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Abstract:
Material flow-based indicators play an important role in indicator sets related to green and resource-efficient growth. This paper examines the global flows of materials and the amounts of materials directly and indirectly necessary to satisfy domestic final demand in different countries world-wide. We calculate the indicator Raw Material Consumption (RMC), also referred to as Material Footprint (MF), by applying a global, multi-regional input-output (MRIO) model based on the GTAP database and extended by material extraction data. We examine world-wide patterns of material extraction and materials embodied in trade and consumption, investigating changes between 1997 and 2007. We find that flows of materials related to international trade have increased by almost 60% between 1997 and 2007. We show that the differences in Material Footprints per capita are huge, ranging from up to 100 tonnes in the rich, oil-exporting countries to values as low as 1.5 to 2 tonnes in some developing countries. We also quantify the differences between the indicators Domestic Material Consumption (DMC) and RMC, illustrating that net material exporters generally have a DMC larger than RMC, while the reverse is observed for net importers. Finally, we confirm the fact that most countries with stable or declining DMCs actually show increasing RMCs, indicating the occurrence of leakage effects, which are not fully captured by DMC. This challenges the world-wide use of DMC as a headline indicator for national material consumption and calls for the consideration of upstream material requirements of international trade flows.

Keywords: International Trade; Material Footprint; Multi-Regional Input-Output Analysis; Raw Material Consumption; Sustainable Resource Management

1. Introduction

In recent years, issues related to resource efficiency and de-coupling have been constantly climbing up the policy agenda around the world. This development is being driven by economic challenges, such as rising competition over strategic resources, as well as environmental considerations through expected positive effects from de-coupling of economic growth from resource use and related environmental impacts (UNEP 2011b; McKinsey 2011; Hinterberger et al. 2013; Transatlantic Academy 2012; Lee et al. 2012).

Resource efficiency was defined as one of seven core policy priorities in the context of the overarching development strategy for Europe, entitled "Europe 2020" (European Commission 2011b, 2011a), and intensive activities are currently on-going to define a set of policy targets for increased resource efficiency and to identify appropriate indicators for their monitoring (European Commission 2011a, 2012; BIO IS et al. 2012). Also a number of international organizations have started including resource efficiency as a core thematic pillar in their policy strategies and have considered resource indicators in their monitoring schemes, most notably OECD's Green Growth Initiative (OECD 2011a) and UNEP's Green Economy Initiative (UNEP 2012).

Economy-wide material flow accounting (EW-MFA) has a long tradition in the analysis of the material use and productivity on the country level and offers a high degree of international standardization and harmonization. EW-MFA has been standardized by the European Statistical Office (EUROSTAT) in regularly updated methodology guides (for the latest version, see EUROSTAT 2013b) and has also been endorsed by the OECD (2007). Indicators of direct material flows derived from EW-MFA, most importantly the Domestic Material Consumption (DMC) indicator, are now routinely reported by all EU Member States (EUROSTAT 2013c). The DMC indicator is also widely available outside Europe, including all OECD countries (OECD 2011b), the Asia and Pacific region (UNEP 2013a; Schandl and West 2010; Giljum et al. 2010), Latin America (UNEP 2013b; West and Schandl 2013; Russi et al. 2008) and Africa (UNCTAD 2012). Also several studies provide comparative assessments of DMC across all countries world-wide (Dittrich et al. 2012; Steinberger et al. 2010; Krausmann et al. 2008; Steinberger et al. 2013; Giljum et al. 2014).

However, the DMC indicator faces the problem that upstream resource requirements of traded goods are not considered. In other words, imported goods are accounted as their actual weight, thus ignoring resources used along their process chains and not included in the final product. As a consequence, countries can reduce their material consumption as measured with the DMC indicator by outsourcing material intensive extraction and processing abroad (Wiedmann et al. 2013; Munoz et al. 2009; Schaffartzik et al. in press; Femia and Moll 2005).

The indicator Raw Material Consumption (RMC), also known as Material Footprint (MF), can be regarded as a further development of DMC and is a consumption-based indicator, which allocates all globally extracted and used raw materials to domestic final demand. RMC thus takes account of the increasing spatial separation of production and consumption and the relocation of material extraction and associated environmental pressure across world regions. However, it is important to note that comprehensive consumption-based indicators considering upstream material requirements, such as RMC, are rather a complement to than a replacement of indicators measuring direct physical flows, such as DMC (Giljum et al. 2014; Marra Campanale and Femia 2013). For example, Domestic Material Consumption (DMC) is a more appropriate indicator to measure the potential environmental pressure on the domestic territory, as it covers all material flows actually entering an economy and which (sooner or later) are partly emitted back to the domestic environment as waste and emissions. Furthermore, when designing national strategies for resource management, actual material flows as measured by DMC are easier to be addressed by governments compared to foreign upstream material flows along international supply chains. Finally, it is important to note that the concept to account for imports and exports in terms of their Raw Material Equivalents (RMEs), i.e. the raw materials used along the global supply chain of a good, requires international data and additional model assumptions and cannot be based on national statistics only. This makes it more difficult for RMC accounting methods to be accepted by statistical offices, which attempt to rely on own data as far as possible.

Several RME accounting methodologies are currently being developed and tested to calculate RMC or MF, for example by EUROSTAT. The RMC indicator, there, is the sum of domestic extraction plus imports minus exports, both expressed in RMEs. This method implements a hybrid approach, which combines mixed-unit input-output analysis with Life Cycle Assessments (Schoer et al. 2012b; EUROSTAT 2013a). Similar approaches have also been applied in various studies on the national level (Weinzettel and Kovanda 2009; Destatis 2009; Schaffartzik et al. in press; Kovanda and Weinzettel 2013).

In recent years, Multi-Regional Input Output (MRIO) approaches were increasingly developed for environmental applications, including assessments of material flows, which explicitly cover flows within and between a larger number of countries, linked by bilateral trade (Tukker et al. 2013; Dietzenbacher et al. 2013; Wiedmann et al. 2011; Lenzen et al. 2013). These models are able to reflect the actual material intensities of industries in different countries and allocate the material extraction in one country via monetary inter-sectoral and trade flows to final demand in other countries. MRIO-based assessments now cover a large range of environmental and resource use issues (Giljum et al. 2013; Murray and Lenzen 2013) and have already been applied to the case of material consumption by several studies (Bruckner et al. 2012; Arto et al. 2012; Wiebe et al. 2012; Wiedmann et al. 2013; Giljum et al. 2011).

