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Solid waste and the Circular Economy:

A global analysis of waste treatment and waste footprints

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Abstract

Detailed and comprehensive accounts of waste generation and treatment form the quantitative basis of designing and assessing policy instruments for a circular economy (CE).

We present a harmonized multiregional solid waste account, covering 48 world regions, 11 types of solid waste, and 12 waste treatment processes for the year 2007. The account is part of the physical layer of EXIOBASE2, a multiregional supply and use table. EXIOBASE2 was used to build a waste-input-output model of the world economy to quantify the solid waste footprint of national consumption.

The global amount of recorded solid waste generated in 2007 was about 3.2 Gt (gigatonnes), of which 1 Gt was recycled or re-used, 0.7 Gt was incinerated, gasified, composted, or used as aggregates, and 1.5 Gt was landfilled. Patterns of waste generation differ across countries but a significant potential for closing material cycles exists in both high and low income countries. The EU, for example, needs to increase recycling by about 100 Mt/yr and reduce landfilling by about 35 Mt/yr by 2030 to meet the targets set by the Action Plan for the Circular EconomySolid waste footprints are strongly coupled with affluence, with income elasticities of about 1.3 for recycled waste, 2.2 for recovery waste, and 1.5 for landfilled waste, respectively. The EXIOBASE2 solid waste account is based on statistics of recorded waste flows and therefore likely to underestimate actual waste flows.

Keywords

Circular Economy; Industrial Ecology; Waste Input-Output; Multi-Regional Input-Output; Consumption-based accounting; Municipal solid waste

<heading level 1> Introduction

<heading level 2> Natural resources, waste flows, and the circular economy

Wealth, well-being, and human development are linked to material consumption (Tukker et al. 2014; Wiedmann et al. 2013; Bruckner et al. 2012; Steinberger et al. 2010). Waste generation is an inevitable consequence of material consumption, because of the entropic nature of the production process (Georgescu-Roegen 1971) and because of product obsolescence. Products can be dissipated into the environment during their use or be discarded as waste when they reach end-of-life. Emissions from product dissipation and waste flows are often considered as externalities by mainstream economic thinking (Ayres and Kneese 1969).

The circular economy (CE) concept is gaining weight as an alternative to the make-use-dispose paradigm (European Commission 2011). The CE concept aims at extending the useful life of materials and promotes recycling to maximize material service per resource input while lowering environmental impacts and resource use. The CE concept is closely related to the 3R Principles: Reduce, Reuse, and Recycle (Ghisellini et al. 2015; Lieder and Rashid 2015), and legislation on the CE has been effective in China as of 2008 (National People's Congress 2008). To stimulate CE strategies in Europe, the European Commission has set ambitious goals within its Circular Economy Package, including a target for recycling of municipal solid waste (MSW, min. 65% of all MSW by 2030) and landfilling of solid waste (max. 10% of all MSW by 2030) (European Commission 2015a, 2016). The CE Package also aims at promoting industrial symbiosis and encouraging eco-design (European Commission 2015a).

Reducing inputs of raw materials to the economy is a main goal of CE strategies. Signs of relative decoupling between use of raw material and economic growth have been identified in the most developed economies (OECD 2011). A recent global assessment, however, finds that recycled materials accounted for only 6.5% of the total material processed in 2005 (Haas et al. 2015). Haas et al. (2015) further identify two major challenges to rolling out the CE: (i) 44% of material inputs are energy carriers, which are burnt and therefore not recyclable; and (ii) material stocks are still growing.

Moreover, by taking a consumption-based perspective[1] (Peters 2008), Wiedmann et al. (2013) show that resource decoupling is not evident, as consumers in high-income countries rely on resources extracted abroad. An assessment of the coupling between waste footprints and affluence is lacking.

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[1] i.e., accounting for waste generated abroad to supply imports, minus waste generated domestically to supply exports

While the CE concept is easy to understand, quantitative indicators to assess the ‘circularity’ of national economies, material cycles, value chains, and product life cycles need to be developed to facilitate implementation (Ellen MacArthur Foundation 2015). Policy-relevant indicators for the ‘circularity’ of an economy depend on both: the definition and the scope of the CE, and a detailed quantitative physical account of the flows and stocks in that economy. While the first part is mainly the result of a policy process, the latter part falls within the scope of industrial ecology. In particular, the physical account needs to focus on waste flows and their treatment, as waste is the single resource for recycled materials as well as for energy and nutrient recovery.

<heading level 2> What do we know about solid waste?

Waste generation has been studied at different regional levels. Work for The World Bank (Hoornweg and Bhada-Tata (2012)) analyses waste generation in 90 countries. Other scholars studied the decoupling of economic growth from waste generation, typically with a European scope and/or a focus on municipal solid waste (excluding industrial waste) (Mazzanti and Zoboli 2008; Mazzanti 2008; Mazzanti and Zoboli 2009; Van Caneghem et al. 2010; Nicolli et al. 2012; Anupam et al. 2012; Mazzanti et al. 2012). Evidence shows that waste generation in the UK and other OECD countries might have passed a peak (Goodall 2011; Hoornweg and Bhada-Tata 2012), and it was suggested that high-income countries’ waste generation rates might decrease from 2.37 kg waste per capita per day in 2008 to 2.26 kg/day by 2025 (Jackson 2009). Some studies analyzed in more detail how the supply chain drives waste generation using input-output tables (IOT) (Lee et al. 2012; Court 2012; Court et al. 2014; Jensen et al. 2013). However, these studies do not allow for the distinction between different waste types and treatment processes, economic sectors generating waste, and the goods and services whose production caused the waste. A comprehensive and consistent global account of waste generation and treatment is still lacking.

The aforementioned studies use waste data compiled for individual countries or a set of developed countries (i.e. European Union), which are not trade-linked with the rest of the world. Without a trade-linked inventory one cannot link consumption with waste generated abroad (Bruckner et al.

