# 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

# <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

77    While the CE concept is easy to understand, quantitative indicators to assess the 'circularity' of

78    national economies, material cycles, value chains, and product life cycles need to be developed to

79    facilitate implementation (Ellen MacArthur Foundation 2015). Policy-relevant indicators for the

80    'circularity' of an economy depend on both: the definition and the scope of the CE, and a detailed

81    quantitative physical account of the flows and stocks in that economy. While the first part is mainly

82    the result of a policy process, the latter part falls within the scope of industrial ecology. In particular,

83    the physical account needs to focus on waste flows and their treatment, as waste is the single resource

84    for recycled materials as well as for energy and nutrient recovery.

85    ## What do we know about solid waste?

86    Waste generation has been studied at different regional levels. Work for The World Bank

87    (Hoornweg and Bhada-Tata (2012)) analyses waste generation in 90 countries. Other scholars studied

88    the decoupling of economic growth from waste generation, typically with a European scope and/or a

89    focus on municipal solid waste (excluding industrial waste) (Mazzanti and Zoboli 2008; Mazzanti

90    2008; Mazzanti and Zoboli 2009; Van Caneghem et al. 2010; Nicolli et al. 2012; Anupam et al. 2012;

91    Mazzanti et al. 2012). Evidence shows that waste generation in the UK and other OECD countries

92    might have passed a peak (Goodall 2011; Hoornweg and Bhada-Tata 2012), and it was suggested that

93    high-income countries' waste generation rates might decrease from 2.37 kg waste per capita per day

94    in 2008 to 2.26 kg/day by 2025 (Jackson 2009). Some studies analyzed in more detail how the supply

95    chain drives waste generation using input-output tables (IOT) (Lee et al. 2012; Court 2012; Court et

96    al. 2014; Jensen et al. 2013). However, these studies do not allow for the distinction between different

97    waste types and treatment processes, economic sectors generating waste, and the goods and services

98    whose production caused the waste. A comprehensive and consistent global account of waste

99    generation and treatment is still lacking.

100    The aforementioned studies use waste data compiled for individual countries or a set of developed

101    countries (i.e. European Union), which are not trade-linked with the rest of the world. Without a

102    trade-linked inventory one cannot link consumption with waste generated abroad (Bruckner et al.

103    2012; Wiedmann et al. 2013). Only the studies by Beylot et al. (2016), Liao et al. (2015), Jensen et al.

104    (2013b) and Lee et al. (2012) accounted for the amount of waste embodied in trade[2].

105    State-of-the-art methods to study waste generation in industrial networks and the CE are life cycle

106    assessment (LCA) (Hellweg and Canals 2014), waste-input-output models (WIO) (Nakamura and

107    Kondo 2002), and the accounting frameworks that these models are based upon (Pauliuk et al. 2015).

108    The extended waste supply and use tables (WSUT) (Lenzen and Reynolds 2014; Reynolds et al.

109    2014) is an accounting framework that is of particular relevance to waste and the circular economy.

110    The accounting frameworks record economic and physical exchange between industries considering

111    different economic sectors, waste types, and waste treatment processes. WIO analysis was applied to

112    study the CE in a case study covering the agri-food industry of Australia (Pagotto and Halog 2015). It

113    was also used to identify the potential for national level industrial symbioses (IS) for Taiwan (Chen

114    and Ma 2015). So far, WIO analyses were only conducted for Japan, Australia, Taiwan, the UK and

115    France (Tsukui et al. 2015; Fry et al. 2015; Liao et al. 2015; Kagawa et al. 2004, 2007; Reynolds et al.

116    2014; Nakamura and Kondo 2002; Chen and Ma 2015; Beylot et al. 2015; Salemdeeb et al. 2016).A

117    global assessment of solid waste footprints at the world level is lacking.

118    The present study focuses on solid waste (SW) and its treatment (SWT), and its aim is to (i)

119    provide an overview of global waste generation and treatment patterns, (ii) discuss the new EU

120    directive regarding the CE in light of the waste accounts, (iii) to quantify the waste flows embodied in

121    international trade and compare them to domestic waste generation, and (iv) study the link between

122    waste generation to affluence. Our study provides a first detailed estimate of global waste generation

123    and treatment. It covers the world in 48 regions (aggregated to 25 regions in some graphs) and

124    includes 11 types of solid waste as well as 12 waste treatment processes, which together allow for

125    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.