In this paper, we present results for the Material Footprint of nations applying the GTAP input-output and trade database in combination with data from *materialflows.net*, a global database on material flows. The objective of the paper is to examine global patterns of material extraction and materials embodied in international trade and consumption and analyze how they changed between 1997 and 2007. We aim to identify major importers and exporters of embodied materials and to analyze which world regions provide the raw materials directly and indirectly consumed by single countries (such as the USA and China) and world regions (such as the EU). We also aim at illustrating differences in national material consumption when using the DMC versus the RMC indicators and assess, whether or not countries showing a declining or stable DMC actually have increasing RMCs. This study for the first time applies the GTAP database, one of the major and most widely applied MRIO databases, for the assessment of global material flows and compares its applicability with other options for global MRIO databases. We also present new ways for illustrating the analytical potential of MRIO-based MFA results by disaggregating RMC of countries by product groups and regions of origin of consumed raw materials.

The structure of the paper is as follows. In section 2, we describe the MRIO methodology, discussing its advantages and disadvantages compared with other methodological approaches to calculate Material Footprints. Section 3 presents the results and analysis of the Material Footprint calculations for continents and selected countries. Section 4 discusses the results in the current policy context and the final section 5 provides conclusions on required methodological and data developments.

2. Methodology

In a nutshell, MRIO models link input-output tables of several countries or regions via bilateral trade data. MRIO models thereby can trace not only domestic supply chains, but supply chains on the international level (Feng et al. 2011) and thus allow taking into account the different resource intensities in different countries (Tukker et al. 2013). This study applies a standard Leontief-type model on the multi-regional input-output system extended by material extraction data (e.g. tonnes of materials mined or harvested), such as done before by others (see Wiedmann et al. 2013; Bruckner et al. 2012). A detailed methodological description is provided in the Supporting Information S1.

2.1 Advantages and disadvantages of the MRIO approach

MRIO models allow calculating various footprint-type indicators for a large number of products and sectors, even those with very complex supply chains (Chen and Chen 2013). This feature allows MRIO models to avoid truncation errors occurring in approaches based on bottom-up process analysis (e.g. Life Cycle Assessment), i.e. errors resulting from the fact that complex production chains cannot be fully analyzed and certain upstream chains have to be "cut off" (Lenzen 2000; Wiedmann 2009a). Furthermore, MRIO-based assessments avoid imprecise definition of system boundaries, as the whole global economy is the framework for the assessment (Wiedmann 2009b; Giljum et al. 2013). Input-output models, by following a top-down accounting logic, also avoid double counting. Thus, a specific resource input can only be allocated once to final demand, as all supply chains are completely represented (Daniels et al. 2011). Last but not least, an advantage of the MRIO approach is that the accounting framework is closely linked to standard economic and environmental accounting (United Nations 2012).

However, applying input-output analysis also imposes disadvantages. MRIO models work on the level of economic sectors and product groups, assuming full homogeneity within the industries or commodities distinguished in the input-output tables. This assumption implies that in one sector, a number of different products and processes with potentially very different resource intensities are mixed together, which limits the level of disaggregation that can be achieved (Ewing et al. 2012). Consequently, this approach can lead to distortions of results, when different materials such as industrial minerals and metal ores are aggregated into one sector (see also results section below). Other disadvantages that are emphasized in the literature related to footprint-type indicators based on input-output analysis are

(1) the relatively large time-lag for the publication of input-output tables (the EORA system (Lenzen et al. 2013) is an exception, as it publishes data with a time-lag of only 2-3 years)

(2) the high sensitivity of input-output models to relatively small errors in the trade data, in cases where imports and exports of a country are relatively large compared to domestic production (Mekonnen and Hoekstra 2011),

(3) the use of monetary economic structures for the allocation of physical flows and the applied proportionality assumption, i.e. that a flow from specific sector has the same material intensity disregarding the receiving country and sector (Bruckner et al. 2012), and

(4) the high sensitivity of results to the way resource use data are allocated to sectors.

A number of recent research projects have been devoted to the refinement of input-output tables and multi-regional input-output systems to calculate footprint-type indicators (Dietzenbacher et al. 2013; Tukker and Dietzenbacher 2013; Tukker et al. 2013; Lenzen et al. 2013). The intention is to create systems with a higher level of disaggregation, in particular in environmentally-sensitive primary sectors, thus avoiding mistakes resulting from the high level of aggregation of IO tables.

2.2 Data sources for the MRIO model

Conventional MRIO models apply input-output tables and bilateral trade data in monetary units in the core of the model. Several global input-output databases have been developed, which have specific strengths regarding different aspects, as described in a special issue on global multiregional input-output frameworks (see Tukker and Dietzenbacher 2013).

For the MRIO model underlying the calculations in this paper, we use the GTAP database (Narayanan et al. 2012; Andrew and Peters 2013), which is a database of harmonized input-output tables and bilateral trade data established and maintained at Purdue University, Indiana, USA. The main reasons for this choice were the availability of data for several points in time and the high number of countries explicitly represented with national tables. In addition, GTAP has so far been the most widely applied database for footprint-type assessments and has been used extensively for the cases of GHG emissions, water and land (for example, Chen and Chen 2013; Lugschitz et al. 2011; Wilting and Vringer 2010; Weinzettel et al. 2013; Andrew and Peters 2013; Peters et al. 2011). GTAP Version 8 (year 2007) covers 129 regions (EU-27 and OECD countries, major emerging economies, a substantial number of developing countries in Asia, Africa, and Latin America) and 57 commodity sectors.

Compared to most other MRIO databases that have been applied for the case of assessing global material flows, the GTAP database has higher country coverage. The OECD input-output database includes 48 countries (Yamano and Ahmad 2006), the WIOD database comprises 40 countries plus a rest of the world region (Dietzenbacher et al. 2013), and the EXIOBASE covers 44 countries plus 5 rest of the world regions (Tukker et al. 2013). In contrast, the EORA database (Lenzen et al. 2013) includes 187 countries.

Currently, only few sources for comprehensive international datasets on material extraction are available (see Giljum et al. 2013). For this paper, we selected the *materialflows.net* database, a global set of material extraction data, which provides a high level of disaggregation for all countries world-wide following the EW-MFA standards (EUROSTAT 2013b) and covering the period of 1980 to 2010. The database covers all material categories (fossil fuels, metals, minerals, and biomass) and has been applied in a number of other global MRIO-MFA assessments (Arto et al. 2012; Giljum et al. 2011; Wiebe et al. 2012; Bruckner et al. 2012).