2012; Wiedmann et al. 2013). Only the studies by Beylot et al. (2016), Liao et al. (2015), Jensen et al. (2013b) and Lee et al. (2012) accounted for the amount of waste embodied in trade[2].

State-of-the-art methods to study waste generation in industrial networks and the CE are life cycle assessment (LCA) (Hellweg and Canals 2014), waste-input-output models (WIO) (Nakamura and Kondo 2002), and the accounting frameworks that these models are based upon (Pauliuk et al. 2015). The extended waste supply and use tables (WSUT) (Lenzen and Reynolds 2014; Reynolds et al. 2014) is an accounting framework that is of particular relevance to waste and the circular economy. The accounting frameworks record economic and physical exchange between industries considering different economic sectors, waste types, and waste treatment processes. WIO analysis was applied to study the CE in a case study covering the agri-food industry of Australia (Pagotto and Halog 2015). It was also used to identify the potential for national level industrial symbioses (IS) for Taiwan (Chen and Ma 2015). So far, WIO analyses were only conducted for Japan, Australia, Taiwan, the UK and France (Tsukui et al. 2015; Fry et al. 2015; Liao et al. 2015; Kagawa et al. 2004, 2007; Reynolds et al. 2014; Nakamura and Kondo 2002; Chen and Ma 2015; Beylot et al. 2015; Salemdeeb et al. 2016).A global assessment of solid waste footprints at the world level is lacking.

The present study focuses on solid waste (SW) and its treatment (SWT), and its aim is to (i) provide an overview of global waste generation and treatment patterns, (ii) discuss the new EU directive regarding the CE in light of the waste accounts, (iii) to quantify the waste flows embodied in international trade and compare them to domestic waste generation, and (iv) study the link between waste generation to affluence. Our study provides a first detailed estimate of global waste generation and treatment. It covers the world in 48 regions (aggregated to 25 regions in some graphs) and includes 11 types of solid waste as well as 12 waste treatment processes, which together allow for recording 30 different treatment routes for solid waste.

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[2] Waste embodied in trade is waste that is generated during the production of goods and services for supplying exports but that is treated in the country where the manufacturing happens.

In section 2 we describe the data, the reconciliation procedure, and the global multiregional waste-input-output model. In section 3 we present the results for waste generation and treatment in the 25 world regions and in their supply chains, and show how waste generation is correlated with per capita income. Section 4 discusses our findings and provides suggestions for future database improvement.

<heading level 1> Methods

<heading level 2> The EXIOBASE waste account

Part of a series of EU-funded research projects, the CREEA project (Compiling and Refining Environmental and Economic Accounts) included the compilation of a global multi-regional (MR) environmentally extended supply and use table (SUT), EXIOBASE. Version 2.2.0 of the EXIOBASE covers the use of 80 natural resources, 170 emissions to nature, and 36 different waste treatment routes for 43 countries and 5 rest of the world (RoW) regions, at a resolution of 163 economic sectors and 200 products by country for the reference year 2007 (Wood et al. 2015; Tukker et al. 2014, 2013). EXIOBASE v2 is the only available multiregional IO database that includes global multiregional physical and monetary supply and use tables (pSUT and mSUT, respectively) (Schmidt et al. 2012; Merciai et al. 2013; Wood et al. 2015)[3]. While the accounting of monetary flows and some policy relevant environmental stressors (e.g. CO_2) at the national statistical offices is well established, physical, and especially waste accounting is far less developed. The implementation of the System of Environmental-Economic Accounts (SEEA) will eventually lead to better physical national accounts (Banerjee et al. 2016), complete and comprehensive waste data, however, is currently not available.

As industry and market balances in monetary units are used as constraints when reconciling raw data into the mSUT, the EXIOBASE pSUT was calculated using mass balance principle, too (Schmidt et al. 2012; Merciai et al. 2013). Unlike with the economic balance, non-economic flows like uptake of natural resources, emissions to nature, and waste also enter the mass balance equations. Comprehensive waste accounts are central to establishing mass balance in the pSUT (Pauliuk et al.

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[3] EXIOBASE v3 will provide a time series of mSUTs and pSUTs until 2011, however, as this database was not available at the time the research was conducted the present analysis uses EXIOBASE v2, which was compiled for the reference year 2007 only.

2015; Merciai et al. 2013), and therefore special attention was given to their compilation during the creation of the EXIOBASE pSUT. The dry matter content of materials and waste is recorded, including solid waste, which is defined here as any solid output from a human activity that remains inside the techno-sphere and that requires further treatment before it can be released to the environment or be used as substitute for other industrial products. Therefore, liquid waste such as manure or wastewater, and unused domestic extraction such as mining overburden or residues from forestry and agriculture that are not harvested are not included in the waste accounts.

A global multiregional account of solid waste generation and treatment is not available at the resolution of the contemporary MRIO tables. For most EXIOBASE countries, however, detailed statistics for waste *treatment* are available, and we used those data to populate the supply table by recording waste usage as supply of waste treatment service. When necessary, the data for the supply of waste treatment services had to be disaggregated into the EXIOBASE waste classification, which is usually more detailed than the statistics. For example, often statistics only report the total amount of waste incinerated or landfilled. In EXIOBASE, incineration and landfilling are divided into waste fractions (e.g. incineration of food waste, incineration of paper waste, etc.), therefore the incineration and landfilling totals needed to be portioned. This procedure was done according to specific studies on the composition of solid waste, and we refer to section 2.5 of Merciai et al. (2013) for a detailed list of sources used to define those partitioning coefficients.

In a second step, we used the monetary use table and available data on price, transfer coefficients from input products to output products, resources and emissions coefficients, and the mass balance of industrial processes to estimate the actual amount of waste generated(Figure 1). The reason for calculating waste from mass balance is that data on inputs of natural resources, products, and emissions are generally of a higher quality compared to data on waste generation, which are provided by national institutions using different waste definitions, classifications and accounting schemes. This mass balance concept was first described in Schmidt et al. (2010) and gives the amount and type (e.g. paper, metal, food…) of waste generated by each industry in EXIOBASE.