126     In section 2 we describe the data, the reconciliation procedure, and the global multiregional waste-

127     input-output model. In section 3 we present the results for waste generation and treatment in the 25

128     world regions and in their supply chains, and show how waste generation is correlated with per capita

129     income. Section 4 discusses our findings and provides suggestions for future database improvement.

130     # Methods

131     ## The EXIOBASE waste account

132     Part of a series of EU-funded research projects, the CREEA project (Compiling and Refining

133     Environmental and Economic Accounts) included the compilation of a global multi-regional (MR)

134     environmentally extended supply and use table (SUT), EXIOBASE. Version 2.2.0 of the EXIOBASE

135     covers the use of 80 natural resources, 170 emissions to nature, and 36 different waste treatment

136     routes for 43 countries and 5 rest of the world (RoW) regions, at a resolution of 163 economic sectors

137     and 200 products by country for the reference year 2007 (Wood et al. 2015; Tukker et al. 2014, 2013).

138     EXIOBASE v2 is the only available multiregional IO database that includes global multiregional

139     physical and monetary supply and use tables (pSUT and mSUT, respectively) (Schmidt et al. 2012;

140     Merciai et al. 2013; Wood et al. 2015)[3]. While the accounting of monetary flows and some policy

141     relevant environmental stressors (e.g. $CO_2$) at the national statistical offices is well established,

142     physical, and especially waste accounting is far less developed. The implementation of the System of

143     Environmental-Economic Accounts (SEEA) will eventually lead to better physical national accounts

144     (Banerjee et al. 2016), complete and comprehensive waste data, however, is currently not available.

145     As industry and market balances in monetary units are used as constraints when reconciling raw

146     data into the mSUT, the EXIOBASE pSUT was calculated using mass balance principle, too (Schmidt

147     et al. 2012; Merciai et al. 2013). Unlike with the economic balance, non-economic flows like uptake

148     of natural resources, emissions to nature, and waste also enter the mass balance equations.

149     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.

150    2015; Merciai et al. 2013), and therefore special attention was given to their compilation during the

151    creation of the EXIOBASE pSUT. The dry matter content of materials and waste is recorded,

152    including solid waste, which is defined here as any solid output from a human activity that remains

153    inside the techno-sphere and that requires further treatment before it can be released to the

154    environment or be used as substitute for other industrial products. Therefore, liquid waste such as

155    manure or wastewater, and unused domestic extraction such as mining overburden or residues from

156    forestry and agriculture that are not harvested are not included in the waste accounts.

157      A global multiregional account of solid waste generation and treatment is not available at the

158    resolution of the contemporary MRIO tables. For most EXIOBASE countries, however, detailed

159    statistics for waste *treatment* are available, and we used those data to populate the supply table by

160    recording waste usage as supply of waste treatment service. When necessary, the data for the supply

161    of waste treatment services had to be disaggregated into the EXIOBASE waste classification, which is

162    usually more detailed than the statistics. For example, often statistics only report the total amount of

163    waste incinerated or landfilled. In EXIOBASE, incineration and landfilling are divided into waste

164    fractions (e.g. incineration of food waste, incineration of paper waste, etc.), therefore the incineration

165    and landfilling totals needed to be portioned. This procedure was done according to specific studies

166    on the composition of solid waste, and we refer to section 2.5 of Merciai et al. (2013) for a detailed

167    list of sources used to define those partitioning coefficients.

168      In a second step, we used the monetary use table and available data on price, transfer coefficients

169    from input products to output products, resources and emissions coefficients, and the mass balance of

170    industrial processes to estimate the actual amount of waste generated(Figure 1). The reason for

171    calculating waste from mass balance is that data on inputs of natural resources, products, and

172    emissions are generally of a higher quality compared to data on waste generation, which are provided

173    by national institutions using different waste definitions, classifications and accounting schemes. This

174    mass balance concept was first described in Schmidt et al. (2010) and gives the amount and type (e.g.