In order to link material extraction to the GTAP input-output tables, more than 250 material commodities need to be aggregated into a small number of commodity sectors. Table 1 below shows how the MFA data are assigned to the GTAP sectors.

Nr.	Material extraction category	GTAP sector
1	Paddy rice	Paddy rice
2	Wheat	Wheat
3	Other cereal grains	Cereal grains nec
4	Vegetables, fruit, nuts	Vegetables, fruit, nuts
5	Oil seeds	Oil seeds
6	Sugar cane, sugar beet	Sugar cane, sugar beet
7	Plant-based fibers	Plant-based fibers
8	Other crops	Crops nec
9	Grazed biomass	Bovine cattle, sheep and goats, horses
10	Forestry	Forestry
11	Fishing	Fishing
12	Coal	Coal
13	Oil	Oil
14	Gas	Gas
15	Industrial minerals	Minerals nec
16	Iron ores	Minerals nec
17	Non-ferrous metals	Minerals nec
18	Construction minerals	Minerals nec (50%), Construction (50%)

Table 1: Allocation of material categories to GTAP sectors

For biomass products and fossil fuels eleven and three extraction sectors, respectively, are distinguished. However, there is still a large number of biomass products of different price levels included in each of the aggregated product groups, for example, in the categories of “Vegetables, fruit, nuts” or “Crops nec”.

Also with regard to metal ores and minerals, the aggregation level of the input-output tables is very high as the material extraction data for all industrial minerals, iron ores, and non-ferrous ores are all allocated to only one GTAP sector “*Minerals nec*.” For construction minerals, we follow the approach recently applied by Schaffartzik et al. (2014) to allocate 50% to “*Minerals nec*” and 50% to the “*Construction*” sector, assuming that half of construction minerals are extracted by the construction industry itself.

With 15 economic sectors involved in resource extraction activities, GTAP allows disaggregating a significantly higher number of material categories compared to the OECD and WIOD databases, which contain 4 material extraction sectors, but less than EXIOBASE with 26 extraction sectors for biotic and abiotic materials. The number of extraction sectors in EORA differs depending on the level of detail of available input-output tables for each country.

The problems arising from limited sectoral detail of input-output tables could be overcome by two ways. Either by further disaggregating a larger number of environmentally-sensitive sectors, such as done for the EXIOBASE (see Tukker et al. 2013) or by using detailed physical data on the product level to model the first stages of material flows from extraction to basic processing industries outside the MRIO system (Ewing et al. 2012; Schoer et al. 2012a) and link the materials to sectors further downstream in the production chain. Both options are currently pursued and need to be further investigated in future research (see conclusions section below).

3. Results

Table 2 presents a summary of the MRIO-MFA results for all continents and selected major countries in 1997 and 2007. We show values for Domestic Material Extraction (DE), materials embodied in imports serving domestic final demand ($IM_{Dom\ FD}$) and domestically extracted materials embodied in exports (EX_{DE}). Imports, which are re-exported directly or after further processing are therefore neither included on the import nor on the export side. The Raw Material Trade Balance (RTB) is calculated as $IM_{Dom\ FD}$ minus EX_{DE} and the RMC as DE plus RTB. We also compare RMC values with results for the DMC indicator, including the percentage difference between RMC and DMC. DMC data for 1997 and 2007 were obtained from a global material flow study by Dittrich et al. (2012).

A comparison of results from our calculations with existing Material Footprint studies for selected countries and world regions is provided in Supporting Information S2.

3.1. Material Footprints: the continental perspective

The development of DE illustrates that global material extraction increased by more than 37% between 1997 and 2007, from 47.7 billion tonnes in 1997 to 65.5 billion tonnes in 2007. More than 50% of all material extraction in 2007 took place in Asia, which also experienced the highest aggregated growth rate of all continents (+87%). Growth in domestic material extraction was generally moderate in developed regions, such as North America (3%) or Europe (16%).

