ are multiplied by the import use matrix in order to give the multiregional import-use tables. Domestic SUTs are unaffected in this procedure (full description in section 2.6 of supporting information S1 on the Web).

To convert the current price time series to constant prices, we compiled product- and country-specific deflators based on several data sources. Deflators related to energy and agricultural products were obtained using physical data from the IEA and FAO (assuming no change in quality), and deflators for other product categories were calculated using data from national accounts or, if not available, from the WIOD (Timmer et al. 2012). The remaining deflators were computed using product-specific averages of available deflators across countries. Details of the deflator calculations as well as checks for consistency and validity can be found in supporting information S1 on the Web. These deflators were also used to convert the bilateral trade cube to constant prices, which was then rebalanced based on constant price import/export values obtained from the UN. Similarly, the MSUTs in current prices were deflated, and rebalanced respecting the bilateral trade and macroeconomic constraints in constant prices.

Energy Accounts

Physical energy flow accounts, which are organized around energy supply-use tables (ESUTs), play a twofold role in EXIOBASE. First, they depict the domestic supply and use of around 60 primary and secondary energy products and therefore represent the core of the energy data in the database. Second, energy accounts also contain data on the emission-relevant energy use, which provide the basis to calculate the air emissions of 27 substances arising from combustion processes (see next section on *Emission Accounts*).

The overall approach used to calculate the ESUTs is very similar to the one applied in previous versions of the database (Tukker et al. 2013; Wood et al. 2015). First, the IEA's extended energy balances (IEA 2012, 2015) have to be aligned with the system boundaries followed in the SEEA. This ensures that the EXIOBASE energy flow accounts are consistent with the accounting rules published by recognized international institutions (UNDESA 2013; European Commission et al. 2014).

The energy balances follow the territory principle, that is, they account for the supply and use of energy within the borders of a territory, while the SEEA—and by extension the physical energy flow depicted in the ESUTs—follow the resident principle, that is, covers the activities carried out by the resident units of a country, independent from where these activities take place. Failing to bridge the gap between the territory and residence, principles can compromise the robustness of the environmental extension and the footprint results (Usubiaga and Acosta-Fernández 2015). Given that international transport activities are the main elements affected by this boundary issue, several transport models have been built to properly allocate the use of fuels from international fishing activities, as well as from international marine and aviation bunkers. Additionally, data from Eurostat and other assumptions have been used to estimate the amount of fuel imported through tank tourism both from households and from road freight and passenger transport.

Once the ESUTs are aligned with the residence principle and consolidated following the energy flow and energy product classification of the IEA, these flows and energy products are allocated to EXIOBASE industries, final consumption categories, and products by means of a variety of auxiliary data sets. These steps are explained in more detail in supporting information S2 on the Web.

Emission Accounts

EXIOBASE provides data on industry-specific and final demand air emissions for 27 pollutants. These have been calculated at the global level in a consistent way for all countries and sectors to the extent possible, covering each country individually and the full time series for 1995–2011 (annual totals). The approach is similar to the approaches applied in the previous versions of EXIOBASE (Tukker et al. 2013; Wood et al. 2015). Several data sets exist which have complete or partial sets of global emissions to air on a territorial basis (e.g., IIASA GAINS, JRC EDGAR, as well as official reported air emissions by individual countries to international conventions), and also the environmental accounts reported to Eurostat. Most of these data sets are not as detailed, complete, transparent, and methodologically consistent as needed for providing a comprehensive picture of the air emissions connected to economic I-O databases. Since combining different existing data sets gives issues with different definitions and scope and would still require significant gapfilling and disaggregation, a bottom-up calculation of the air emissions was performed, aligned with the energy definitions used by the IEA for combustion emissions, which ensures consistency between energy and emission accounts.

