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Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments☆

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ABSTRACT

The European Union (EU) has proposed in its Resource-efficiency roadmap a 'dashboard of indicators' consisting of four headline indicators for carbon, water, land and materials. The EU recognizes the need to use a consumption-based (or 'footprint') perspective to capture the global dimension of resources and their impacts. In this paper, we analyse how the EU's footprints compare to those of other nations, to what extent the EU and other major economies of the world rely on embodied resource imports, and what the implications are for policy making based on this comparison. This study is the first comprehensive multi-indicator comparison of all four policy relevant indicators, and uses a single consistent global Multi-Regional Input Output (MRIO) database with a unique and high level of product detail across countries. We find that Europe is the only region in the world that relies on net embodied imports for all indicators considered. We further find that the powerful economies of China and others in the Asia-Pacific already dominate global resource consumption from a footprint perspective, while they still haven't reached the prosperity of developed countries. Competition for resources is hence likely to increase, making Europe even more vulnerable. A hot spot analysis suggests that final consumption of food, transport and housing are priorities for reduction efforts along the life cycle. Further, countries with a similar Human Development Index can have very different footprints, pointing at societal organisation at macro-level as option for improvement. This points at options for countries for lowering their footprint, becoming less dependent on embodied imports, while maintaining a high quality of life.

1. Introduction

Resource efficiency has a global dimension, and increasingly regional resource efficiency policy takes into account the resource impacts that occur not only locally, but also in foreign states. Such approaches take a "consumption based" or "footprint" perspective to the impacts of consuming goods and services, rather than the traditional ("production based") approach of accounting for impacts at the source. The European Union (EU) has proposed focusing on four environmental categories (carbon, water, land and materials) in its 'dashboard of indicators' in the Resource-efficiency roadmap and recognised the role of footprint-type indicators for its monitoring and implementation (EC, 2011). Significant research over the last 10 years has come out on footprint accounting – but mostly on single indicators instead of a full dashboard. Examples for carbon (usually limited to CO_2 emissions) include Ahmad and Wyckoff (2003), Hertwich and Peters (2009), Davis and Caldeira (2010), Peters et al. (2011), and Wiebe et al. (2012a); for land include Weinzettel et al. (2013) and Yu et al. (2013); for water include Hoekstra and Chapagain (2007), Feng et al. (2011), Hoekstra and Mekonnen (2012), Zhan-Ming and Chen (2012) and for materials include Bruckner et al. (2012), Wiedmann and Barrett (2013), Giljum et al. (2014) and Huysman et al. (2014). Examples of the well-known Ecological Footprint include Moran et al. (2009), Ewing et al. (2010), WWF, (2014).

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Other authors published conceptual suggestions how a 'footprint family' best could be constructed (e.g. Giljum et al., 2011; Cucek et al., 2012; Galli et al., 2014; Fang et al., 2014).

There are however just a handful of studies that provide a multi-indicator perspective for the global level, using a single consistent data set (e.g. Steen-Olsen et al., 2012: carbon, land and water; Wiebe et al., 2012a,b: carbon and materials; and Moran et al. (2013): various extensions). None of these used the dashboard proposed by the EU. Moreover, Steen-Olsen et al., (2012) indicate that more research with improved and detailed models is needed to develop a proper understanding of the relation between production and consumption of different resources at a global scale. Particularly researchers interested in water and land footprints preferred applying footprint-specific 'coefficient approaches' (e.g. Hoekstra and Mekonnen, 2012; Moran et al., 2009) rather than the integrated, but less detailed Multi-regional input output (MRIO) approaches. As a consequence, different footprints often are calculated using different conceptual bases, leading to difficulties or even confusion in interpretation (and hence mutual comparison) of the results (e.g. Feng et al., 2011; Peters et al., 2012; Tukker et al., 2013a; Kastner et al., 2014).

We set out to overcome these problems with an analysis for precisely the footprints central in the EU environmental policy, using one single, consistent conceptual approach and data set. The key research question we want to answer is to what extent Europe and other developed countries rely on emissions and resource extraction abroad. We further look at the distribution of these footprints between countries, identify the main products contributing to these footprints, how footprints relate to quality of life, and derive implications for resource management and policy making. For these analyses we apply the EXIOBASE database (version 2.1; see www.exiobase.eu), which has been specifically constructed for assessing issues of resource efficiency, having an unprecedented, consistent detail in resource intensive product groups, economic sectors, and trade relations by which final consumption is linked to emissions of substances to and extraction of primary resources from nature. This reflects an additional advance compared to the state of the art.

The remainder of the paper is structured as follows. Section 2 discusses approaches to calculate footprints, and Section 3 discusses the approach, database and indicators we used. Section 4 gives results while Section 5 forms the discussion and conclusion.

2. Approaches for calculating footprints

To get an impression of environmental impacts caused by a country, it has been custom to monitor resource extraction as well as emissions due to production and consumption processes within a territory. However, due to ongoing liberation of trade and economic specialisation in the last decades, growth in international trade has outpaced growth in global GDP. Impacts related to consumption in one country hence increasingly take place abroad (e.g. Peters et al., 2011; Wiedmann et al., 2010). Consumption in one country drives production in value chains spanning many countries, creating a complex, global web of activities which impact the environment in multi-faceted ways (cf. Tukker and Dietzenbacher, 2013). Practitioners apply in essence two approaches to calculate such impacts driven by national consumption in countries abroad.

Particularly for water and land use, *coefficient approaches* are applied to calculate impacts embodied in imports and exports (e.g. Hoekstra and Chapagain, 2007; Moran et al., 2009). These can make full use of the detailed international trade databases, discerning some 5000 products and over 200 agricultural products, which are usually assumed to dominate land use and water use (UN Comtrade, undated). Agricultural production and related water use in physical terms are covered in great detail by Food and Agriculture Organization (FAO) databases (FAOSTAT, Undated). Imported agricultural products usually are produced in the country of exports, with no further supply chains behind it that entail important levels of water or land use. Consequently, knowing, for instance, the physical amount of bananas imported from Costa Rica to Germany, as well as the average land use and water use per ton bananas grown in Costa Rica, the land and water embodied in this banana trade can be estimated with a reasonable level of detail and accuracy. However, while agriculture is the main user of land and water worldwide, coefficient-based approaches – so far – still lack an integration of non-agricultural production and related direct and indirect water and land use. Yu et al. (2013) and Hubacek and Feng (2016) showed this can lead to relevant errors in consumption based accounts for e.g. land.