175    paper, metal, food…) of waste generated by each industry in EXIOBASE.

176      In most cases, the calculated amount of waste generated was higher than the amount reported as

177  treated by official statistics. We therefore split the waste generation account determined by mass

178  balance into a part that is covered by the treatment statistics and a part that is not, and we called the

179  latter 'unregistered waste'. The fraction of the waste generated that is matched by the treatment

180  statistics is recorded in the physical use table by recording waste generation as use of waste treatment

181  service, after being split into the different treatment options with the partitioning coefficients derived

182  from the supply of waste treatment services. The unregistered waste is recorded as a physical

183  extension to the PSUT. Further reading about the reconciliation/balancing algorithm can be found in

184  section 7.2 in Merciai et al. (2013). A discussion and comparison of the mass balance approach to

185  reported waste data can be found in Schmidt (2010) and Verberk et al. (2013). They report that the

186  main differences between the available waste statistics and the results of the mass balance approach

187  are due to differences in the scope of waste statistics across countries and uncertainties of product life-

188  times to estimate postconsumer waste and scrap flows.

189    It is difficult to establish accurate physical balances for industrial sectors as only monetary use

190  data are widely available, sector-specific price data are absent in most cases, and average prices

191  therefore had to be used. The unregistered waste estimates are hence the result of a reconciliation

192  routine with highly uncertain constraints, and they are not matched by statistical data either, as those

193  do not exist. The resulting high uncertainty of the total mass balance difference, which we interpreted

194  as uncertainty of the total waste generation, led us to exclude the unregistered waste fraction from our

195  analysis and to focus on that part that is matched by official statistics. The current waste account used

196  in this article is therefore likely to underestimate the total waste generated, as it only covers the

197  fraction of the waste for which statistical data exists. We believe that this narrow scope of waste flows

198  is more credible than using the estimated total values.
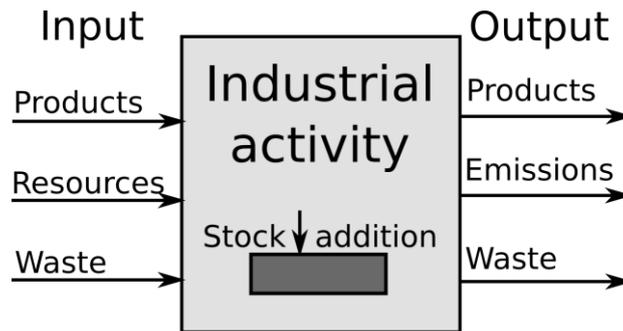
**Figure 1:** Input- and output flows for a generic industrial activity. The output of waste is calculated from the process mass balance if no statistical data are available

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.

221    To build a WIO model from the EXIOBASE mSUT and pSUT we first compiled a mixed unit

222    square WSUT with 48  regions (25 for aggregated results), 128 products and services measured in

223    million euros (MEUR), and 35 waste treatment services measured in tonnes (Lenzen and Reynolds

224    2014). Since our focus is on solid waste and because of lack of data in EXIOBASEv2, wastewater,

225    sewage sludge, and manure were excluded from the analysis, which reduces the number of waste

226    treatment services to 30[4]. The reference year for our analysis is 2007. We used the 'product

227    substitution construct', which is a generalization of the byproduct technology construct, to build the

228    $A$-matrix of the WIO model from the mixed unit SUT (Majeau-Bettez et al. 2014). The procedure is

229    explained in the Supplement S1.


230    The WIO model equation is shown in equation 1 (we refer to Nakamura and Kondo (2002) for a

231    detailed description and to the sheet 'WIO_Model_Example' of the Supplement S2 for a simple

232    worked example), where subscripts $I$ describes the goods producing sectors of the economy and $II$ the

233    waste treatment sectors. $X$ is the total output of the economy, divided into total output of goods $X_I$ and

234    total waste treated $X_{II}$. $Y_I$ and $W_{.,F}$ are the final demand for goods (households and government

235    consumption for example) and for waste treatments services (waste generated directly by households

236    and governments), respectively. $A = \{a_{i,j}\}$ and $G = \{g_{k,j}\}$ are the technical coefficients matrices of

237    the industries, which denote the amount of sector $i$ output required per unit output of sector $j$ and the

238    quantity of waste $k$ generated per unit output of economic activities $j$. In general, there is no one-to-

239    one correlation between waste and waste treatment industry, as there can be several treatment options

240    for one waste type.