The calculation of air emissions has been conducted by combining activity data with consolidated emission factors retrieved from the TEAM model (Pulles et al. 2007). This model has been filled with emission factors from various sources, including from the Guidelines for National Greenhouse Gas and Air Pollutant Inventories (IPCC 2006; European Environment Agency 2009) and from the GAINS model (Amann 2009). The TEAM model chooses for each activity the most appropriate technology or set of technologies, where appropriate refers to the typical technology level in the country (e.g., in Europe, more efficient technologies are applied compared to developing countries). The main advantage of using this model is that it allows for the introduction of new (mostly cleaner) technologies over time, thus changing the emission factors associated with certain activities.

For emissions arising from combustion processes, energy-use data are combined with emission factors obtained from the TEAM model. In order to do so, the energy balances from the IEA (IEA 2013) have to be aligned with the system boundaries described in the SEEA, which follows the so-called residence principle (see previous section on *Energy Accounts*). As a result, international transport activity data have to be reallocated in the system following internationally agreed guidelines (UNDESA 2013; European Commission et al. 2014). These consolidated activity data are combined with emission factors that have been previously checked, as explained in the supplementary material (supporting information S3 on the Web). The resulting emissions are then allocated to the EXIOBASE 3 industries, final consumption categories, and product groups based on auxiliary data sets as in the case of the energy accounts. These data sets are described in supporting information S2 on the Web.

For emissions resulting from noncombustion activities, activity data are collected from various sources (e.g., UN Statistics, U.S. Geological Survey, British Geological Survey, FAOSTAT, etc.) and combined with one or more chosen technologies, similar to the combustion emissions. The noncombustion emissions are then each associated to one or more EXIOBASE products, either in the supply or the use of these products (see supporting information S3 on the Web for further information).

Water Accounts

Three basic data sources were used for the compilation of the water use and consumption extension for EXIOBASE 3. For agricultural water consumption, we used a data set building on data compiled by Pfister and colleagues (Pfister et al. 2011; Pfister and Bayer 2014) as well as the Water Footprint data set (Mekonnen and Hoekstra 2011), which is based on FAO data. For industrial water use and water consumption, the WaterGAP model (Flörke et al. 2013) was used. These three data sets are currently among the most comprehensive global databases. They were chosen according to their individual strength: the agricultural water consumption data sets encompassing a vast amount of agricultural categories and the WaterGAP data set covers multiple livestock categories as well as electricity production and manufacturing sectors; the latter being an area where special requirements of an MRIO database system meet the general poor data coverage situation.

The extensions on water use and water consumption in EXIOBASE encompass 13 categories for water consumption in agricultural activities for both green and blue water, 12 categories of blue water consumption in livestock production, seven blue water consumption categories in aggregated manufacturing sectors, and two related to electricity production. For the seven manufacturing and the two electricity production sectors, data on withdrawal of blue water are also provided. In cases where the number of water categories exceeds the water-using sectors contained in EXIOBASE, they were aggregated accordingly. In cases where the number of categories in the water data are below the number of sectors in EXIOBASE (i.e., in the case of manufacturing sectors), water data were disaggregated using physical output of these sectors in tonnes. The WaterGAP data set covers a time period from 1950 to 2010. Values for 2011 were extrapolated. The Water Footprint data set covers the period 1996–2005—with an average value provided for 2007 being used to up- and downscale data on agricultural production for the years 1995–2011. Furthermore, data were extended in the area of water requirements for grazing (see supporting information S4 on the Web for further details).

Material Accounts

The main data source for the compilation of the material extension in EXIOBASE 3 was the Global Material Flow Database compiled by the research group "Sustainable Resource Use" at the Vienna University of Economics and Business (WU 2015). This database currently covers more than 300 different types of biotic and abiotic raw materials for more than 200 countries. In the course of the DESIRE project, updates of this database were performed to include the years 2010–2012. In addition, various methodological improvements of the calculation routines were performed, for example, a split between industrial roundwood and wood fuel, in order to be in consistence with the land accounts; and a completion of extraction data for previously missing mineral commodities using various geological data sources (see supporting information S5 on the Web).