For carbon and material footprints such coefficient approaches are however in any case problematic. As exemplified by Fig. 1, manufactured products are now usually produced in a supply chain passing through various countries, leading to more complex interrelationships regarding the creation of value added or the production of emissions. The figure shows that the imports of country C from B are 110 units, but in fact consist of 10 units added value created in country B and 100 units added value in country A. Value added creation in country A hence largely depends on imports by country C, rather than imports by country B. Or conversely, the emissions related to the imports of country C take place mainly in country A, despite the fact that imports come fully from country B. Coefficient approaches assume that all embodied emissions in imports of country C take place in country B. Such differences in allocation approaches have been a source of confusion among practitioners who tried to compare results of studies into embodied emissions in trade (e.g. Kastner et al., 2014; Feng et al., 2011; cf Peters et al., 2012; Tukker et al., 2013a)

To tackle this problem for the materials case, over the last years Eurostat has developed more refined coefficients called 'Raw materials equivalents (RMEs)', that use life cycle inventories (LCIs) related to products imported to Europe to estimate life-cycle wide materials extraction (Schoer et al., 2012). This makes estimates of materials embodied in imports to one specific country more precise – later work of Schoer et al. (2013) showed that material footprints calculated with this approach are in reasonable agreement with those of calculated with the MRIO approach discussed below. Yet, RMEs do not provide information regarding the countries of origin of the indirectly imported products. Further, RMEs only have been calculated for Europe. Finally, if the RME approach would be applied for all countries in the world, the calculated material footprint of all countries together may differ from the global material extraction whilst they should be equal. The material footprints are calculated by a mix of domestic extraction data and LCI data, which is a different data set as used for global material extraction (typically based on geological surveys, e.g. USGS).

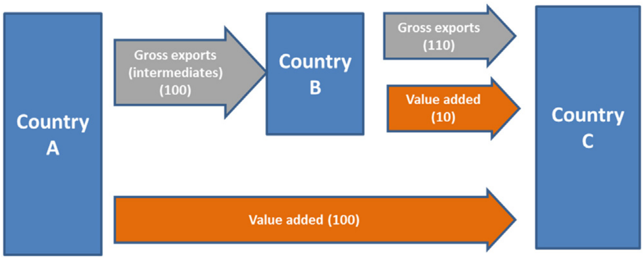


Fig. 1. Gross exports and trade in value added (Figure elaborated from: Ahmad and Ribarsky, 2014).

In view of these drawbacks, *environmentally extended MRIO models* are now widely seen as a promising alternative for the calculation of consumption-based indicators, particularly if one wants to calculate different footprints side-by-side with one consistent data set (see Fig. 2).

In short, an input-output model is based on Supply-Use tables which show a country's total economy, with production divided into a few dozen economic sectors, and consumption divided into a few dozen product (and service) groups. The tables show how much of these specific products, for instance cars, each economic sector produces (output), expressed in monetary value (e.g. Euros or $). The tables also show for each economic sector how much of other products they need to realise this production – e.g. the amount of steel, glass, plastics, electricity and electronics the car industry in that country needs to produce the output of cars (input). Furthermore by adding environmental extensions, for each economic sector, one can identify the primary resource use and emissions ('environmental extensions') – for instance land use by the agricultural sector, or CO_2 emissions by the electricity production sector. It then becomes possible to analyse how the economy is interconnected. For instance, for the final use of cars by consumers, it becomes possible to analyse how much production value came from the car industry, the glass production industry, the steel industry, and so on. Since we also know the emissions and primary resource extraction of each economic sector, we can also estimate the total primary resource extraction and life cycle emissions for the total consumption of cars in that country (cf. Miller and Blair, 2009; Eurostat, 2008). This example is for one country only, and we know that imports and exports in the current global economy are substantial. Hence, one must also understand the emissions and primary resource use involved in trade. For that, one needs to create environmentally extended IO tables for the most important economies of the world and identify the trade flows between the specific sectors of all the countries (Tukker et al., 2013b; Peters et al., 2012). This exercise results in the aforementioned MRIO, which paints a detailed picture of all linkages between production and consumption in the global economy (see Fig. 2 for a three-region example). One of the great strengths of this MRIO approach is that it is inherently consistent. All direct emissions of greenhouse gas (GHG) emissions and primary extraction/use of water, land and materials, next to number of jobs and added value created by industries are, by definition, directly related to the final consumption of products. There is a balance between inputs and outputs so that resources cannot be 'lost' in the calculations.

Fig. 2. Example of an environmentally extended MRIO with three regions.

A problem of footprints calculated with MRIO is that products with different physical characteristics are aggregated into product groups using a common unit of economic value. This then implies that there is an economic allocation of impacts, based on the value of a transaction. If one would like to calculate footprints based on physical allocation, MRIOs have the problem that monetary transactions do not fully reflect physical transactions, since monetary value per physical weight can vary significantly between supply chains (e.g. Weisz and Duchin, 2006). Another drawback of MRIO is that – certainly compared to import data used in coefficient approaches or hybrid approaches – products and sectors are relatively aggregated. Some authors go so far as saying that MRIO should not be applied to footprints mainly related to agriculture, such as land and water, due to the poor product resolution (Weinzettel et al., 2014). Other authors have a more moderate view on this (e.g. Feng et al., 2011; Hubacek and Feng, 2016) pointing at the drawbacks of coefficient approaches already listed above, and calculating water and land footprints with MRIO stays common practice (e.g. Serrano et al., 2016).

As we will discuss in Section 3, this prompted us to use the MRIO EXIOBASE 2 with a fairly detailed agricultural sector in this study, which discerns the 15 most used agricultural commodities.

3. Database and indicators used in this study

3.1. Available MRIO tables

For the reasons outlined in Section 2 we use an MRIO approach for our analysis. Building MRIO is however a complicated task, since such databases require harmonization of the individual SUT and IOT of countries, linking them via trade, and adding environmental extensions to them. Usually all such data come from different databases and are provided in different classifications and level of detail. They are often also mutually inconsistent – hence, when combining such raw data into an MRIO framework initially fundamental requirements like closed economic and mass balances are not met. Significant harmonization and additional estimation of data hence has to be done. Having a harmonized trade data set is even not sufficient – it appears that if one adds up all exports and imports from all IO tables in the world, totals do not match. Only improving the IO tables by individual statistical offices based on this type of information from a global perspective can solve this fundamental problem.