		DE		IM Dom FD		EX DE		RTB		RMC		RMC Δ	RMC/cap (t)		DMC		DMC Δ	DMC/cap (t)		RMC/ DMC
		1997	2007	1997	2007	1997	2007	1997	2007	1997	2007		1997	2007	1997	2007		1997	2007	
Africa		**3,690**	**4,924**	**383**	**891**	**1,187**	**2,003**	**-803.4**	**-1,111.9**	**2,886**	**3,812**	**32%**	**4.0**	**4.0**	**3,458**	**4,544**	**31%**	**4.8**	**4.7**	**84%**
of which	*South Africa*	*n.a.*	*682*	*n.a.*	*139*	*n.a.*	*435*	*n.a.*	*-296.0*	*n.a.*	*385*	*n.a.*	*n.a.*	*8.1*	*607*	*588*	*-3%*	*14.3*	*12.3*	*66%*
Asia		**18,827**	**35,220**	**4,670**	**8,962**	**4,360**	**10,713**	**309.8**	**-1,750.7**	**19,137**	**33,469**	**75%**	**5.7**	**8.1**	**21,632**	**35,049**	**62%**	**6.4**	**8.5**	**95%**
of which	*China*	*8,254*	*17,017*	*474*	*2,163*	*1,608*	*3,896*	*-1,133.5*	*-1,732.7*	*7,120*	*15,285*	*115%*	*6.0*	*11.6*	*8,439*	*17,741*	*110%*	*7.1*	*13.5*	*86%*
	India	*2,957*	*4,346*	*188*	*760*	*417*	*989*	*-229.2*	*-229.1*	*2,728*	*4,117*	*51%*	*2.8*	*3.7*	*3,004*	*4,428*	*47%*	*3.0*	*3.9*	*93%*
	Japan	*971*	*774*	*1,809*	*1,737*	*58*	*81*	*1,750.9*	*1,656.1*	*2,722*	*2,430*	*-11%*	*21.6*	*19.0*	*1,640*	*1,447*	*-12%*	*13.0*	*11.3*	*168%*
	Russia	*n.a.*	*2,575*	*n.a.*	*507*	*n.a.*	*1,254*	*n.a.*	*-746.9*	*n.a.*	*1,828*	*n.a.*	*n.a.*	*12.9*	*1,485*	*1,862*	*25%*	*10.1*	*13.1*	*98%*
Europe		**6,337**	**7,335**	**4,602**	**6,974**	**2,385**	**2,685**	**2,216.5**	**4,289.5**	**8,553**	**11,625**	**36%**	**17.7**	**19.7**	**7,957**	**8,618**	**8%**	**16.4**	**14.6**	**135%**
of which	*Germany*	*1,262*	*1,009*	*931*	*1,157*	*445*	*359*	*486.1*	*797.9*	*1,748*	*1,807*	*3%*	*21.3*	*22.0*	*1,496*	*1,212*	*-19%*	*18.3*	*14.7*	*149%*
	UK	*737*	*575*	*616*	*937*	*254*	*219*	*361.5*	*717.6*	*1,099*	*1,293*	*18%*	*18.8*	*21.2*	*757*	*690*	*-9%*	*13.0*	*11.3*	*187%*
Latin America		**5,931**	**7,959**	**794**	**1,153**	**1,980**	**3,539**	**-1,185.6**	**-2,387.0**	**4,746**	**5,572**	**17%**	**9.5**	**9.8**	**5,623**	**7,421**	**32%**	**11.3**	**13.1**	**75%**
of which	*Brazil*	*2,048*	*2,920*	*246*	*261*	*310*	*1,051*	*-63.8*	*-789.8*	*1,984*	*2,131*	*7%*	*11.9*	*11.2*	*1,935*	*2,583*	*34%*	*11.6*	*13.6*	*82%*
	Mexico	*860*	*1,070*	*163*	*316*	*279*	*292*	*-116.1*	*24.2*	*743*	*1,094*	*47%*	*7.8*	*10.4*	*797*	*1,049*	*32%*	*8.4*	*10.0*	*104%*
North America		**7,922**	**8,162**	**2,675**	**3,913**	**1,847**	**1,935**	**828.0**	**1,978.6**	**8,750**	**10,141**	**16%**	**28.5**	**30.3**	**8,080**	**8,572**	**6%**	**26.3**	**25.6**	**118%**
of which	*USA*	*6,866*	*7,098*	*2,362*	*3,459*	*1,176*	*1,271*	*1,186.2*	*2,188.2*	*8,052*	*9,286*	*15%*	*29.0*	*30.8*	*7,274*	*7,783*	*7%*	*26.2*	*25.8*	*119%*
Oceania		**1,371**	**1,838**	**160**	**294**	**863**	**1,299**	**-702.3**	**-1,004.9**	**668**	**833**	**25%**	**30.0**	**24.0**	**1,058**	**1,262**	**19%**	**47.5**	**36.3**	**66%**
of which	*Australia*	*1,229*	*1,600*	*131*	*236*	*784*	*1,162*	*-652.6*	*-925.8*	*576*	*674*	*17%*	*31.1*	*32.0*	*861*	*1,036*	*20%*	*46.5*	*49.2*	*65%*
World *		**47,711**	**65,481**	**13,655**	**22,188**	**13,655**	**22,188**	**0.0**	**0.0**	**47,711**	**65,481**	**37%**	**8.2**	**9.9**	**47,809**	**65,467**	**37%**	**8.2**	**9.9**	**100%**

Notes: DE = Domestic Material Extraction; IM $_{Dom\ FD}$ = Materials embodied in imports for domestic final demand; EX $_{DE}$ = Domestically extracted materials embodied in exports; RTB = Raw Material Trade Balance; RMC = Raw Material Consumption; DMC = Domestic Material Consumption

* Note that at the global level, RMC and DMC should be equal. In this table, they are not exactly equal because different versions of the *materialflows.net* database have been used, which is regularly being updated and improved. However, these deviations are below 0.2% and therefore negligible for the results of the analyses.

Table 2: Material Footprints (RMC) of continents and selected major countries and comparison with DMC, in million tonnes, 1997 and 2007

A dramatic increase can be observed with regard to materials embodied in international trade. In 1997, 13.6 billion tonnes (around 29%) of global material extraction were directly or indirectly related to the production of traded products. This value increased to 22.2 billion tonnes in 2007 or almost 34% of global material extraction. Materials embodied in international trade thus grew by 62% in absolute terms, illustrating the significant effects of increasing globalization on global material flows. With almost 9 billion tonnes, Asia was the most important destination of directly and indirectly imported materials. Europe ranked second with almost 7 billion tonnes (only slightly less than domestic material extraction within European borders), followed by North America (almost 4 billion tonnes). Imports of embodied materials were relatively minor in Africa and Oceania. Asia was by far the largest exporter of embodied materials. 10.7 billion tonnes, or almost 50% of all materials embodied in exports, were directly and indirectly delivered by Asian countries to the rest of the world, with China alone contributing almost 4 billion tonnes to the Asian total. Asia was followed by Latin America as the second most important exporter (3.5 billion tonnes). Oceania was the continent with the smallest absolute numbers, but directly and indirectly exported around 70% of their domestic extraction (the highest share of all world regions), mainly due to the large amounts of fossil fuels and metal ore exports from Australia.

Looking at the Raw Material Trade Balance (RTB), it can be observed that there is a clear distinction between developed regions, most notably Europe and North America, which are net-importers of embodied materials, and the other continents serving as net-exporters. With almost 4.3 billion tonnes of net-imports, Europe had by far the biggest RTB in absolute terms in 2007, mainly caused by the categories of fossil fuels and metal ores, and to a minor extent biomass. North America also had significant net-imports of around 2 billion tonnes. Latin America was the biggest net-exporter of direct and indirect raw materials, supplying 2.4 billion tonnes (mainly metal ores and biomass) to other world regions. Asia was also a net-exporter (1.8 billion tonnes), as were Africa and Oceania.

More than 51% of global material extraction was directly and indirectly consumed by Asian countries, which had an aggregated RMC of 33.5 billon tonnes in 2007, indicating a growth in RMC by 75% compared to 1997. In Europe, aggregated RMC was 11.6 billion tonnes in 2007, up from 8.5 billion tonnes in 1997 (with 36% the second largest RMC growth rate). North America closely followed Europe (10.1 billion tonnes of RMC, a growth of 16% compared to 1997). Growth in aggregated RMC was also strong in Africa (+32%), although on a much lower absolute level (3.8 billion tonnes in 2007).

Relating Raw Material Consumption of countries and regions with population numbers provides insights into the different levels of consumption from an individual’s perspective. Global average RMC per capita was slightly below 10 tonnes in 2007, up from 8.2 tonnes in 1997. On the continental level, a difference in the order of a factor 8 can be observed between the highest and lowest consuming world regions. While in Africa, average RMC per capita is only around 4 tonnes, it is more than 30 tonnes in North America. The other continents range in between: Asia with 8.1 tonnes, Latin America with 9.8 tonnes, Europe with 19.7 tonnes and Oceania with 24 tonnes per capita.