Compared to earlier versions of EXIOBASE, the list of material extensions has been broken down significantly in order to enable more detailed analysis. It now covers 222 items, including 193 biomass items (179 crops, seven forestry and four fishery items, two crop residues, and grazing), 12 metal ores, eight industrial and construction minerals, and nine fossil fuels. Unused extraction refers to materials that never enter the economic system and comprises overburden and parting materials from mining, by-catch from fishing, wood and agricultural harvesting losses, as well as soil excavation and dredged materials from construction activities (for more information, see supporting information S5 on the Web). Concordance between the material and land accounts as well as between the extensions and the EXIOBASE sectors was increased on the basis of a six-digit product concordance table, which is now applied across all parts of EXIOBASE (MSUTs, physical SUTs [PSUTs], and extensions) and thus ensures particularly high consistency of data related to biomass flows.

In EXIOBASE 3, the items of fodder crops, grazing, and crop residues were directly allocated to the respective animal production sectors which use these commodities. This approach is considered to gain more robust results, as production and supply structures for nonmarket commodities are, in many cases, incompletely covered by IOTs. In order to implement this allocation at the use stage, detailed data on fodder crop use by various animal production sectors from the AgroSAM database were used (Müller et al. 2009) (see supporting information S5 on the Web).

Land Accounts

Land-use data in the EXIOBASE 3 model were integrated on a yearly basis for the EXIOBASE 3 time frame. The land-use extension includes statistical data (mainly FAO; FAOSTAT [2014]) integrated with spatially explicit land-use data (Erb et al. 2007; Ramankutty et al. 2008; Schepaschenko et al. 2015; Potapov et al. 2017). The approach by Erb and colleagues (2007) served as a starting point to construct a series of thematic global 5 arc min (c. 10 × 10 kilometer) resolution land-use maps for the year 2000. In EXIOBASE 3, three land-use categories (cropland, grazing land, and forestland) were allocated to 16 industrial sectors, that is, sectors of biomass extraction, whereas settlement areas, including transportation and settlement infrastructure (based on Krausmann et al. 2013), as well as areas under subsistence uses, were allocated to final demand.

Areas with a productivity below 20 grams of carbon per square meter per year were labeled as "unproductive" and excluded from the assessment. Productive, but unused, land was derived from previous estimates (Potapov et al. 2017; Venter et al. 2016), and estimated values for the time period were constructed using linear interpolations (see supporting information S6 on the Web). Settlement and infrastructure area was derived from the time cuts available from Krausmann and colleagues (2013) by means of linear interpolation.

For cropland, the main data source in EXIOBASE 3 is the FAO, which includes data for about 250 countries on a yearly basis from 1961 onward. Additionally, we used country-specific information from various sources (Council of Agriculture, Executive Yuan R.O.C. 2011; Erb et al. 2007; Krausmann et al. 2013) to close data gaps or to account for changes in country borders during the time series. Cropland data are further split up into nine subcategories, in line with the sectors available in EXIOBASE: two sectors corresponding to single crops (rice, wheat), six sectors representing aggregates of crop types (e.g., other cereals and oil crops), and one sector representing fodder crops.

For forestry, we used a recent map for the year 2000 that integrates available data sets and uses a citizen science approach for validation (Schepaschenko et al. 2015) combined with the temporal development of forested areas from the FAO. Unused and used forest were separated on the basis of information on intact forest landscapes (Potapov et al. 2017). Used forest area was allocated to the forest sector. The differentiation between industrial roundwood and wood fuel was based on FAO and UN data and equally applied to land-use and material-use data. Further details can be found in supporting information S6 on the Web.

Permanent pastures for 2000 was taken Ramankutty and colleagues (2008), consistently integrated with the cropland maps by Ramankutty and colleagues (2008) and the forest map. This procedure resulted in downward correction of the global permanent pasture extent in order to warrant spatial consistency (see supporting information S6 on the Web). The temporal development was derived from the FAO time series for permanent pastures. For the land area used for the cultivation of fodder crops on cropland and permanent pasture, we developed a procedure that allowed for allocating these land-use types to five livestock sectors: raw milk, cattle meat, pig meat, poultry, and other meat (see supporting information S6 on the Web). The same procedure was applied to land-use and material-use extensions.