There are currently around five main global MRIO databases available. Their main characteristics are summarized in Table 1 (Tukker and Dietzenbacher, 2013). It concerns:

1. GTAP-MRIO (Narayanan et al., 2012; Peters et al., 2012)
2. GRAM (EE MRIO tables on the basis of OECD IOTs, Bruckner et al., 2012; Wiebe et al., 2012a,b)
3. WIOD (Dietzenbacher et al., 2013) and the related Trade in Value Added (TiVA) database developed by OECD and WTO (Ahmad and Ribarsky, 2014).
4. EORA (Lenzen et al., 2012a,b, 2013)
5. EXIOBASE (Tukker et al., 2009, 2013a,b; Wood et al., 2014, 2015).

3.2. MRIO requirements for environmental footprint analysis and the characteristics of EXIOBASE

Table 1 shows that the different MRIO databases have quite different characteristics making them suitable for different purposes (Tukker and Dietzenbacher, 2013).

For instance, analysis done from an economic, employment and value added perspective do not need much detail in sectors like agriculture, resource extraction, or electricity production. These sectors form just a few percent of GDP of developed countries, and the value added and jobs created in sub-sectors probably do not differ highly. Since creating detail adds to the complexity of making MRIO tables, it is understandable that most projects reviewed in Table 1 did not pursue this. However, for the analysis of environmental pressures the opposite is the case. Here detail in economically less relevant sectors can be essential. Animal husbandry gives totally different impacts e.g. on land use than crop production; electricity generation by coal, gas or wind have very different CO_2 emissions; steel and aluminium production require very different levels of energy input; and manufacturing or service sectors often are irrelevant with regard to their direct inputs of natural resources.

So, to understand, for instance, properly the environmental footprint of specific diets, a high resolution in agriculture is essential (compare e.g. Tukker et al., 2011; for other examples see Tukker, 2006; Weidema et al., 2005). This explains why databases specifically developed for environmental applications (e.g. EORA, EXIOBASE) place a high emphasis on sector and product detail. They, in essence, try to combine the strengths of the coefficient approaches (high detail in processes, products and trade flows) with that of the MRIO approaches (a consistent, complete view on all relations in the global economy).

In comparison, EXIOBASE is the only database that encompasses a consistent, high level of detail in economic sectors and product flows across all countries covered. The construction process of EXIOBASE including the data sources used is summarised in Box 1. More information can be found in Tukker et al. (2009, 2013a,b) and Wood et al. (2015), the latter describing in detail the construction of the most recent published version of EXIOBASE used here. Version 2.1 of EXIOBASE (December 2013) used in this paper has the following characteristics (see the Supplementary information for more detail):

- Covering 43 countries (representing 90–95% of the global economy in terms of GDP) and 5 Rest of Continent regions, implying that in total the full global economy including all environmental pressures are covered. The 27 EU member states and 16 major economies like the US, China, Japan, and Indonesia are individually visible.
- Base year 2007
- Having 163 economic sectors, 6 final demand categories and 200 product groups per country
- Covering per economic sector and country:
  - Over 30 energy related and non-energy emissions to air and water, including a full set of greenhouse gases (rather than just energy related CO_2 emissions, as used in many earlier studies)
- 80 types of resource extractions
- Rain ('Green') water and river/aquifer ('Blue') water extraction by agricultural and non-agricultural sectors
- Land use

3.3. Indicators and possible reference values for footprints

In the footprint calculations, we used the following indicators:

The carbon footprint adds up greenhouse gases like CO_2, CH_4 and N_2O as CO_2-equivalents, using weights reflecting the contribution to global warming of a ton of emissions of a specific greenhouse gas relative to a ton of emissions of CO_2 with a time horizon of 100 years (IPCC, 2013). This indicator is scientifically and politically accepted and has been used by the life cycle assessment community for over two decades now (e.g. Guinée et al., 2002; Goedkoop et al., 2009; Huijbregts et al., 2014). GHG emissions related to land use cover change are not included in the carbon footprint indicator used here.

For the water footprint, we followed the convention applied by the Water Footprint Network and accounted for hydrological water consumption in m3 per sector (e.g. Hoekstra and Mekonnen, 2012). We included Blue water consumption from rivers or aquifers only, as it is here where human activities have most impact and put most

Table 1
Review of the main global MRIO databases.

Database name	Countries	Type	Detail (ixp)[*]	Time	Extensions	Approach
GTAP-MRIO	World (129)	MR IOT	57 × 57	1990, 1992, 1995, 1997, 2001, 2004, 2007	5 (GWP), Land use (18 AEZ), energy volumes, migration	Harmonize trade; use IOTs to link trade sets; IOT balanced with trade and macro-economic data
GRAM	World (54 + RoW)	MR IOT	48 × 48	1995–2010	Various	Use harmonized OECD IOTs; neglect differences like ixi and pxp; use OECD bilateral trade database to trade link.
WIOD	World (40 + RoW)	MR SUT	35 × 59	1995–2009, annually	Detailed socio- economic and environmental satellite accounts	Harmonize SUTs; create bilateral trade database for goods and services; adopt import shares to split use into domestic and imported use; trade information for RoW is used to reconcile bilateral trade shares; add extensions
EORA	World (around 150)	MR SUT/ IOT	Variable (20–500)	1990–2009	Various	Gather all data in original formats; populate an initial estimate of all data points in the global MR SUT/IOT, formulate constraints; let routine calculate global MR SUT/IOT
EXIOBASE[**]	World (43 + 5 Rest of continent)	MR SUT	163 × 200	2007	30 emissions, 60 IEA energy carriers, water, land, 80 resources	Create SUTs; split use into domestic and imported use; detail and harmonize SUTs; use trade shares to estimate implicit exports; confront with exports in SUT; RAS out differences; add extensions

[*] i = number of industries, p = number of products.
[**] In an FP7 follow-up project (DESIRE), EXIOBASE is expanded with time series and additional extensions.

Box 1. The main steps in creating EXIOBASE 2.1 (Tukker et al., 2009, 2013a,b; Wood et al., 2014, 2015)

Step 1: Creating harmonized SUT

SUT and IO tables were sourced from statistical offices. Since SUT form the basis of EXIOBASE, where needed, IO tables were transformed into SUT by assuming a diagonal Supply table.

Using any available data on valuation layers, the Use table in purchaser prices was transformed into a Use table in basic prices. Using additional, more detailed information about total sector turnover and product output from other statistical sources (e.g. Eurostat's PRODCOM on total product output, FAOSTAT), the SUT's rows and columns for economic sectors and products could be split up to the desired level of detail of 163 sectors and 200 products.