In most cases, the calculated amount of waste generated was higher than the amount reported as treated by official statistics. We therefore split the waste generation account determined by mass balance into a part that is covered by the treatment statistics and a part that is not, and we called the latter ‘unregistered waste’. The fraction of the waste generated that is matched by the treatment statistics is recorded in the physical use table by recording waste generation as use of waste treatment service, after being split into the different treatment options with the partitioning coefficients derived from the supply of waste treatment services. The unregistered waste is recorded as a physical extension to the PSUT. Further reading about the reconciliation/balancing algorithm can be found in section 7.2 in Merciai et al. (2013). A discussion and comparison of the mass balance approach to reported waste data can be found in Schmidt (2010) and Verberk et al. (2013). They report that the main differences between the available waste statistics and the results of the mass balance approach are due to differences in the scope of waste statistics across countries and uncertainties of product life-times to estimate postconsumer waste and scrap flows.

It is difficult to establish accurate physical balances for industrial sectors as only monetary use data are widely available, sector-specific price data are absent in most cases, and average prices therefore had to be used. The unregistered waste estimates are hence the result of a reconciliation routine with highly uncertain constraints, and they are not matched by statistical data either, as those do not exist. The resulting high uncertainty of the total mass balance difference, which we interpreted as uncertainty of the total waste generation, led us to exclude the unregistered waste fraction from our analysis and to focus on that part that is matched by official statistics. The current waste account used in this article is therefore likely to underestimate the total waste generated, as it only covers the fraction of the waste for which statistical data exists. We believe that this narrow scope of waste flows is more credible than using the estimated total values.

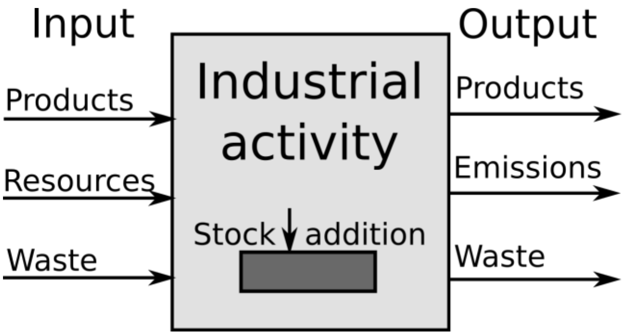

Figure 1: Input- and output flows for a generic industrial activity. The output of waste is calculated from the process mass balance if no statistical data are available

Trade of waste was not included because of limited data on trade of waste and because of mis-classification of waste flows in trade statistics, which are often labelled with a different code than those related to waste (Merciai et al. 2013). The EXIOBASE solid waste accounts are reported in dry mass content. If waste treatment statistics report weight in wet mass a dry matter coefficient was applied (cf. section 6.2 in (Merciai et al. 2013)).

<heading level 2> The global multiregional waste-input-output model

Because waste requires further industrial treatment it cannot be considered as an extension to the mSUT, like, for example, emissions to nature in environmentally extended Input-output (EEIO) (Leontief 1972). The waste input-output (WIO) model (Nakamura and Kondo 2002) provides the appropriate framework for the study of waste flows in global supply chains, as it allows us to endogenously model waste treatment and the displacement of primary production by recycling and reuse of wastes (Chen and Ma 2015). The WIO model mirrors the supply chain of consumer goods by allowing modelers to consider cascades of waste treatment, for example, the conversion of retired vehicles into steel scrap and then into secondary steel and slag with subsequent landfilling. Technically, there is no difference between waste and commodities in the WIO model, hence waste generation coefficients are part of the technological coefficients matrix. The WIO model is an important tool for studying the CE, including waste footprints, because of its ability to model ‘downstream’ chains of waste in the same fashion as ‘upstream’ supply chains of consumer goods and the coupling between them.

To build a WIO model from the EXIOBASE mSUT and pSUT we first compiled a mixed unit square WSUT with 48 regions (25 for aggregated results), 128 products and services measured in million euros (MEUR), and 35 waste treatment services measured in tonnes (Lenzen and Reynolds 2014). Since our focus is on solid waste and because of lack of data in EXIOBASEv2, wastewater, sewage sludge, and manure were excluded from the analysis, which reduces the number of waste treatment services to 30[4]. The reference year for our analysis is 2007. We used the 'product substitution construct', which is a generalization of the byproduct technology construct, to build the *A*-matrix of the WIO model from the mixed unit SUT (Majeau-Bettez et al. 2014). The procedure is explained in the Supplement S1.

The WIO model equation is shown in equation 1 (we refer to Nakamura and Kondo (2002) for a detailed description and to the sheet 'WIO_Model_Example' of the Supplement S2 for a simple worked example), where subscripts *I* describes the goods producing sectors of the economy and *II* the waste treatment sectors. *X* is the total output of the economy, divided into total output of goods X_I and total waste treated X_{II}. Y_I and $W_{\cdot,F}$ are the final demand for goods (households and government consumption for example) and for waste treatments services (waste generated directly by households and governments), respectively. $A = \{a_{i,j}\}$ and $G = \{g_{k,j}\}$ are the technical coefficients matrices of the industries, which denote the amount of sector *i* output required per unit output of sector *j* and the quantity of waste *k* generated per unit output of economic activities *j*. In general, there is no one-to-one correlation between waste and waste treatment industry, as there can be several treatment options for one waste type.

$$\begin{bmatrix} X_I \\ X_{II} \end{bmatrix} = \begin{bmatrix} A_{I,I} & A_{I,II} \\ SG_{\cdot,I} & SG_{\cdot,II} \end{bmatrix} \begin{bmatrix} X_I \\ X_{II} \end{bmatrix} + \begin{bmatrix} Y_I \\ SW_{\cdot,F} \end{bmatrix} \qquad (1)$$

The *S* matrix allocates waste to different treatment options where $s_{t,k}$ gives the share of waste type *k* treated by treatment process *t*. This allocation matrix is particularly relevant when studying changes in waste treatment policies.