Land not allocated to settlement, cropland, forest, or permanent grazing, but also not wilderness or unproductive, was separated on basis of remote sensing data (DiMiceli et al. 2011) into three classes. Other land with tree cover >10% was allocated to the forest sector. For advanced economies (based on the World Economic Outlook Database: International Monetary Fund [2016]), we allocated other land used for grazing to the respective sectors. For all other countries, we allocated the remaining other land classes to final demand, assuming that subsistence activities prevail on these areas (grazing and woodfuel collection).

Waste Accounts

Waste is assumed to be the materials, processed or not, that enter into the activities but that are not incorporated in their outputs, neither discharged as emissions. In this way, the waste is what assures that the law of the conservation of mass is respected within each and any activity of national economies. Therefore, in DESIRE, waste has a wider meaning than that commonly used because it includes both waste residuals and waste products (UNDESA 2013; Schmidt et al. 2012). As in the previous project, Compiling and Refining Environmental and Economic Accounts (CREEA) (Wood et al. 2015), waste is defined as "material for treatment" (Schmidt et al. 2012) that includes all the materials that need further reprocessing in order to be turned into new products, emissions, or stock addition in landfills. This treatment may be reprocessing of scrap into new materials that can substitute virgin materials; it may be waste incineration, landfill, waste water treatment, composting, or just storage of uncontrolled discharged waste in the environment involving emissions from degradation.

The idea behind the adoption of this definition is that recycling can be properly modeled. Indeed, recycling is the processing of waste and scrap and other articles, whether used or not, into secondary raw material. A transformation process is required, either mechanical or chemical. This definition of waste is fully in line with the technical principle widely used in the life cycle assessment community (Weidema et al. 2011), and it diverges from an economic perspective that considers, for example, homogenous scraps with a positive economic value as products and not as waste (UNDESA 2013).

Waste accounts are divided into two sets. The first one relates to the users of waste, while the second one with the producers. Waste treatment activities are essentially filling the first account, while all the activities and final consumers encompass the second one. Trade of waste is also taken into account. In practice, a third account is produced showing the unregistered waste, which equals the supply of waste less the use of waste. This third account contains residual values.

Waste accounts derive from a general procedure determining PSUTs, or hybrid SUTs (HSUTs), which includes a physical layer. The module of the HSUTs procedure that determines the waste accounts is based on what was developed within the Forwast project (Schmidt et al. 2010) plus further developments for EXIOBASE 2 within the CREEA project (Merciai et al. 2013; Schmidt et al. 2012).

In the Forwast project, time series of waste accounts were determined; hence, in the DESIRE project, that methodology is fully applied. The Forwast procedure (Schmidt et al. 2010) includes the account of stock addition to which is applied a degradation function to estimate the delayed production of waste. As a consequence, the supply of waste in an accounting period is the sum of the commodities purchased and discharged within the accounting period, plus what was traded in previous periods and has become obsolete. The use of waste is what emerges from statistic sources plus some own estimations for detailing or extending data coverage.

Labor Accounts

Socioeconomic accounts in EXIOBASE 3 comprise total and vulnerable employment, both in persons and in hours. For total persons in employment and for total hours in employment, the indicators were further disaggregated in gender and skill levels. These indicators represent an expansion of the labor indicators in previous EXIOBASE versions: the labor data were extended from availability by only skill levels in EXIOBASE 2 to the availability by both skill levels and gender. Vulnerable employment (ILO 2013a), consisting of unpaid family workers and self-employed persons, is also a new addition to the socioeconomic indicators in EXIOBASE 3.