This left the problem of estimating the intermediate transactions at this greater level of detail. A variety of sources would allow estimating the use of intermediate products and output of products per unit of turnover in a specific economic sector (e.g. coefficients from countries with very detailed SUT, life cycle inventory databases, other sources). This could give a first estimate of the full detailed table, but one that was not balanced.

Via a minimum entropy optimization procedure the best 'fit' was calculated that created least deviation from the input data, but that fulfilled the requirements of closed economic balances, while the values at the original more aggregated level of the original SUT still holding

Step 2: Adding extensions

Resources extraction was available in a global database relying on data from IEA, FAOSTAT, combined in a comprehensive database on material extraction (SERI and WU Vienna 2014; available at www.materialflows.net). Based on engineering knowledge they could usually simply be related to extracting sectors (e.g. the iron mining sector extracts iron ore, etc.). In similar ways, land use and water use were derived from FAOSTAT and Aquastat and where needed additional sources, and allocated to using sectors.

The detailed product categories in the SUT would include the few dozen energy carriers discerned in the IEA database. Combining these energy flows with emission factors specific for the combination of energy carrier, economic sector using them, per specific country, combustion related emissions could be estimated. In a similar vein, physical activity variables could be estimated for other sectors (e.g. number of livestock in specific agricultural sectors) which combined with emission factors give insights into emissions.

Step 3: Linking Environmentally extended SUT via trade

Using information about trade in SUT, the now harmonized Use tables from the SUT were split in a domestic Use and import Use table.

Using shares from trade databases (e.g. COMTRADE) the countries of origin for imported products could be estimated. If done for all products and all countries, this implicitly estimates the exports from a country. Usually these estimated exports do not match the real exports in the SUT of that country.

Hence, an optimisation procedure on the global bilateral trade data had to be applied to ensure consistency to each country's SUT and such that imports match exports.

Step 4: Creating the global environmentally extended MRIO

The global environmentally extended MR SUT produced this way is transformed into a product by product MRIO using the industry technology assumption described by Eurostat (2008) as "Model B"

pressure on the hydrological environment. A significant drawback is that all water appropriation is seen as equally relevant, regardless if there is water scarcity in the region of extraction (e.g. Pfister and Hellweg, 2009; Ridoutt and Huang, 2012), which led to the development of indicators adjusting for water scarcity (Pfister et al., 2009; not applied here).

For the land footprint, we simply counted the amount of real land use in m^2. This can be criticised since this disregards the quality or productivity of land (c.f. Steen-Olsen et al.,, 2012). However, the methods for impact assessment of land use or land use change are still rather immature (Hauschild et al., 2013; Jolliet et al., 2014), and we argue that land use as such can be used as the first proxy for related impacts.

For the material footprint, we used the convention applied by the Material Flow Analysis (MFA) community of simply adding tons of materials extracted. This material footprint is equivalent to the "Raw material consumption" indicator in MFA (Eurostat, 2012). Again, this does not differentiate between scarcity or environmental impacts related to specific materials. However the absolute quantities are a significant indicator for pressures put on the environment and thus are also relevant with regard to analysis of the compliance to planetary boundaries.

This paper is not the place to finalise the complex, ongoing discussion on planetary limits and maximum per capita resource extraction and emissions (e.g. Rockström et al., 2009; Steffen et al., 2015). Yet, the current state of debate gives some indications of what levels may be required.

For carbon, the UNEP Emissions Gap report states that in order to stay within the 2 °C limit, greenhouse gas emissions need to shrink to zero sometime between 2080 and 2100, and should be in an 18–25 Gt CO_2-eq range by 2050 (UNEP, 2014; see also IPCC, 2013; Meinshausen et al., 2009). With a global population between some 9–10 billion (Gerland et al., 2014), this is around 2-2.5 ton per capita in 2050 while the EU average in 2007 was 13.8 ton per capita and the global average 5.7 ton per capita.

For water, Hoekstra and Wiedmann (2014) mention a maximum global blue water footprint of 1100–4500 billion m3/year, which implies some 110–450 m^3 per capita in 2050. The Water resources group (WRG, 2009) estimates that taking into account economic and population growth between 2010 and 2030 without efficiency improvements a 'water gap' will develop of 40% of existing accessible reliable supply. This suggests that current blue water use of 250 m^3/capita (see Section 4) probably needs a reduction, maybe to around 150 m^3/capita, in the lower ranges of the aforementioned calculation based on Hoekstra and Wiedmann (2014). The recent planetary boundary paper of Steffen et al. (2015) suggests a more generous blue water availability of 4000–6000 billion m^3 at global level, or some 400–600 m^3 per capita by 2050.

The potential for expanding agricultural land use is limited: "halting biodiversity loss requires agricultural land [cropland +

permanent pastures], at least, to stabilize from 2020" (van Vuuren and Faber, 2009). UNEP (2014) suggests a maximum possible expansion of cropland with about 1.5 million km^2, in part at the expense of pastures and forests, on a total amount of existing agricultural and forest land of 88 km^2 (see Section 4). Simply dividing this 88–89.5 million km^2 by the future population in 2050 of 9–10 billion people provides a land availability of 0.009–0.01 km^2 per person. This is probably a generous target since it accepts the existing levels of biodiversity pressures by land use, while reduction of such pressures is widely seen as necessary (Mooney et al., 2005)

For materials, some initial targets of 8 ton per capita have been proposed (Dittrich et al., 2012; used later also by Hoekstra and Wiedmann, 2014). The material footprint however combines material categories for which reduction targets should differ. It concerns energy materials (related to the aforementioned carbon reduction target), biomass (related to the aforementioned targets for agricultural productivity and land use), industrial minerals and building and construction materials (the latter not scarce). More recently Bringezu (2015) worked out somewhat more differentiated targets (10 ton per capita for the abiotic Total material consumption (TMC), 2 ton per capitan for biotic Total material consumption, and 5 ton per capita for Raw material consumption). However, as was the case in the work of Dittrich et al., these values have been derived by using a starting point that material use should be reduced to half of the global level in 2000. Hence, unlike the carbon, water and land footprint targets the material targets are not based on an assessment of physical limits or levels of unacceptable damage (compare further the concept of Safe operating space elaborated by Rockström et al., 2009; and Steffen et al., 2015). We hence refrain from using a single, indicative target for per capita material use.