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[4] There are two types of wastewater and manure, respectively, in EXIOBASE.

In the EXIOBASE MR-SUT, there is a 1:1 correspondence between waste types and treatment sectors, as in Leontief's pollution abatement model (Leontief 1972), and the *S*-matrix of the EXIOBASE-WIO model is the identity matrix.

<heading level 2> Regression analysis and aggregation of results

The link between waste generation and affluence is analyzed by a regression analysis of solid waste generation rates and solid waste footprints (tonnes/capita) with purchasing power parity (PPP) scaled GDP per capita (GDP: Gross Domestic Product). Population and PPP data were retrieved from World Bank statistics and aggregated to the regional classification of the MRIO model (World Bank 2015), while GDP was extracted from EXIOBASEv2. From the regression analysis, income elasticities of waste generation and waste footprint are estimated, which indicate the percentage increase in waste generation for a given percentage increase in income. For example, an elasticity of waste generation of 1.2 means that for a 1% increase in income 1.2% more waste is generated.

In order to simplify the presentation of the results the 30 waste treatment services were aggregated into 11 types of solid waste, and 12 waste treatment processes (cf. Tables S4 and S5 of Supplement S1). We applied two categories of solid waste: municipal solid waste (MSW), which includes waste directly generated by final demands and service sectors, and industrial waste, which include wastes generated by industry. We considered three broad categories of waste treatment: (i) recycling (re-use, re-processing, and re-melting), (ii) recovery of a different quality of a material, either energy, nutrients, or aggregates, through the treatment and partial utilization by incineration with or without heat recovery and electricity generation, bio-gasification, composting, and construction waste to aggregates, and (iii) loss of materials in landfill sites.

<heading level 1> Results

<heading level 2> The waste accounts in EXIOBASE

In high-income countries industries, services sectors, and households generate 1-2 tonnes of solid waste per capita per year (figure 2). While construction waste often dominates for European countries, Canada and the US show substantial contributions from metal, inert, and paper/wood waste. The reported per capita waste flows decline with income, as shown here for Brazil, China, and Turkey, with the exception of Russia (figure S1 in Supplement S1). In many countries, especially those with higher personal income, MSW contributes up to 40-50% of total landfilled and recycled waste, respectively. While industrial waste tends to contain high shares of metal, wood, construction, and inert waste, MSW flows contain large fractions of food, paper, plastics, and textile waste.

The patterns of waste generation are quite diverse and differ substantially across countries and regions but in general, there is significant unseized potential for closing material cycles. In many European countries, for example, large fractions of final consumer waste end up in landfill sites (around one third for France, Italy, Spain and Other Central Europe, more than half for the UK, and almost 100% in Russia, figure S1 in Supplement S1). The US, Canada, Mexico, and Brazil rely on landfilling for both industrial and final consumer wastes. Most food waste is landfilled, except for in Japan and in most Western European countries. Construction waste flows are significant mainly in developed countries, where buildings and infrastructure turnover is high. Construction waste is classified differently across countries, which is a problem inherent to MRIO modelling, where statistics from different countries are combined.

The total amount of waste generated worldwide in 2007 was about 3.2 Gt (1 gigatonne = one billion metric tonnes), of which 1 Gt was recycled or re-used, 0.7 Gt was incinerated, gasified, composted, or used as aggregates, and 1.5 Gt was landfilled. The solid waste account for 48 regions, 11 waste types, and ten sectors is included in the Supplement S2.