Labor and hours worked accounts are based on available statistics from EUROSTAT (European Commission 2016), the International Labor Organization's (ILO) ILOSTAT database (ILO 2014) and from the OECD's Statistics (OECD 2014). Skill levels—high-, medium-, and low-skilled work—correspond to that of the International Standard Classification of Occupations (ILO 2012).

Socioeconomic indicators were collected annually for the period from 1995 to 2011. Adjustments were made to disaggregate and combine different data sources and industry classifications throughout the period. Those adjustments are detailed on the annex report for labor accounts (supporting information S7 on the Web).

Final Compilation

In the final step, the MSUTs trade block and satellite accounts were arranged in a multiregional supply-use table (MR SUT) framework and converted into MRIO tables (see supporting information S1 on the Web) given in million Euros.

EXIOBASE Structure

Two official versions of EXIOBASE 3 will be provided:

1) A product by product table based on the industry technology assumption; and
2) An industry by industry table based on the fixed product sales assumption.

Further details of the two constructs are available in the EUROSTAT manual (EUROSTAT 2008).

The high level of detail in EXIOBASE results in a large amount of data. The tables for one year of EXIOBASE require about 800 MB (compressed), which represents around 14 GB for the full time series. Given that large amount of data to be handled, some programming skills are required to use the data sets. We aimed to ease the task by providing an open source tool for analyzing the data set which can also be used for the analysis of other EE MRIO tables (Stadler 2015). We recommend about 8 GB of RAM for a basic run of EXIOBASE (e.g., calculating consumption-based accounts). A full description of the file format and naming can be found in supporting information S8 on the Web.

Characteristics of the Final EXIOBASE 3 Database

EXIOBASE 3 consists of a time series of EE MRIO tables ranging from 1995 to 2011, including 44 countries (28 EU member plus 16 major economies) and five rest of the world regions (summarizing the remaining countries in Europe, Asia, Africa, America, and Middle East, respectively). The EE MRIO tables (and underlying MR SUTs) exhibit a consistent sector classification of 200 products and 163 industries. In comparison to previous versions of EXIOBASE, we also increased the level of detail in the satellite accounts, in particular for the material accounts (table 1). Further information on the sector, country, and stressor classification can be found in supporting information S9 on the Web.

Discussion

In this paper, we described the latest developments of EXIOBASE (version 3) which, in its current version, consists of a time series of detailed EE MRIO tables from 1995 to 2011. Providing a time series of EE MRIO tables addresses the main shortcoming of the previous versions of EXIOBASE (Wood et al. 2015), which were only available for two distinct snapshots of the global economy (2000 and 2007).

Extending the temporal scope of EXIOBASE within the resource and time constrains of an EU FP7 project was only possible by building upon the experiences, data, and code of the previous versions. Most importantly, we again used monetary domestic supply-use tables (MSUTs) as the basic building blocks for the database. Using SUTs as the basis for building up an I-O framework allows for flexibility of modeling in terms of both products and industries, while keeping tractability of data—which are usually collected for supply and use of products, by industries or activities. As such, modeling and data inventory can be kept separate. The main difference to the EXIOBASE 2 workflow is the top-down approach followed in EXIOBASE 3 starting with macroeconomic parameters that were used as a constraint in every subsequent data processing step. The advantage of this approach is that the final database is consistent with these macroeconomic parameters (UN 2016). EXIOBASE 3 tables are, however, not in absolute compliance with national MSUT data since the time series was constructed by superimposing structural change data from national statistical agencies onto available EXIOBASE tables from 2007 (version 2). If such adherence with official MSUT data is required, EXIOBASE 3 can be used as a background system within a "single country national account consistent" approach (Edens et al. 2015), as discussed in another paper of this special issue (Tukker et al. 2018).