3.4. Calculating footprints

The calculation of the four footprint indicators was done as follows. Using the product by product version of EXIOBASE (see Box 1) the emissions and primary resource extraction related to a final demand in a country are calculated via the standard approach of the Leontief inverse (c.f. Miller and Blair, 2009):

$$x^E = Sx = S(I - A)^{-1}\ y$$

where y = final demand, A is the matrix of direct input coefficients, S is the matrix of direct resource or emission coefficients, and x^E is the total requirement of environmental factors. These environmental factors subsequently were aggregated to the footprint indicators presented in Section 3.3. Note that in our approach we did not allocate fixed capital formation to production sectors. For this, investment matrices are required, and such data lacks for most countries. Fixed capital formation in a country is hence seen as contributing to the national footprint of that country, whilst the reality is more complex. Capital is after all used for both the production of goods used domestically, and goods for exports, and clearly has a temporal dimension – capital used today was produced sometime in the past, and data about past production practices is not readily available. Our analysis hence misallocates the carbon emissions, water use, land use and material use embodied in imports and exports related to capital goods. Particularly for countries with a high level of capital formation and high exports (e.g. China) this can lead to an underestimation of pollution embodied in exports. This problem is less pronounced for water and land, since water and land use is mainly related to crop production rather than capital formation. This approach is consistent with all current global footprint approaches (e.g. Wiedmann et al., 2015), whilst research is occurring to resolve this discrepancy (Södersten et al., 2016)

In the next sections, we show:

- Total and per capita footprints of countries, including footprints created outside the country of consumption (Section 4.1)
- Final consumption categories per country or country cluster contributing mostly to the footprints of consumption (Section 4.2)
- The relation between the Human Development Index (HDI), happy life years, and footprints of consumption by country (Section 4.3).

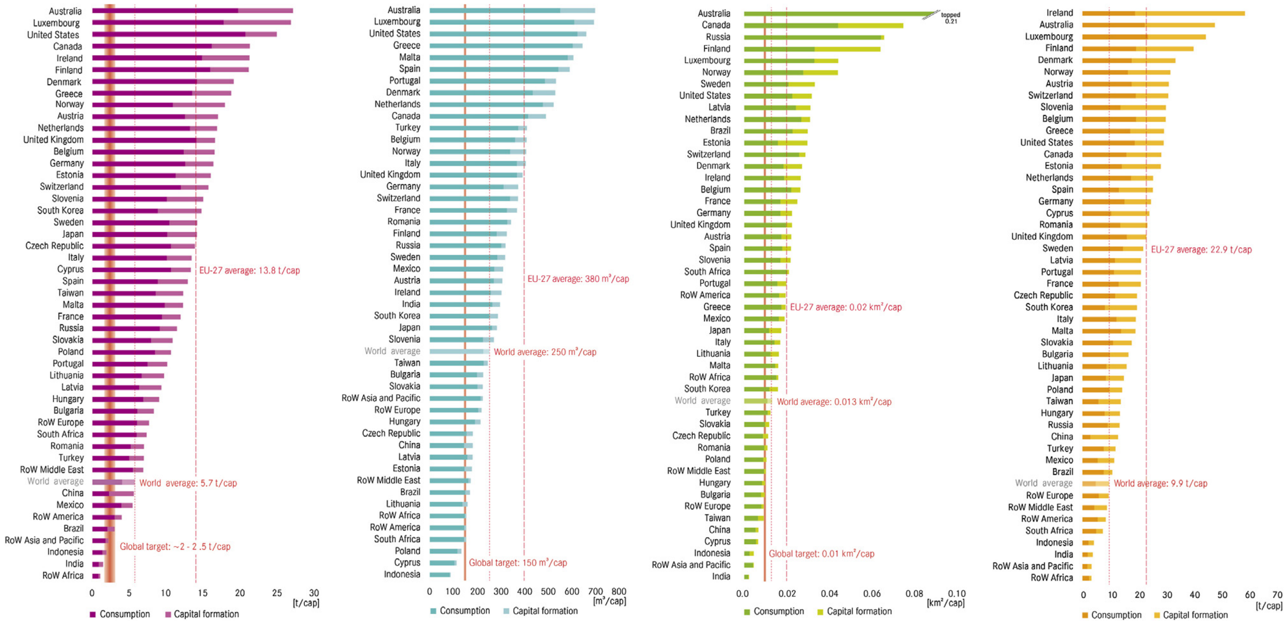


Fig. 3–6. Carbon, water, land and material footprint per capita and country with indicative targets by 2050.

4. Results: the global environmental footprint of nations

4.1. The uneven distribution of carbon, water, land and material footprints – country rankings and country rankings per capita

Figs. 3–6 provide the four footprint rankings, next to the production, or territorial, pressures – the difference being net embodied imports and exports respectively. Two lines give the global average and the EU27 average footprint per capita, next to the indicative targets for 2050. The total footprint per country is a combination of the per capita footprints and population – leading to insight in which countries matter most. These total footprints and territorial pressures per world region are indicated in Table 2. Table 2 further shows the quotient of these two numbers, which indicates which part of the footprint of consumption could theoretically be covered by territorial extractions and emissions. For more elaborated figures, including more detailed trade relations between world regions, we refer to the Supporting information (SI).

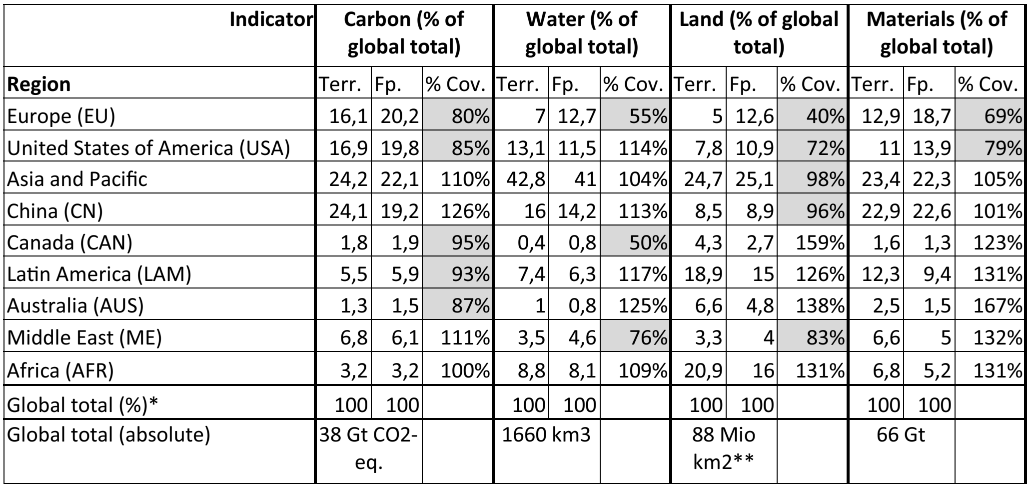
The total and per-capita carbon, material, water and land footprints are unevenly distributed across countries. In general, rich developed countries have a high environmental footprint, while poor underdeveloped countries have a low environmental footprint per capita. It is fairly obvious that while the latter will increase their footprint whilst trying to eradicate poverty, the former have a particular responsibility to avoid using more than their share of 'environmental space' (Moffat 1996; Hille 1997).