3.2. RMC of selected countries

Figure 1 shows the Material Footprint of the five countries with the highest RMC in 2007 and compares them with their values in 1997. With 8 billion tonnes in 1997, the USA had the highest RMC of all countries, followed by China (7.1 billion tonnes), India and Japan (both 2.7 billion tonnes). However, until 2007, China has more than doubled its Material Footprint to 15.2 billion tonnes and today is by far the largest material consumer, holding a share of 23% of global RMC. The USA ranked second in 2007 with around 9 billion tonnes, followed by India (4.1 billion tonnes), Japan (2.4 billion tonnes) and Brazil (2.1 billion tonnes). While growth in RMC was moderate in the USA, the increase in China was primarily due to the use of minerals in the construction sector, which constantly expands, as China builds up its infrastructure in the housing, transport and energy sectors. Minerals constituted 63% of Chinas total Material Footprint in 2007, mostly serving investments and not private or government consumption (see below for details). China has also almost doubled its fossil fuels consumption whereas its biomass consumptions remained stable. Following the same path, the significant growth in India's RMC was likewise mainly due to extended use of mineral resources.

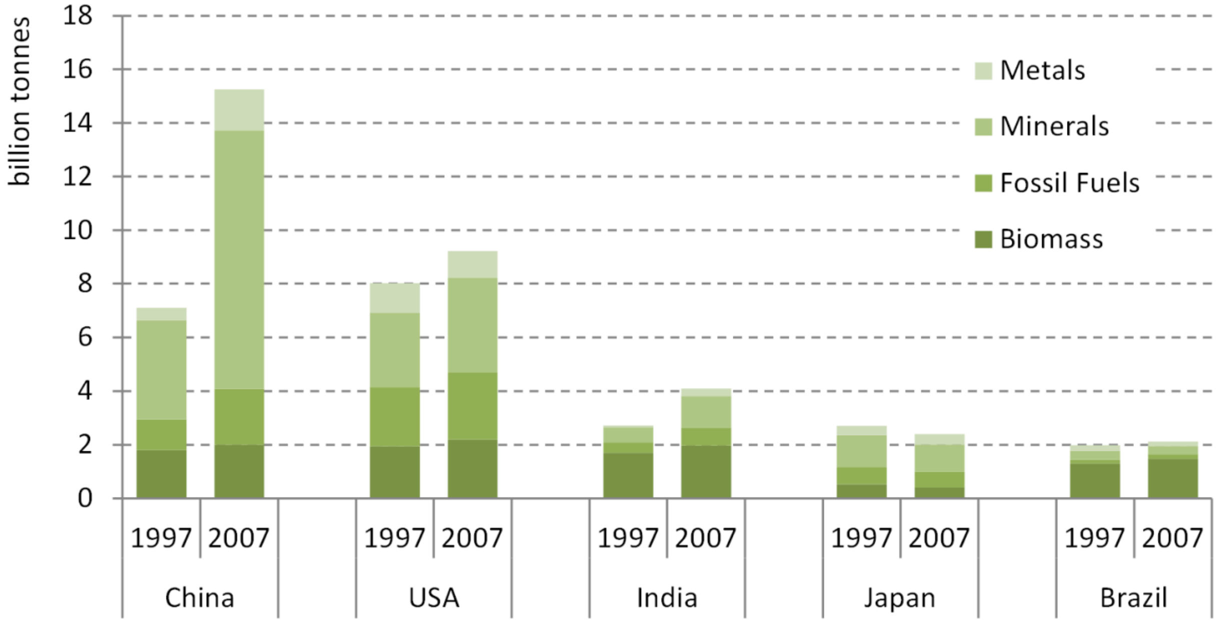

Figure 1: Raw Material Consumption of the 5 biggest consuming countries, 1997 and 2007, in billion tonnes

With regard to biomass, it can be observed that the share of biomass consumption is relatively higher in developing and emerging economies such as India and Brazil compared to countries with higher GDP per capita and the share of biomass also decreases as countries get richer. In 1997, India's biomass consumption constituted 62% of its total Material Footprint, whereas in 2007 it decreased to 48%. On the other hand, the Brazilian biomass consumption had a share of 70% in 2007 (up from 65% in 1997) due to the expansion of biomass-producing sectors in the domestic economy. The shift towards non-renewable resources in total RMC as countries increase their affluence can also be observed for China where the biomass share decreased (25% to 13%), fossil fuels remained stable (15%), and metals and minerals increased (from 6% to 10% and 52% to 63%, respectively). Japan actually decreased its RMC by 11% from 1997 to 2007, the only case in the observed major economies, mainly due to a decrease in fossil fuel and biomass consumption. The reasons for Japan's shrinking RMC need to be analyzed in more detail in the future, but the low levels of economic growth in that 10-year period, with even negative growth rates in some years, could at least partly explain this trend.

On a per capita basis, the United Arab Emirates had the largest Material Footprint of more than 100 tonnes in 2007, followed by Qatar with more than 80 tonnes (no data available for both countries in 1997). The following countries with the highest RMC per capita in 2007 were found in Europe: Luxembourg (50 tonnes), Ireland (42 tonnes), and Finland (40 tonnes). On the other hand, the lowest RMCs per capita were found for developing countries in Africa (Malawi and Mozambique) and South Asia (Bangladesh) with values below 2 tonnes, at around the same level as in 1997.

3.3. RMC versus DMC

Figure 2 shows a comparison between RMC and DMC in 2007 of selected countries, which illustrates the impacts of different paths of economic specialization on the two indicators. Highly developed countries – such as the USA, Japan and the UK in Figure 2 – generally show higher RMC than DMC. Specifically, RMC in 2007 was 2% higher than DMC for the USA, 77% higher for Japan and 84% higher for the UK. This illustrates that industrialized countries, which have to a large extent specialized in (financial) services, such as the UK, or countries with an important industrial base, but lacking sufficient endowment with domestic raw materials (such as Japan) have a significantly higher material consumption when indirect material flows related to international trade are considered. These findings confirm results of MRIO-MFA assessments undertaken with other databases such as EORA (Wiedmann et al. 2013) and the OECD database (Bruckner et al. 2012).