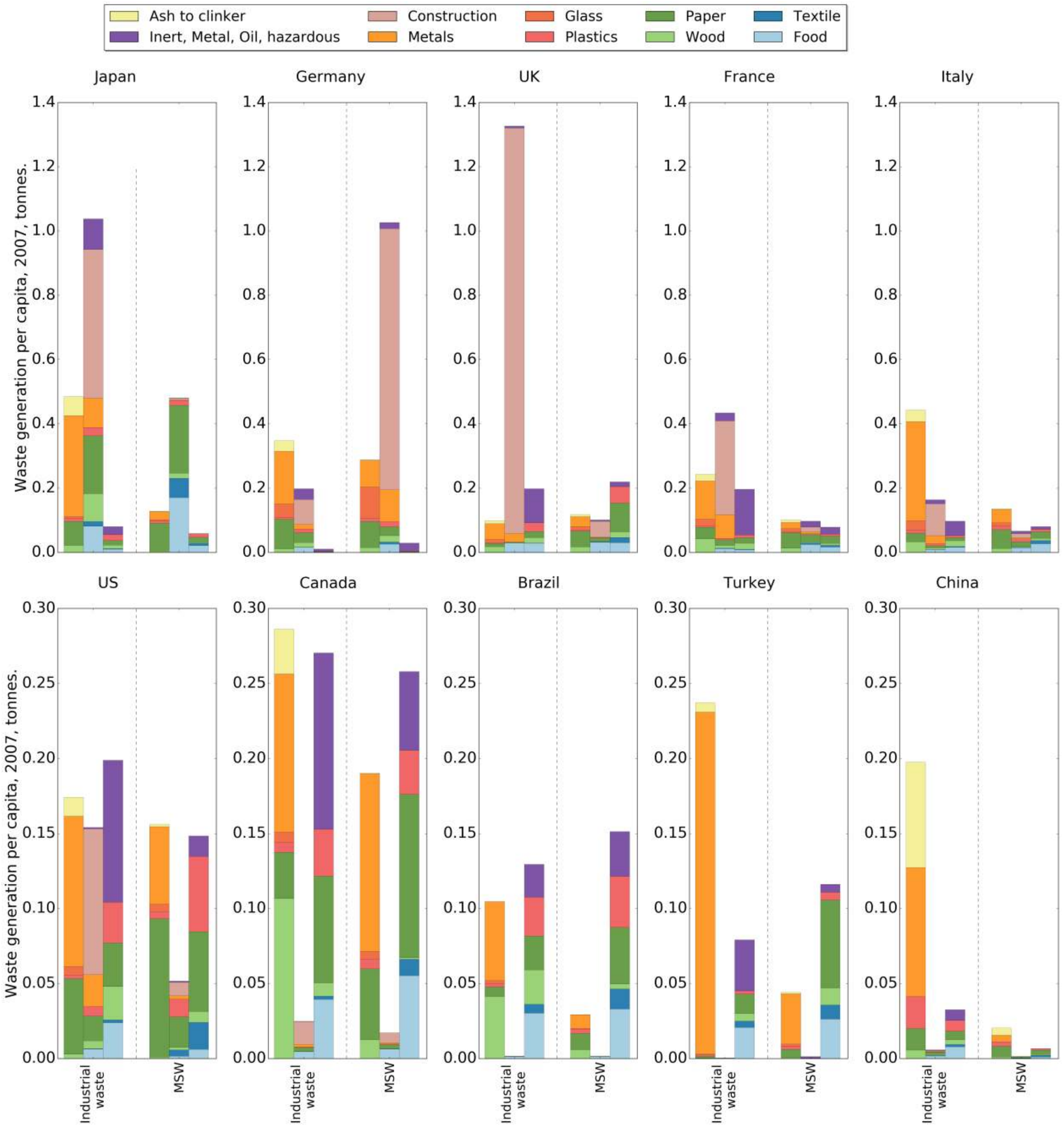

Figure 2: EXIOBASE2 accounts of waste supply per capita, by aggregated economic sectors for a selection of countries (all regions are available in the Supplement S1). MSW (municipal solid waste) consists of waste generated by final demands and service sectors. Industrial waste is solid waste generated by industry sectors. The figure shows how much waste is re-processed or re-used (**left bar**), how much waste that is not recycled but for which energy or nutrient are potentially recovered (**middle bar**) and how much waste that is landfilled (**right bar**).

<heading level 2> The EU directive on the CE

The Circular Economy Package adopted by the European Commission in 2015 has set targets for 2030, including an increase in the MSW recycling rate to 65% and a reduction of MSW landfilling to

10% by 2030 (European Commission 2015a, 2015b). In 2007, only 29% of MSW was recycled, and the recycling of an additional 97 Mt (megatonnes) of MSW would be needed to reach the goal set by the European Commission (table 1, detailed table for all EU countries can be found in Supplement S1). According to the SUT, however, the part of the 2007 MSW that shows potential for recycling[5] in the EU was just about 56 Mt, meaning that a level of recycling of 65% of MSW would not have been possible in 2007, as only two third of the required additional 97 Mt to be recycled were actually recyclable waste. The share of landfilling would have to be reduced by another 9 percentage points (33 more Mt) in order to reach the goal set for 2030 at the 2007 waste generation levels.

The EU27 performs worse than the other developed economies (except Japan) in terms of the share of MSW recycled. Australia, Canada, and the US have much higher recycling shares than the EU, but also their MSW fraction going to landfill sites is more than twice as high as in the EU. In absolute terms the EU generates about as much landfilled waste as the US.

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[5] As potentially recyclable fractions of MSW, we included wood, metal, paper, glass, plastics.

Table 1: Overview of municipal solid waste (MSW) and landfilled waste flows in different developed countries and world regions, 2007. The shares of MSW recycled and landfilled, and the share of MSW in total solid waste are shown. The table also shows how much additional MSW needs to be recycled and diverted from landfill sites to meet the EU Circular Economy directive targets. The rightmost column shows the total landfilled solid waste.

Country/Region	Share of municipal waste recycled (%)	Share of municipal waste landfilled (%)	Share of MSW in total solid waste (%)	Additional MSW to be recycled (Mt)	Additional MSW to be diverted from landfilling (Mt)	Total landfilled waste (Mt)
EU Target 2030	**65 %**	**10 %**	---	---	---	---
Australia	46	47	30	1.2	2.2	6
Canada	41	55	44	3.7	7	17
EU(27)	29	19	37	97	33	110
Japan	19	9	29	39	0	18
Norway	53	16	44	0.2	0.1	0.9
Switzerland	35	3	31	1.1	0	0.2
United States	44	42	40	23	34	105

<heading level 2> Global Supply Chain effect on CE

According to the EXIOBASEv2 database, Russia is the largest generator of waste, followed by China, the US, the larger Western European Economies, and Japan (figure 3). This ranking does not change substantially if one takes a consumption-based perspective. China's waste footprint is about 15% smaller than its territorial waste account, while the waste footprint of the North American and Western European countries is up to 25% higher than their territorial account.

The relative shares of different waste treatment processes vary by region (figure 3). Russia, Brazil, Mexico and Canada rely mainly on landfill sites, whereas Japan has the highest share of incineration. Those regional differences may be explained, at least partly, by the size and population density of the country: Russia, Brazil, Mexico and Canada are among the largest countries in the world and therefore are not as constrained by space as some other regions when disposing of waste. Japan, on the other hand, has a high population density and thus incineration is of high institutional priority (Nakamura and Kondo 2002).

Not all regions show the same coverage of waste types. High income countries usually have more comprehensive waste accounts than low and middle income countries. Low and middle income countries have only a few waste types for which data are available, and in particular, they do not seem to report incineration or landfilling at all, which is clearly the result of poor coverage of often unregulated landfill sites in official statistics and informal dumping and burning. Due to this apparent data gap the solid waste footprints are to be seen as first estimates that need to be improved in the future.