The global **carbon footprint** per capita in 2007 was close to 6 ton CO_2-eq, which is significantly higher than the indicative target for 2050 of 2–2.5 ton CO_2-eq. Australian, US and Luxembourg citizens were responsible for emissions over five times this volume, reflecting their high per capita consumption. The EU average was about 13.8 ton CO_2-eq per person – much higher than the indicative target for 2050, but low compared to most other rich OECD nations. The footprints per capita of countries in Africa and India were well below average. France had relatively low carbon footprints per capita due to its high reliance on nuclear power. When looking at the import and export balance, about 20% of Europe's carbon footprint takes place abroad, mainly in China and Asian Pacific (see SI). In absolute terms, just five countries are responsible for 52% of the global carbon footprints (US, 19.7%; China, 19.3%, and Japan, India and Russia following with each about 4–5%; see SI). China is the only country whose carbon footprint in 2007 due to gross fixed capital formation was more than 50% of the total footprint, reflecting the tremendous investments in infrastructure in that country.

The (blue) **water footprint** per capita for 2007 was the highest for Australia, US and Luxembourg, on account of their high per capita GDP. Further, rich countries with limited precipitation, such as Greece, Spain, and Turkey, had high levels of water consumption per capita, since their agricultural systems largely rely on irrigation. For water, the difference between the countries with the highest and lowest footprint was around a factor of 8, which is less pronounced than in the case of the land and material footprints. There are only a few countries which have a per capita water footprint of 150 m3 per annum, which may be required in future. In absolute terms, China and the Asian Pacific region have a footprint of over 55% of the world's blue water resources, followed by Europe (12.7%) and the US (11.5%). Again, when looking at the import and export balance, Europe relies on other countries. Some 45% of the European water footprint is imported, with the Asian-Pacific and China again as important contributors.

In the case of the **land footprint**, the average land use was 0.013 km^2 per capita in 2007. Sparsely populated countries with extensive land use, such as Australia, Canada, Finland and Russia, were at the top. For these countries, the amount of land directly available for its population was the determining factor. We further see that countries with high GDPs or those using land-intensive products, which is for instance the case for wood in Finland, can have high per capita footprints. Interestingly, next to China, relatively developed countries like Hungary, Poland and Slovakia have a land use below the world average. In absolute terms, the global land footprint is more evenly distributed than in the case for the other footprints, with a consumption of embodied land of 33% of the global total by China and the Asian Pacific, 16% by Africa, and

Table 2
Contributions in% of regions to the global Territorial (Terr.) emissions and extractions and Footprints (Fp) of consumption, and fraction of the Footprint that is covered (% Cov.) by Territorial emissions and extractions, 2007.



Indicator	Carbon (% of global total)			Water (% of global total)			Land (% of global total)			Materials (% of global total)		
Region	Terr.	Fp.	% Cov.	Terr.	Fp.	% Cov.	Terr.	Fp.	% Cov.	Terr.	Fp.	% Cov.
Europe (EU)	16,1	20,2	80%	7	12,7	55%	5	12,6	40%	12,9	18,7	69%
United States of America (USA)	16,9	19,8	85%	13,1	11,5	114%	7,8	10,9	72%	11	13,9	79%
Asia and Pacific	24,2	22,1	110%	42,8	41	104%	24,7	25,1	98%	23,4	22,3	105%
China (CN)	24,1	19,2	126%	16	14,2	113%	8,5	8,9	96%	22,9	22,6	101%
Canada (CAN)	1,8	1,9	95%	0,4	0,8	50%	4,3	2,7	159%	1,6	1,3	123%
Latin America (LAM)	5,5	5,9	93%	7,4	6,3	117%	18,9	15	126%	12,3	9,4	131%
Australia (AUS)	1,3	1,5	87%	1	0,8	125%	6,6	4,8	138%	2,5	1,5	167%
Middle East (ME)	6,8	6,1	111%	3,5	4,6	76%	3,3	4	83%	6,6	5	132%
Africa (AFR)	3,2	3,2	100%	8,8	8,1	109%	20,9	16	131%	6,8	5,2	131%
Global total (%)*	100	100		100	100		100	100		100	100	
Global total (absolute)	38 Gt CO2-eq.			1660 km3			88 Mio km2**			66 Gt		

[*] May not add up due to rounding off differences.

[**] Forest (38 Mio km^2) and agricultural land (35 Mio km^2 pastures, and 15 km^2 arable land) only. Settlements and infrastructure, accounting for 3.6 Mio km^2, not included (cf. UNEP, 2014). Grey: regions whose footprints net rely on emissions and resource provision abroad.

13% by Europe. Europe's footprint creates however a massive land use abroad: Europe has a net embodied land use in imports of no less than 60% of its footprint. Otherwise formulated, Europe uses for its consumption about 1.5 times its own territorial land use abroad, mainly in Latin America and Africa (see SI).

With regard to the **material footprint** per capita, conforming to the trend, countries with high per capita GDP score high. Rich countries like Australia and Finland, hosting large primary industries such as mining and forestry, or those like Ireland that experienced a building and construction boom, had particularly high ranks. In this context, it is notable that construction materials are usually responsible for half of the material footprint per capita of a country. In absolute terms, China and Asia and Pacific are responsible for 46% of the global material footprint, Europe for 19%, and the US for 14%. Again, Europe relies for its material footprint heavily on others – in net terms its needs are covered by 31% by other regions, mainly the Middle East, Latin America and the Asian Pacific.

Since we did not allocate capital formation and related pressures to industrial production sectors, the impacts of capital formation in a country are included in its national footprint. As indicated in Section 3.4, particularly the material and carbon footprints of countries with high capital formation and high exports (most notably China) include environmental impacts of capital that may eventually be used to produce commodities imported by other countries. This probably led to overestimation of footprints of these countries and underestimation of footprints of their trading partners.