On the other hand, the indicator comparison for less developed countries such as Brazil, Chile, and China reveals the opposite case: RMC was 15% lower than DMC for China, 75% lower for Chile, and 18% lower for Brazil. In particular in metal-exporting countries, such as Chile, the difference between DMC and RMC is huge, since the waste stemming from metal concentration processes, which makes up the largest amount of DMC in these countries (see Russi et al. 2008; Giljum 2004), is allocated to consumers abroad in the Material Footprint perspective, thus significantly reducing its RMC.

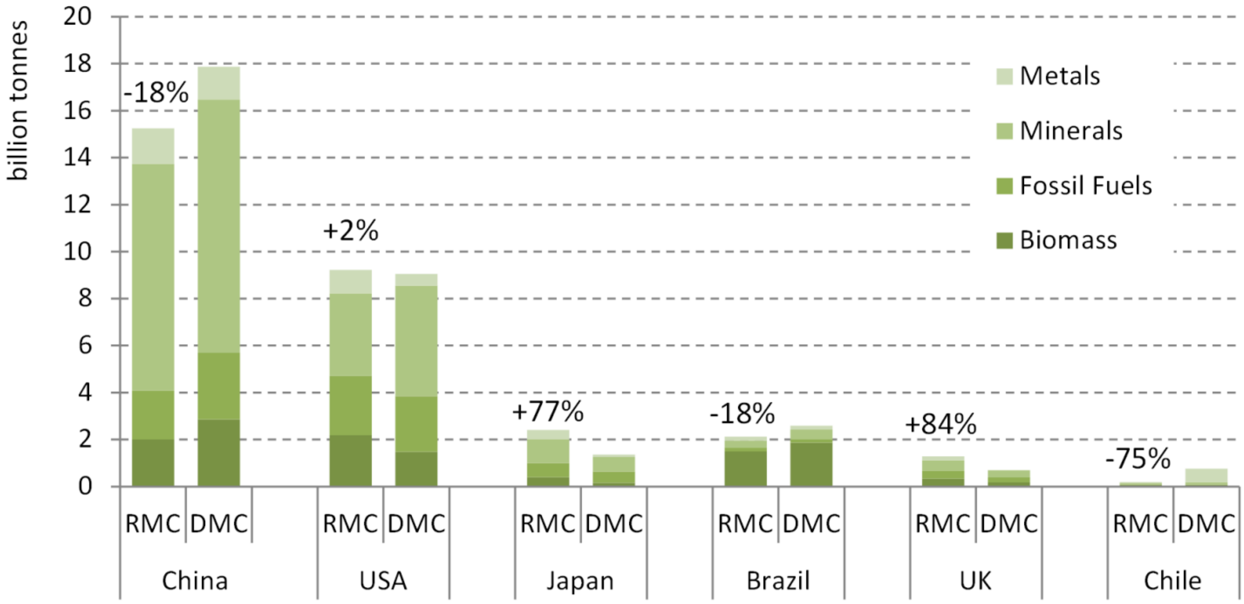

Figure 2: RMC vs. DMC of selected countries, 2007

3.4. Patterns of international trade

Figure 3 shows a world map indicating the Raw Material Trade Balance (IM $_{Dom\ FD}$ minus EX $_{DE}$) of all 129 countries and regions distinguished in the MRIO model, with net-exporters of embodied materials (EX>IM) shown in light colors, whereas net-importing countries (IM $_{Dom\ FD}$ > EX $_{DE}$) have darker colors. The map illustrates that significant net-exports are concentrated in only a few countries. China (1.73 billion tonnes of net-exports), Australia (926 million tonnes), Brazil (790 million tonnes) and Russia (747 million tonnes) as well as Indonesia, Peru and Chile were the main net-exporters.

Most countries in Africa, Central America and South and South-East Asia have a more or less balanced international trade.

In 2007, as a single country, the USA was the biggest net-importer of raw materials (2.2 billion tonnes), followed by Japan (1.7 billion tonnes) and some European countries (Germany with 0.8 billion tonnes, and UK and Italy with 0.7 billion tonnes each).