In general, the approach followed during the EXIOBASE 3 compilation allowed for a modular workflow structure, with parts developed almost independently in different working

Table 1 Characteristics of EXIOBASE 3 compared to previous versions of the database

	EXIOBASE 1	*EXIOBASE 2*	*EXIOBASE 3*
Base-year(s)	2000	2007	**1995–2011**
Products	129	200	**200**
Industries	129	163	**163**
Countries[a]	43	43	**44**
RoW[b] **regions**	1	5	**5**
Emissions			
Combustion	26	26	**27**
Noncombustion		11	**27**
HFC/PFC/SF6		3	**3**
N/P/SOx from waste			**5**
N/P from agriculture			**7**
Water accounts (per activity)			
Green	47	172	194
Blue	47	172	194
Material accounts			
Energy products[c]	69	69	**69**[d]
Extraction (used/unused)	48/48	48/48	**222/222**
Land accounts	14	15	**15**[e]
Employment accounts	6[f]	6[f]	**14**[g]

Note: The detailed classification can be found in supporting information S9 on the Web.
[a]EU27 for version 1 and 2 and EU28 for version 3 plus 16 major economies.
[b]Rest of the world regions, aggregating all countries not explicitly modeled. In EXIOBASE 2 and 3, the RoW was split into five separate RoW regions based on the geographical location: Europe, Asia, Africa, America, and Middle East.
[c]Including energy products within the final demand table.
[d]Disaggregated into gross/primary energy supply and gross/emission relevant energy use.
[e]Including built-up land for final demand. See supporting information S6 on the Web for data availability.
[f]Hours and persons for three skill levels.
[g]Disaggregated into employment (hours/persons) per skill level and gender, including vulnerable employment.
HFC = hydrofluorocarbon; PFC = perfluorocarbon; SF6 = sulfur hexafluoride; N = nitrogen; P = phosphorous; SOx = sulfur oxides.

groups (see supporting information S1 on the Web). Potentially, the approach could be further compartmentalized into fully independent parts which would enable the parallelization (in terms of working groups as well as computational steps) of the EE MRIO database compilation process.

Despite the efforts for streamlining the compilation process, the building of an EE MRIO database remains a data-intensive task. Most of the problems we encountered were due to data inconsistencies across time and countries, ranging from changes in classifications to modifications of the underlying accounting concepts over time. It is understandable that the statistical agencies improve their approaches over time, but in case the older time series are not revised by the statistical agencies according to the new concepts, the time series are not directly usable for analyzing structural changes over time. To solve this issue, we manually build concordance matrices to convert available data for each country to a consistent classification over time. Similarly, statistical offices occasionally changed the data format, requiring adaptations of the parsing scripts and manual consistency checking. In addition, language barriers are still present when dealing with non-European national statistical agencies' data. During the development of EXIOBASE 3, international experts were involved in order to overcome this issue. In a lot of cases, data available in the original language and those available in English differ to an extent that the local knowledge becomes essential for appropriate data usage. More information about data refinement can be found at supporting information S1 on the Web.

The distinguishing characteristics of EXIOBASE are the high level of consistent sectorial (200 products, 163 industries for all countries and regions included) and environmental detail. This high level of detail is of particular importance for the analysis of environmental pressures which are limited to certain sectors (as, e.g., for material extraction, as shown by an analysis based on EXIOBASE 2 by de Koning et al. [2015]). The high sector detail, the accordance with the accounting principles proposed in the UN SEEA manual (European Commission et al. 2012), and the geographical focus on the EU and major economies make EXIOBASE 3 highly suitable for policy analysis of developed economic regions (Giljum et al. 2016). Within this setting, EXIOBASE 3 provides the level of detail necessary for a macro-level policy screening of consumption-oriented policies in regard to carbon emission savings (Wood et al. 2017). The high sector detail of EXIOBASE facilitates the unambiguous linking to other classification schemes. This is a necessary prerequisite for linking MRIO accounts with consumer expenditure (Ivanova et al. 2017; see also www.environmentalfootprints.org/regional) and also allows for building scenarios with a detailed modeling of consumer behavior. For policy and trade analysis focusing on developing and emerging economies, however, the limited country set of EXIOBASE 3 must be taken into account. For such analysis, EE MRIO databases with a larger set of countries (e.g., Eora or GTAP-based MRIO databases) might be better suited. Within the currently available EE MRIO databases, a tradeoff exists between databases with high country detail and high sector detail. We plan to overcome this issue with the future development of EXIOBASE.