Overall this section shows that, particularly for rich countries, reduction of footprints is unavoidable. They all have footprints well over the global average, where particularly for the carbon footprint high reductions are needed. Though Europe compared to other OECD countries already has relatively low per capita footprints, reduction in Europe is still relevant. Europe is the only region in the world where the carbon, water, land and material footprint are all higher than the territorial emissions and resource extractions (Table 3). In part this may be due to the fact that Europe has more efficient production technologies than most of the developing countries, and it may be that Europe's footprint can hence be reduced when the countries from which Europe receives its imports improve their energy and resource-efficiency in the first place (cf. Tukker et al., 2013a). However, the fact remains, that for all footprint categories Europe relies on other countries, which increases the level of vulnerability related to supply security. This leads to two pertinent questions: which final consumption categories have priority in a resource-efficiency policy (addressed in Section 4.2), and is there a possibility to reduce footprints while maintaining quality of life (addressed in Section 4.3).

4.2. Final consumption hot spots

In the following we provide an analysis in which we use the high product detail of 200 categories of EXIOBASE to final consumption hot spots in the EU27 versus non EU27 countries. Table 3 shows the final consumption categories that have the highest carbon, water, land and materials footprint per capita for the EU27 and non EU27. To retain a manageable number of products, Table 3 shows only those products specifically that had on any of the footprints a contribution of more than 3% of the total footprint per capita in the EU27 or in the non EU27. For the purpose of presentation, we further aggregated all food products and products related to electricity provision. Note that we did not distribute the direct impacts from household and e.g. the use of electricity to consumption categories (e.g. cooking of food, or driving of cars) but showed the impacts of purchases of final consumers and direct impacts of households only.

The figures in essence confirm earlier work done by us and others (Tukker, 2006; Steen-Olsen et al., 2012): that food products, motor vehicles, and buildings (including direct fuel emissions under households) have the highest footprints and as such can be considered as priority areas for policies, including consumption policies. Not surprisingly food and food products dominate with regard to the land and water footprints, whereas construction work dominates the material footprint. There are, however, some differences in the patterns of the contribution of different product categories to footprints between the EU27 and non-EU27 countries. Construction work is relatively more important for the carbon and material footprint for non EU27 countries, reflecting the fact that most of the required stock of housing and infrastructure in the EU27 is already available. Hotel and restaurant services have, particularly in the EU27, a rather high contribution to the water and land footprint, which in earlier work already was found to relate to food consumption (Tukker, 2006).

4.3. Relation between footprints and quality of life

It is well known that GDP is not a good indicator for quality of life (EC, 2009). Therefore, alternative indicators have been developed such as, the Human Development Index (HDI; UNDP, 2009) and the Happy Life Years (HLY) index. The HDI is published annually in the Human Development Report by the United Nations Development Program and includes life expectancy, education,

Table 3
Final consumption categories with the highest carbon, water, land and material footprint per capita in the EU27 and non EU27 countries (having at least a 3% contribution on one of the footprints).

	Footprint type	Carbon		Water		Land		Materials	
Exiobase product code	Product category	EU27	Non EU27	EU27	Non EU27	EU27	Non EU27	EU27	Non EU27
0	Direct household	16,2%	10,5%	2,6%	3,9%	0,0%	0,0%	0,0%	0,0%
1–17, 19, 43–54	Food and food products	6,5%	7,0%	57,4%	72,4%	44,7%	44,9%	19,5%	22,4%
118	Machinery and equipment n.e.c.	3,8%	4,1%	1,0%	0,8%	1,1%	0,7%	2,5%	2,3%
123	Motor vehicles, trailers and semi-trailers	5,0%	3,4%	1,4%	0,7%	1,7%	0,9%	3,3%	2,0%
125	Furniture; other manufactured goods n.e.c.	2,0%	1,6%	1,2%	0,7%	3,3%	2,0%	2,1%	1,5%
128–141	Electricity, transmission, distribution	4,6%	10,2%	0,7%	0,4%	0,5%	0,1%	1,7%	1,0%
150	Construction work	10,3%	18,7%	2,8%	3,1%	8,3%	8,7%	27,2%	37,8%
156	Hotel and restaurant services	2,6%	2,1%	9,9%	5,5%	6,0%	3,2%	3,6%	2,0%
168	Real estate services	2,5%	1,7%	0,9%	0,3%	1,6%	0,9%	3,2%	1,2%
173	Public administration, defence, social security	2,9%	4,2%	1,6%	1,2%	2,0%	2,0%	2,9%	3,9%
175	Health and social work services	3,2%	3,0%	3,4%	1,5%	2,8%	1,4%	2,7%	1,8%
	Other	40,3%	33,6%	17,2%	9,6%	28,1%	35,2%	31,3%	24,2%
	Total	100%	100%	100%	100%	100%	100%	100%	100

and per capita income (UNDP, 2009). HLY is calculated by multiplying life expectancy by a happiness index (Veenhoven, 1996). Figs. 7–10plot the HDI and HLY for countries against their carbon, water, land and materials footprint to see if higher footprints correlate with a higher HDI or HLY.

The figures indicate that this is only partially the case. At low footprint levels, we see indeed that countries with higher footprints tend to have a higher HDI and HLY. But for all four footprints, the curve levels off. Countries such as Japan, Italy and Spain consistently have much lower footprints as e.g. Luxembourg or Australia, while all having HDIs of more than 0.95. This phenomenon has been reported earlier for the ecological footprint and carbon emissions (e.g. Abdallah et al., 2012; Steinberger et al., 2012), but not for the full footprint family reported here. The conclusion is straightforward: countries with the highest footprints in principle have scope for reduction, without loss of quality of life. It has to be noted though, that none of the countries with a HDI higher than 0.95 has a footprint that is below the global average.

We further include in the figures the lines for the global average footprint, the EU average footprint, and indicative target levels for 2050. From this, a more concerning message arises. No country with a high HDI manages to come close to the indicative per capita resource footprint targets, for instance for carbon and water. This implies that radically new policies need to be set in place to allow a high level of human development and adequate resource efficiency.