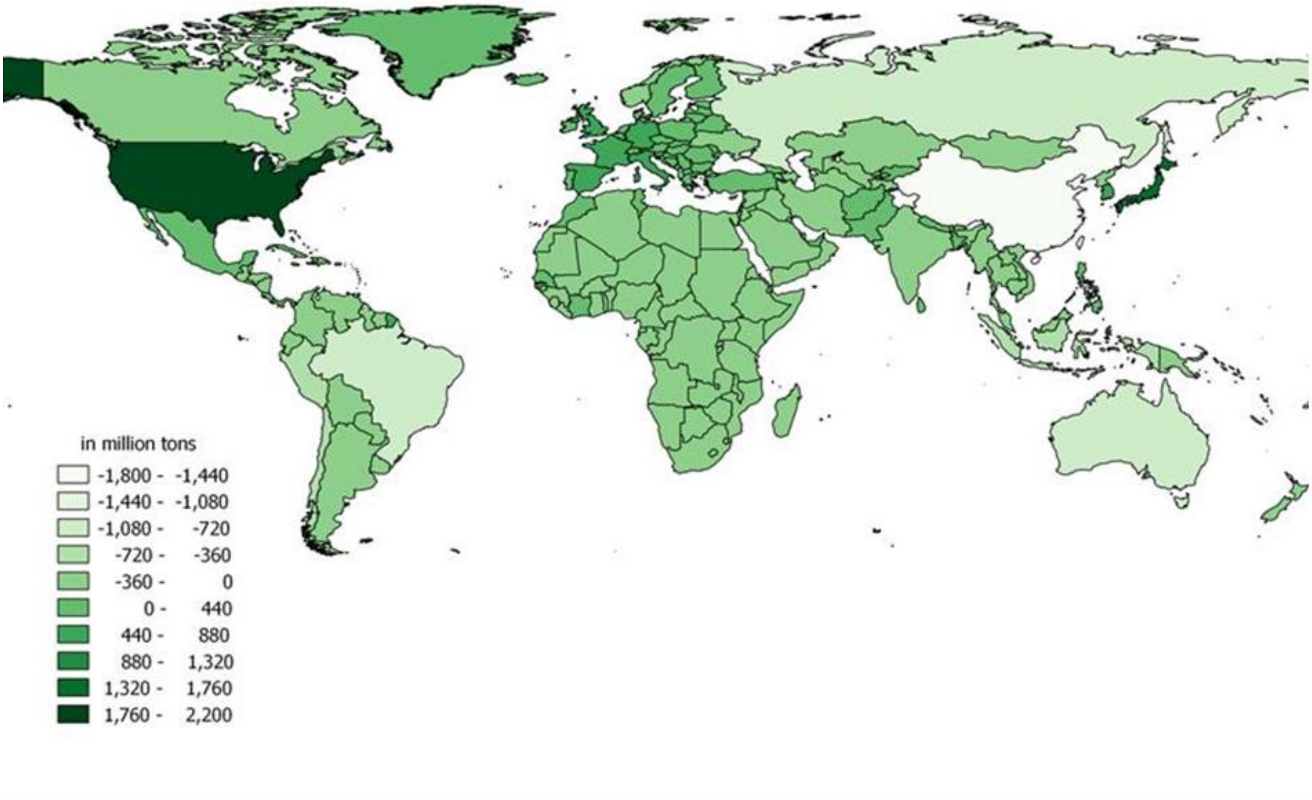

Figure 3: Raw Material Trade Balances across the world, 2007, million tonnes

One key advantage of MRIO-based assessments is that specific geographical trade patterns can be analyzed, which allows identifying the major flows of embodied materials on a bilateral basis. The biggest single flow of embodied materials (928 million tonnes) could be found from China to the USA, closely followed by the export flow from China to the EU-27 (926 million tonnes). The third biggest international flow concerned exports from Russia to the EU-27 (540 million tonnes). Brazil's biggest out-flow of embodied materials had the EU-27 as destination (276 million tonnes), whereas China was the number one destination for Australian exports (212 million tonnes).

Using input-output tables as the basis for the calculations not only allows disaggregation by country of origin and destination, but also disaggregation by sectors and product groups of final demand. Figure 4 presents the RMC per capita for the EU-27, the USA and China both, by origin of raw materials as well as by aggregated product category of final demand. The more a cell in the matrix contributes to the overall RMC per capita, the darker it is shaded. It is important to note that in Figure 4, the various rows reflect the relative size of trade flows, as it is not possible with a MRIO approach to calculate specific material intensities for domestic consumption versus exports. A unit of a certain product thus has the same material intensity when consumed domestically as when consumed abroad.

Total RMC per capita in the EU-27 countries in 2007 was almost 21 tonnes. Most of the Material Footprint was related to final demand of construction activities (31% of RMC) followed by the manufacturing sectors (26%) and the service sectors (23%). With regard to the geographic origin of raw material for producing this final demand, most raw materials consumed stem from Europe itself (55%), followed by Asia (24%). It can be seen that the construction sector receives most of its material inputs within the continent, as construction materials are hardly traded between continents. In contrast, manufactured products have a much higher share of materials originating from abroad, most notably from Asia, which is particularly due to high imports from China to Europe (see also above). The clothing products are the only product category, where a majority of raw materials originate from outside European borders, in particular from Asian countries.

EU-27 (a)

	Oceania	Asia	North America	Latin America	Europe	Africa	Total	% of Total
Crop products	22	313	77	251	1,364	213	2,239	11%
Animal products	36	103	29	141	898	52	1,259	6%
Wood products	4	59	12	18	191	34	318	2%
Clothing	13	381	18	45	113	42	613	3%
Manufactured products	170	2,017	325	453	2,049	393	5,407	26%
Construction	64	856	196	328	4,634	312	6,390	31%
Services	100	1,364	245	378	2,216	409	4,712	23%
Total	410	5,092	901	1,613	11,465	1,455	20,937	
% of Total	2%	24%	4%	8%	55%	7%		

USA (b)

	Oceania	Asia	North America	Latin America	Europe	Africa	Total	% of Total
Crop products	20	250	1,499	272	36	46	2,123	7%
Animal products	77	49	1,808	126	19	15	2,095	7%
Wood products	8	186	723	81	17	25	1,040	3%
Clothing	15	506	131	57	14	20	743	2%
Manufactured products	203	2,778	4,502	1,035	335	395	9,248	30%
Construction	35	455	6,284	223	58	72	7,128	23%
Services	105	1,364	5,549	697	196	300	8,211	27%
Total	463	5,588	20,497	2,492	675	873	30,588	
% of Total	2%	18%	67%	8%	2%	3%		

China (c)

	Oceania	Asia	North America	Latin America	Europe	Africa	Total	% of Total
Crop products	4	694	8	19	2	5	**732**	**6%**
Animal products	3	285	4	6	1	2	**301**	**3%**
Wood products	1	54	1	2	1	4	**62**	**1%**
Clothing	3	140	2	5	1	2	**153**	**1%**
Manufactured products	59	1,794	36	114	21	40	**2,064**	**18%**
Construction	79	6,738	42	167	25	59	**7,111**	**61%**
Services	22	1,032	17	44	10	21	**1,146**	**10%**
Total	**172**	**10,736**	**109**	**358**	**61**	**134**	**11,569**	
% of Total	**1%**	**93%**	**1%**	**3%**	**1%**	**1%**		

Figure 4: Disaggregation of RMC in kilograms per capita by continent of raw material origin and product group in 2007: EU-27 (a), USA (b), China (c)

With 30.6 tonnes, the RMC of an average US citizen was around 50% larger compared to the EU-27. In the USA, the hot spot of material consumption were manufacturing products (30%) followed by services (27%) and construction work (23%). With 67%, North America had a higher rate of self-sufficiency compared to Europe. Asia ranked second as a supplying region (18%), as for the EU-27.

China, with a total RMC per capita of only 11.6 tonnes, differs from the structure observed for developed countries in two main aspects. First, construction activities play a much larger role, as physical stocks in the form of infrastructure are only now being built-up. Construction work contributed more than 60% to the Chinese RMC in 2007. We further disaggregated the Chinese final demand by the three main categories, i.e. private consumption, government consumption and investments, in order to test the assumption of the dominant role of infrastructure investments. It turned out that around 8.5 tonnes (or 73% of the 11.5 tonnes RMC per capita) are related to investments and within that category, construction work makes up by far the largest part (7 tonnes per capita), followed by manufactured products, i.e. machinery (1.3 tonnes). Household spending only contributed around 2.5 tonnes per capita (22% of total RMC) to the overall indicator and government spending around 0.5 tonnes per capita (5%). The RMC of emerging economies thus reveals a very specific pattern, focusing on investments rather than consumption, which confirms the results recently presented for Chinese RMC by Wang and colleagues (2014).

A second distinct feature of the Chinese case is that 93% of materials originated within Asia, most notably within China itself, as there are few raw materials extracted in other world regions, which serve final demand in China; the huge raw material imports were thus almost entirely used for export production (see also above).