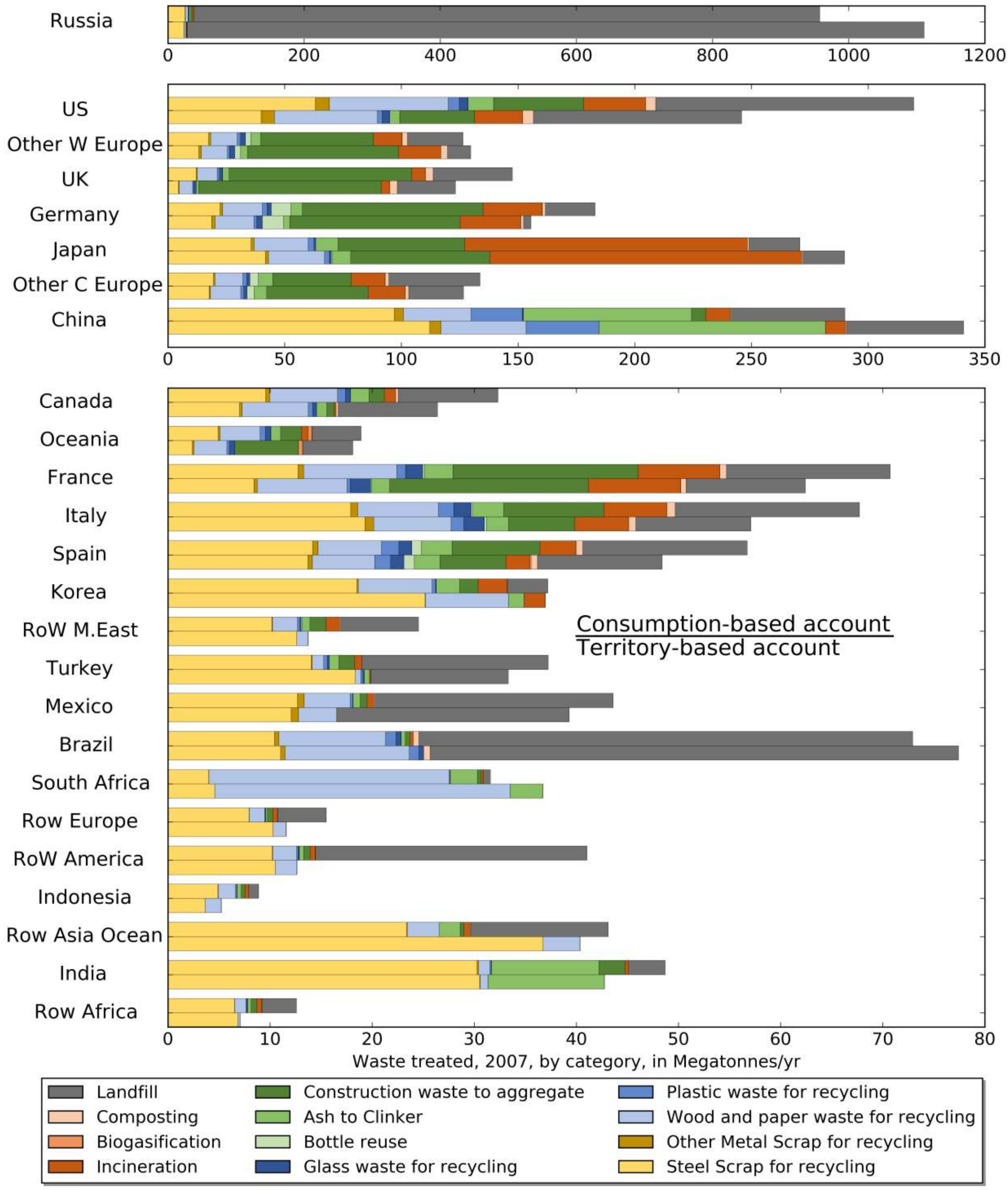

Figure 3: Regional demand for solid waste treatment demand, by 12 groups of treatment processes. For ease of readability three different scales are used and within each subplot the regions are sorted by decreasing GDP per capita from top to bottom. For each region, the **top bar represents the waste footprint** (consumption-based perspective) and the **bottom bar represents domestic waste generation** (territorial-based perspective).

The possible correlation between affluence and waste generation is investigated using the full country resolution of EXIOBASEv2 (48 regions) in order to have the maximum number of data points (figure 4).

As income per capita increases, a country's waste management industry tends to rely more on recycling, although a clear relationship is hard to establish because of differences in economic structure among countries and insufficient data coverage ($R^2 = 0.46$, figure 4, left). The coupling becomes stronger when adopting a consumption perspective. One possible explanation is that with increasing income, consumers tend to purchase products with higher level of fabrication, which involve more industrial processes with waste generation. With increased income countries and regions tend to rely on foreign recycling activities to supply their consumption more than on domestic recycling activities, because the consumption-based income elasticities of waste generation are higher than the territorial elasticities ($\varepsilon = 1.31$ for consumption-based instead of $\varepsilon = 1.15$ for territorial-based). Recovery waste (figure 4, middle) shows a particularly high income elasticity ($\varepsilon = 2.22$ and 2.12 respectively for consumption-based and territory-based accounts). One possible explanation could be the combination of increasing waste flows due to affluence and better access to technical knowledge and investment required for recycling and recovery assets. The landfilled waste regression (figure 4, right) must be interpreted cautiously, as the correlation result ($\varepsilon = 1.53$, $R^2 = 0.56$) might be biased because of incomplete data for lower income countries, as already seen in figures 2 and 3. Even so, waste footprints appear to rise faster than income for landfilled waste.