Different classification frameworks, country resolution, and sets of included satellite data make it difficult to compare available EE MRIO databases against one another. One way to overcome this problem is to aggregate the available EE MRIO tables into a common classification scheme (Steen-Olsen et al. 2014). We set up a webpage (accessable at www.environmentalfootprints.org/mriohome) which allows to compare and visualize EXIOBASE 3 accounts against the other available EE MRIO databases (Stadler et al. 2015). In general, we find EXIOBASE 3 accounts within the range of available EE MRIO databases. Aggregated EXIOBASE 3 accounts are also available at this webpage.

In summary, the EXIOBASE EE MRIO database provides a consistent framework for tracking emissions, resource use, and other environmental pressures along global supply chains and thus linking consumption patterns to production processes elsewhere. The high sectorial detail and wide spectrum of environmental data allow for both economy-wide assessments as well as the identification of environmental hotspots, such as energy production, food, and mobility (see Wood et al. [2018] for results based on the new version). The newly available time series of EE MRIO tables in EXIOBASE 3 provides researchers and policy makers with a unique tool to identify priority sectors and consumption areas (see Giljum et al. 2016; Wood et al. 2017) and to assess the outcome of policies set in place to reduce environmental impacts, increase resource efficiency, and ultimately decouple the economic activity from the environmental impacts it leads to.

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Note

1. Aggregated results of EXIOBASE 3 are available at www.environmentalfootprints.org/mriohome. The full database (as specified in table 1) will be published on www.exiobase.eu and aggregated results of EXIOBASE 3 are available at www.environmentalfootprints.org/mriohome. New versions and bugfixes of EXIOBASE will be announced on the EXIOBASE email list at https://goo.gl/sAhvD4.

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information includes information about the compilation of the monetary Supply-Use tables (SUTs) for EXIOBASE 3.

Supporting Information S2: This supporting information includes information on energy accounts and energy balances, the territory versus residence principle, the general approach used to generate the energy extensions in EXIOBASE, and a detailed methodology for bridging the gap between the territory and the residence principles, allocation to EXIOBASE classification, and the calculation of emission relevant energy use and the primary energy supply.

Supporting Information S3: This supporting information describes the methodologies used for estimating emissions to air, soil, and water in the EXIOBASE database.

Supporting Information S4: This supporting information includes a compilation of water accounts from agricultural water consumption, livestock breeding, manufacturing, electricity production, and domestic use.

Supporting Information S5: This supporting information describes the data collection procedures on Domestic Used Extraction (DEU) applied for each of the four major material categories, i.e., biomass, metal ores, minerals, and fossil fuels. This is followed by a description of the procedures applied to estimate Unused Domestic Extraction (UDE).

Supporting Information S6: This supporting information describes the construction of land-use information for the EXIOBASE regions and their allocation to the EXIOBASE sectors. Land-use data are available at two aggregation levels and their use is free for scientific purposes. The aggregate data represents the sum of land categories allocated to the corresponding EXIOBASE sectors, and are part of the EXIOBASE 3 download. Disaggregated data (e.g., country level or level of land-use categories; see table S6-1), or more detailed data, are available upon request.

Supporting Information S7: This supporting information describes the collection, processing, and presentation of the socioeconomic extension for EXIOBASE 3. Socioeconomic data in EXIOBASE 3 consist of labor indicators collected for 44 countries plus five "rest of the world" regions for the period between 1995 and 2012.

Supporting Information S8: This supporting information includes information about the storage of the EXIOBASE3 raw data file storage.

Supporting Information S9: This supporting information provides the industry and product sector classification, the country resolution, and stressor list of EXIOBASE version 3.