4. Discussion

4.1 Methodology and data sources

This paper for the first time applied the GTAP database for the case of assessing materials embodied in international trade and final demand. We found that the GTAP database has a number of advantages for MFA-related applications, compared to other MRIO datasets. First, a large number of countries can be separately modelled in GTAP, which is important, as material extraction often takes place in developing countries. MRIO databases, which have large "rest of the world" regions, cannot reflect this detail. Second, the number of material categories that can be separately modelled is higher in GTAP compared to other databases such as OECD or WIOD. However, in particular regarding mining of minerals and metal ores, GTAP only provides one mining sector and thus has a lower level of detail compared to e.g. EXIOBASE and many country models in the EORA database. This leads to errors due to the aggregation of various materials with very different price-weight ratios into one sector and due to the assumption of similar use structures for a large group of materials (see Schoer et al. 2012a). Transparency and robustness of the base data is regarded a critical issue, as the procedures applied to original data to transform them into the harmonized GTAP data system are not well documented (for more detail see Peters and Hertwich 2008b).

This paper confirmed general results presented in other papers on material footprints (Wiedmann et al. 2013; Arto et al. 2012; Bruckner et al. 2012), for example, regarding the global structure of net-importers versus net-exporters of embodied materials. However, on the level of single countries, deviations to existing results can be significant. Possible reasons include differences in the structure and sector composition of the applied IO tables and different procedures to allocate material extraction data to the sectors of the IO tables. More information on these sources for uncertainty is provided in Supporting Information S2. A detailed comparative evaluation of the differences between existing MRIO-MFA models and their impacts on the calculation results is an urgent next step for the further development of this methodology.

4.2. Resource management and policy

The results presented in this paper closely link up with various current (policy) discussions in the area of sustainable resource management (Bringezu and Bleischwitz 2009; OECD 2008; UNEP 2011a, 2011b). They strongly emphasize the need to consider up-stream material requirements, in order to properly evaluate the global effects on material extraction related to final demand of a country or world region. As international trade increases and supply-chains are organized ever more on the global level, the results generated with indicators of direct material flows (such as DMC) significantly diverge from indicators, which take into account indirect flows related to trade (such as RMC). In the area of climate change, there is an intensifying debate on the question, whether producers or consumers should be accountable for the generated environmental pressures along the supply chain and which options exist for sharing responsibilities (for example, Davis and Caldeira 2010; Peters and Hertwich 2008a; Peters 2008; Barrett et al. 2013). Results as presented in this paper provide the empirical basis for discussing the global responsibilities of consumers in the field of material use.

The results of MRIO-MFA assessments can also quantify the dependency of countries regarding imports from other parts of the world. Europe was identified as the continent with the highest share of materials embodied in imports and thus most vulnerable regarding developments in other world regions (see also Schoer et al. 2012a). As a consequence, Europe has started policy initiatives such as the “Raw Material Initiative” (European Commission 2008, 2011c) which aim to secure reliable and undistorted access to raw materials for European industries and will devote further efforts in identifying “critical materials” and how to overcome possible access restrictions. Also the promotion of resource efficiency in Europe, as defined as the main objective in the “Roadmap to a resource efficient Europe” (European Commission 2011a) aims to contribute to reducing European vulnerability on developments on global markets.

Also distribution issues and issues related to the “fair share” debate (Evans 2011) need to be addressed when discussing the obtained results. We have shown vast differences in the individual Material Footprint around the world. While RMC per capita is up to 100 tonnes in some rich, oil-exporting countries, in many developing countries it is as low as 1.5 to 2 tonnes. In most least developed countries, not even basic material needs, including food and shelter, can be satisfied, which calls for an increasing material consumption in these parts of the world in the future. In a world increasingly facing resource scarcities, in particular in the areas of inputs for food production, energy and water (McKinsey 2011), representing some of the most vital basic human needs, these issues will need to be addressed in a broader context on the global distribution of the planet's limited natural resources (Evans 2011; Dittrich et al. 2012).

Although there are some exceptions, notably Australia and Canada, international trade is currently organized in a way that generally shifts resources from countries and world regions with low per capita consumption and low levels of economic affluence to countries with high consumption levels and high GDP. Raw material prices have significantly increased after the year 2000 (World Bank 2013), thus making exports of raw materials more profitable. However, revenues from these commodity exports often do not profit the poorest part of societies, as the governance structure in many developing countries favors local elites and multi-national enterprises. Governance of global material flows towards environmentally and socially acceptable standards is a highly complex, multi-level, multi-stakeholder effort (Lee et al. 2012). Trade liberalization policies in raw material exporting developing countries thus need to integrate aspects such as reforms of existing institutions and embedding the opening of the economy in a broader program of domestic development and the diversification of export industries (Samen 2010; UNDP 2011).

5. Conclusions and future work

This paper presented results of Material Footprints for a large number of countries world-wide, calculated in a framework of multi-regional input-output analysis based on the GTAP database and the *materialflows.net* database. We illustrated that MRIO-MFA assessments open up a number of options to address key issues in the international debate on sustainable resource management, including assessments of the impacts of globalization on the international distribution of raw materials, the contribution of specific materials to economic development, and the main sectors and consumption areas directly and indirectly responsible for the overall material use of countries and world regions. We also argued that consumption indicators considering only direct flows, most notably DMC, need to be complemented by indicators including indirect material flows related to international trade in order to avoid wrong conclusions on the overall resource efficiency of the domestic economy.

However, so far, there is still a lack of a standardized methodology to calculate Material Footprints on the international level, which significantly restricts the policy-oriented use of the indicator.

In order to proceed towards the development of a robust methodology, further improvement need to focus on the following issues (see Wiedmann et al. 2011; Giljum et al. 2013): improving the level of disaggregation in input-output models in order to reduce the error when aggregating a large number of products with different resource intensities; developing and testing models which integrate input-output and process-based data including uncertainty assessments (see Schoer et al. 2013); improving the quality and allocation of certain MFA data entering the MRIO models (e.g. construction minerals, grazing); assessing the results of MRIO-MFA models on a more disaggregated basis, for example focusing on single materials instead of aggregated groups containing materials of very different physical use; designing MRIO-based models which allow assessing the unequal distribution of material consumption within countries, not only between countries; putting efforts into producing more timely data (in particular in the area of input-output tables); and developing and testing now-casting methods, i.e. methods that allow estimating Material Footprints for the current year, and scenario tools (see Giljum et al. 2008) in order to increase the policy relevance of Material Footprint indicators.

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