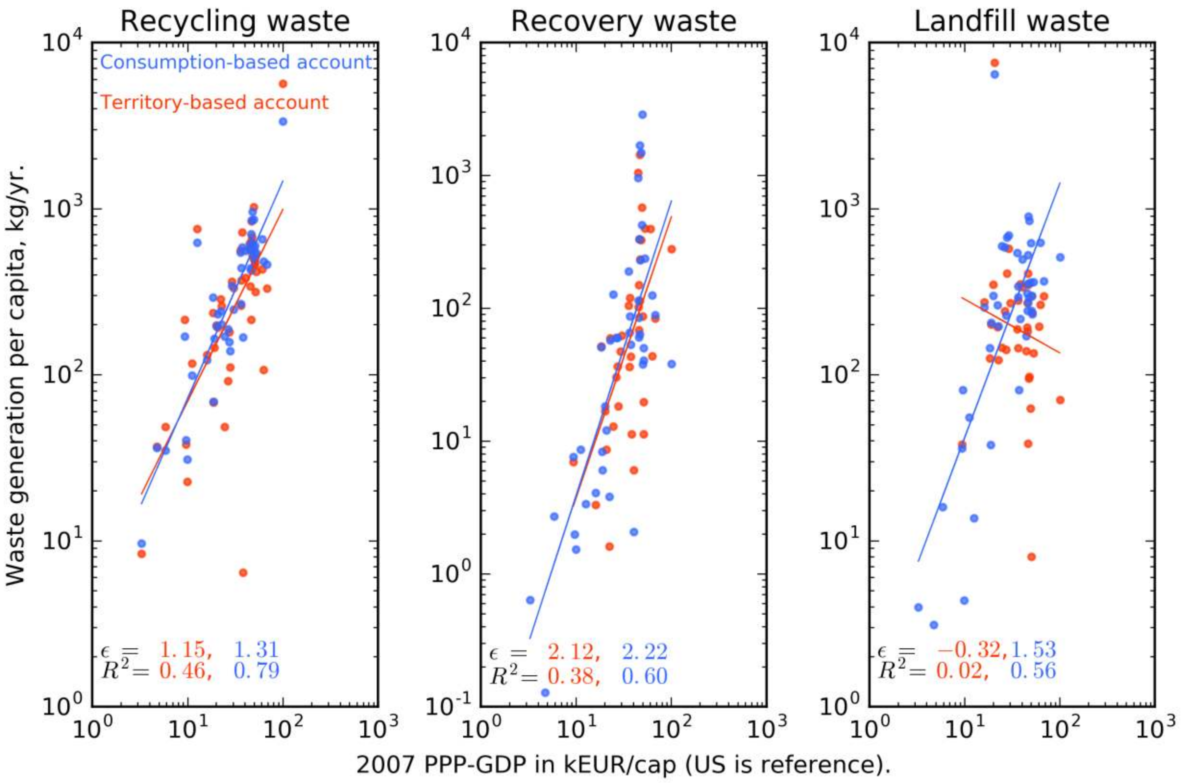

Figure 4: Per capita waste generation over per capita PPP-GDP. **Red plot** for territorial-based accounting and **blue plot** for consumption-based accounting of waste. Same broad treatment categories as in figure 1: re-processing or re-used waste (**left plot**); waste that is potentially utilized by energy or nutrient recovery or biogas production (**middle plot**); and waste that is sent to landfill sites (**right plot**). ε is the elasticity, and R^2 is the standard coefficient of determination.

<heading level 1> Discussion

<heading level 2> The ‘circular economy’ in light of the EXIOBASE global multiregional waste account

In 2007, 1.5 Gt of solid waste were landfilled, corresponding to about one third of all solid waste generated globally. This flow contains large amounts of potentially useful resources and therefore represents a great potential for enhancing the ‘circularity’ of the global economy. These 1.5 Gt are very unevenly distributed across regions, with Russia showing the largest potential, followed by the US, Brazil, and Mexico. On the contrary, countries like Switzerland, Japan, and Germany have well-established waste processing and recycling systems, and less than ten percent of their total waste supply goes to landfill sites. It is worth noting that almost 0.8 Gt of the 1.5 Gt of landfilled waste can potentially be recycled, as it consists of wood, metal, paper, glass and plastic waste.

While incineration and other forms of energy recovery are certainly helpful in reducing waste tonnage and greenhouse gas emissions from landfill sites, they also preclude recycling, for example of paper or plastics. In this group, which accounts for 0.7 Gt globally, or 15 % of the total global waste generation, lies another potential to reduce material loss and the dependency on virgin resources, as at least 0.2 Gt thereof are potentially recyclable materials (wood, paper, glass, plastics, and metal). Finally for the recycling and re-use flows, the EXIOBASE pSUT lists 1 Gt. The resolution of the SUTs does not allow us to assess the quality of the recycled materials, but from other, more detailed studies it is known that quality loss is a major issue during the recycling process, especially for metals like aluminum that are sensitive to tramp elements (Løvik et al. 2014; Cullen and Allwood 2013).

Waste accounts like the one presented here allow for a first rough estimate of the maximum potential for increased recycling and recovery. It is well established that the actual potential is lower, due to economic reasons (price), physical reasons like contamination with tramp elements (metals) or organic waste (paper, plastics), or system-wide trade-offs between energy costs and material recovery (What is the energy cost of recovering the material from waste compared to primary production?). The waste accounts allow policy makers to identify hotspots of waste generation. They provide a quantitative basis for estimating which of the many circular economy strategies proposed may have an impact on the large scale and which do not.

In the EU, MSW represents only of 37% of total waste flows. In 2007, a recycling rate of 65% of MSW might not have been possible, because the EXIOBASE waste account shows that the wood, metal, plastics, glass, and paper fraction, which is potentially recyclable, in the non-recycled MSW (recovered and landfilled MSW) was too small (about 56 Mt, but about 100 Mt would have been needed to meet the target). CE policies need to target industrial waste, too, as this waste fraction shows a potential for additional recycling (wood, metal, plastics, glass, and paper content) of about 55 Mt in the EU, and about 350 Mt globally. As industrial waste never goes through the use phase, it should be eliminated at source as much as possible or be directly recycled on site.