5. Reflection and conclusions

This paper finds that the different resource footprints vary significantly among countries, particularly if one looks at per capita figures. Consistently, rich developed countries like Australia, the US, Luxembourg and some other EU countries have the highest carbon, water, land and material footprints per capita. Less developed countries such as Indonesia and India tend, in general, to have the lowest footprints per capita. This result is well in line with the earlier, separate footprint analyses referred to in the introduction (e.g. Hoekstra and Chapagain, 2007; Davis and Caldeira, 2010; Bruckner et al., 2012). From the developed nations, the EU27 belongs to the most resource-efficient. The US, Canada and Australia all have higher footprints per capita, particularly for carbon, materials and land. Japan and Korea have slightly lower water, land and material footprints than the EU27. In absolute terms, we see the dominance of China and the Asian-Pacific region, responsible for 41% of the carbon footprint, 54% of the water footprint, 35% of the land, and 45% of the material footprint (all in 2007).

When one analyses which region depends on embodied imports from other regions for the footprint of its final consumption, particularly the situation of Europe is striking. Our analysis showed that for all four footprints the territorial impacts of Europe are significantly lower compared to the carbon, water, land and material footprint of consumption. Europe is the only world region with such an outstanding role of foreign resources to maintain domestic consumption. Formulated differently: for all indicators on the dashboard defined in the Resource Efficient Europe communication (EC, 2011), Europe is currently living on emission and resource credits provided by other parts of the world. The same applies for Japan and Korea. Developed nations with rich domestic resource endowment, like the US, Canada and Australia, however, still have net embodied exports of at least one of their footprints.

We live in a world that inevitably will become more resource-constrained. Powerful players from China and the Asian Pacific, that now already need a dominant share of the Earth's resources for their consumption, still have not reached European or US wealth levels. With competition for resources from these players enhancing, Europe's position seems to be a difficult one. Enhancing resource availability in Europe itself could be one answer. However, improving resource-efficiency of European consumption is another option (cf. EC, 2011). The analysis undertaken in this paper gives some important insights into priority areas of action. First, we saw that within the EU27 some countries have a markedly higher footprint than others. Apart from the consistent high score of Luxemburg different countries are located in the EU27 top group, such as Finland and Denmark in the case of materials, and Spain, Portugal and Malta in the case of water. Second, we show a number of products that have a high life cycle impact per Euro or a high absolute life cycle impact, and that are candidates for

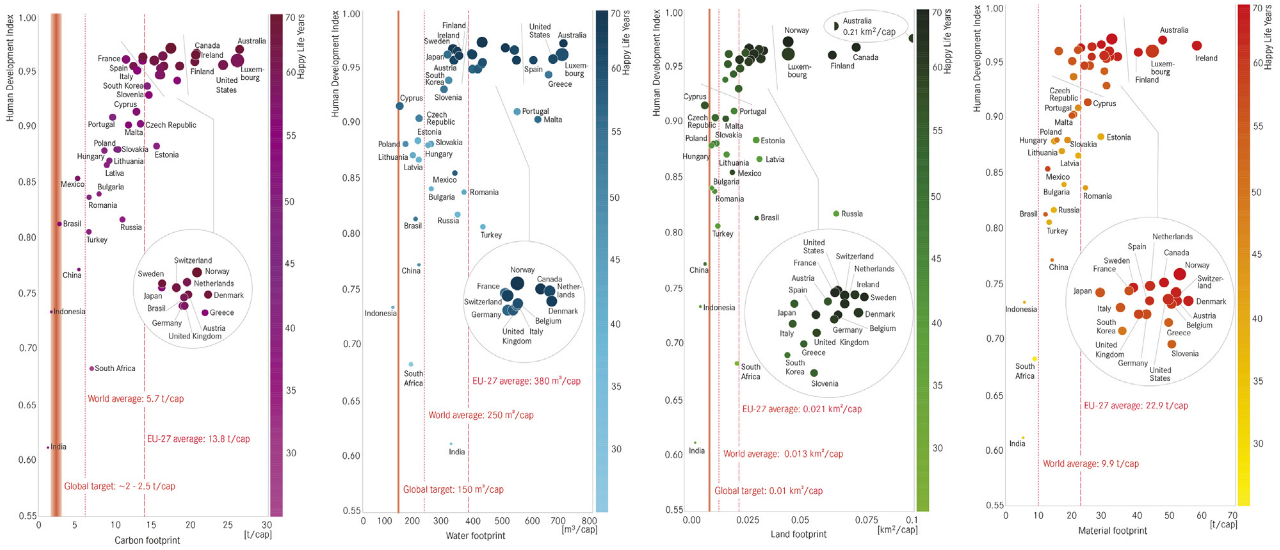


Fig. 7–10. Dependence between human development index (y axis) and happy life years (colour) and per capita environmental impact (x-axis; consumption based approach) and indicative targets for 2050. The dots are sized according to the purchasing power parity GDP per capita of the country.

resource-efficiency improvements along their life cycles (e.g. food products and hospitality services, construction and transport services). Finally, on a more structural level, the plot between HDI/HLY and the four footprints illustrated that countries with similar high HDIs can differ as much as a factor of 2–3 in carbon, water, land and material footprint. Countries as different as Japan, Italy and Spain all have HDI of over 0.95 but compared to other developed countries, low footprints (apart from Spain for water). This calls for further investigation which socio-economic structures such countries have in place that allow them delivering high HDI levels with a relatively limited footprint. It is further notable that countries with HDI of 0.95 or higher all have an above average carbon, water, land and material footprint. Particularly for carbon, but probably also for the water and material footprint absolute reductions are likely to be necessary (c.f. Meinshausen et al., 2009; Tukker, 2013; Hoekstra and Wiedmann, 2014). The EU hence cannot follow any example – radically new policies need to be set in place to allow a high level of development and adequate resource efficiency. The EU, being on the forefront of global leadership, is in a good position to take the lead and should not wait for other regions to catch up.

This exercise also shows that detailed global MRIO databases such as EXIOBASE are well suited to analyse a wide range of questions related to environmental impacts, trade and economic globalisation, in a consistent framework. Global MRIO databases have the big advantage that they are inherently consistent and complete and can follow supply chains at a global level. All direct emissions of greenhouse gases and primary extraction/use of water, land and materials, next to the number of jobs and value added created by industries are, by definition, related to the final consumption of products – they follow basic material balance principles and cannot be 'lost' in the calculations. With the growing detail of global MRIOs, exemplified by EXIOBASE 2.1, the main strong point of coefficient approaches – product detail – becomes less and less pronounced. More detailed MRIOs and hybrid approaches (Galli et al., 2013; Weinzettel et al., 2014) are probably the most promising way forward. A further added value of MRIO approaches is that they use an integrated environmental-economic data set, which can form the basis for analysis of economic trade-offs of policy interventions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2016.07.002.

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