<heading level 2> The relation between international trade and the circular economy

A circular economy does not have to be confined to a country's national borders. While a country's national economy can show high rates of recycling and recovery, the picture is often different from a consumption-based perspective, as many imported products embody high flows of non-recycled waste.

As seen in figure 4, solid waste embodied in trade increases faster than waste generated domestically, as per capita income rises. Waste footprints appear better correlated with personal affluence than the territorial accounts. With the current dataset those two observations hold for landfilling, re-processing, and recovery alike.

<heading level 2> Data quality and reliability of results

The EXIOBASE2 waste accounts are not complete, as the sum total of waste generation equals the sum total of reported waste treatment, for which no consistent and complete global statistics are available. Figure 2 and the territorial accounts in figure 3 show that some regions, including the "RoWs" ("Rest of the World"), Indonesia, India and South Africa, report only a few different waste types, most of them waste for recycling. There is an underestimation of the total amount of waste treated in these and probably also in other regions, as data on dumping and landfilling in low income countries are not available in official statistics. In the reports about data gathering it is recognized that waste data stem from many different sources and that "Waste has often no economic value, is composed of different fractions frequently mixed together, reused in industrial processes or illegally dumped" ((Merciai et al. 2013), p. 20). These facts exacerbate the compilation of complete and coherent waste accounts for all regions. The possible gaps in the data might come from either: (i) legal dumping or other treatment that is not recorded and therefore not captured by the SUT tables; (ii) illegal dumping or other treatment, thus also not captured by the tables; and (iii) direct reuse at the households or industries of origin (e.g., food waste composted or used as feed without market transactions involved). Hoornweg and Bhada-Tata (2012b) estimate that Africa and south Asia have the lowest collection rates of solid waste (46 and 65% respectively), while OECD countries together have a collection rate of 98%. Even for high income countries, like the US, estimates of waste disposal rate can be underestimated: Powell et al. (2016) revised the estimate of the landfill disposal rate from 122 to 262 million tonnes per annum in the US in 2012. The really high flow of landfilled wastes in Russia is based on statistical sources (Perelet and Solovyeva 2011) and it is acknowledged that Russia generates 1.5 times more waste that the EU, which is unexpectedly high given the population of the country (UNECE 2012). In table S6 in the Supplement S1 we indicate the completeness and reliability of the waste statistics from which the accounts are derived. The incomplete coverage of waste flows in poorer regions affects the consumption-based accounting of waste in higher income regions, as Figure S6 in the SI shows that high-income regions ‘consume’ 50-80% of the exports of embodied waste from low-income regions. As such the solid waste footprints presented here are a first estimate, and more resources are needed to complete the waste accounts to better understand the effect of global supply chains on waste generation and to properly address the issue of waste embodied in trade in CE and waste policies.

<heading level 2> Directions for future work

Decisions on waste management at the country level have traditionally been informed by material flow cost accounting and life cycle assessments (LCA) of waste treatment technologies, where assessments of given technologies on the small scale were scaled up to the levels of actual waste generation in different countries (Tukker 1999; Morrissey and Browne 2004; Parkes et al. 2015). As shown by Nakamura and Kondo (2002), Kondo and Nakamura (2005) and Chen and Ma (2015), global input-output models that include waste treatment like the one presented here, can provide additional insights into how waste management and material efficiency could be optimized, for example, by coupling these models to linear programs. The WIO model (Nakamura and Kondo (2002)) allows for studying networks of waste generation and treatment, where different policies can be modelled through the choice of the waste allocation matrix S (see equation 1). Kondo and Nakamura (2005) use a linear program (LP) to identify optimal waste management and recycling strategies, which can provide policy-relevant advice for making material cycles more sustainable.

The WIO model could be linked to LCA studies of specific waste treatment routes thus extending their system boundary. Since the WIO model covers waste flows at scale it overcomes a typical limitation of LCA, the focus on small units of consumption.

Chen and Ma (2015), for example, use a WIO model of Taiwan to unravel industrial waste and by-product flows between industries and identify over- or under-supply of wastes/by-products. Performing similar analysis at the country or regional level could help to understand how to enhance industrial symbiosis (IS) and how to improve industry-wide material efficiency by favoring inter-industry waste exchanges and by diverting waste from down-cycling, recovery or landfill processes. A global scenario for enhanced IS could be estimated by determining optimal sector specific bilateral waste flows using a modified version of the World Trade Model with Bilateral Trade[6] (Duchin 2005; Strømman and Duchin 2006).

Direct bilateral trade of waste is not yet included explicitly in the database. Adding traded waste to the SUTs would allow for studying the downstream treatment of waste that is sent abroad for treatment or reuse (Nakamura et al. 2014). The tracing of domestically generated waste might be relevant for policy makers as it would allow them to estimate the losses of secondary resources and related environmental impacts. Trade of waste also plays an important role in redistributing secondary resources across the world.

Multiregional pSUTs have another important application for studying the circular economy, as they allow for assessing the material efficiency of industrial production across different countries by estimating how much material is turned into scrap in fabrication processes, recycled, or lost in landfill sites. pSUTs are also the basis for IO models with a byproduct technology or product substitution construct that allow us to study the potential and impacts of substitution of virgin by recycled material. The application of multiregional physical transaction tables to study sustainable material cycles has just begun.

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[6] Based on a LP, as well, the World Trade Model aims at optimizing trade based on comparative advantage in order to minimize factor cost.

Supporting information available

Additional supporting information may be found in the online version of this article:

Supplement S1: Contains the details of the EXIOBASE and WIO model classification and aggregation, the construct used to build the WIO model, and additional results.

Supplement S2: Contains the waste accounts for 48 and 25 regions for 11 types of solid waste and 12 waste treatment processes for the year 2007.

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