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


242    The $S$ matrix allocates waste to different treatment options where $s_{t,k}$ gives the share of waste type

243    $k$ treated by treatment process $t$. This allocation matrix is particularly relevant when studying changes

244    in waste treatment policies.

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

245    In the EXIOBASE MR-SUT, there is a 1:1 correspondence between waste types and treatment

246    sectors, as in Leontief's pollution abatement model (Leontief 1972), and the *S*-matrix of the

247    EXIOBASE-WIO model is the identity matrix.

248    <heading level 2> Regression analysis and aggregation of results

249    The link between waste generation and affluence is analyzed by a regression analysis of solid

250    waste generation rates and solid waste footprints (tonnes/capita) with purchasing power parity (PPP)

251    scaled GDP per capita (GDP: Gross Domestic Product). Population and PPP data were retrieved from

252    World Bank statistics and aggregated to the regional classification of the MRIO model (World Bank

253    2015), while GDP was extracted from EXIOBASEv2. From the regression analysis, income

254    elasticities of waste generation and waste footprint are estimated, which indicate the percentage

255    increase in waste generation for a given percentage increase in income. For example, an elasticity of

256    waste generation of 1.2 means that for a 1% increase in income 1.2% more waste is generated.

257    In order to simplify the presentation of the results the 30 waste treatment services were aggregated

258    into 11 types of solid waste, and 12 waste treatment processes (cf. Tables S4 and S5 of Supplement

259    S1). We applied two categories of solid waste: municipal solid waste (MSW), which includes waste

260    directly generated by final demands and service sectors, and industrial waste, which include wastes

261    generated by industry. We considered three broad categories of waste treatment: (i) recycling (re-use,

262    re-processing, and re-melting), (ii) recovery of a different quality of a material, either energy,

263    nutrients, or aggregates, through the treatment and partial utilization by incineration with or without

264    heat recovery and electricity generation, bio-gasification, composting, and construction waste to

265    aggregates, and (iii) loss of materials in landfill sites.

266    <heading level 1> Results

267    <heading level 2> The waste accounts in EXIOBASE

268    In high-income countries industries, services sectors, and households generate 1-2 tonnes of solid

269    waste per capita per year (figure 2). While construction waste often dominates for European countries,

270    Canada and the US show substantial contributions from metal, inert, and paper/wood waste. The

271    reported per capita waste flows decline with income, as shown here for Brazil, China, and Turkey,

272    with the exception of Russia (figure S1 in Supplement S1). In many countries, especially those with

273    higher personal income, MSW contributes up to 40-50% of total landfilled and recycled waste,

274    respectively. While industrial waste tends to contain high shares of metal, wood, construction, and

275    inert waste, MSW flows contain large fractions of food, paper, plastics, and textile waste.

276    The patterns of waste generation are quite diverse and differ substantially across countries and

277    regions but in general, there is significant unseized potential for closing material cycles. In many

278    European countries, for example, large fractions of final consumer waste end up in landfill sites

279    (around one third for France, Italy, Spain and Other Central Europe, more than half for the UK, and

280    almost 100% in Russia, figure S1 in Supplement S1). The US, Canada, Mexico, and Brazil rely on

281    landfilling for both industrial and final consumer wastes. Most food waste is landfilled, except for in

282    Japan and in most Western European countries. Construction waste flows are significant mainly in

283    developed countries, where buildings and infrastructure turnover is high. Construction waste is

284    classified differently across countries, which is a problem inherent to MRIO modelling, where

285    statistics from different countries are combined.

286    The total amount of waste generated worldwide in 2007 was about 3.2 Gt (1 gigatonne = one

287    billion metric tonnes), of which 1 Gt was recycled or re-used, 0.7 Gt was incinerated, gasified,

288    composted, or used as aggregates, and 1.5 Gt was landfilled. The solid waste account for 48 regions,

289    11 waste types, and ten sectors is included in the Supplement S2.
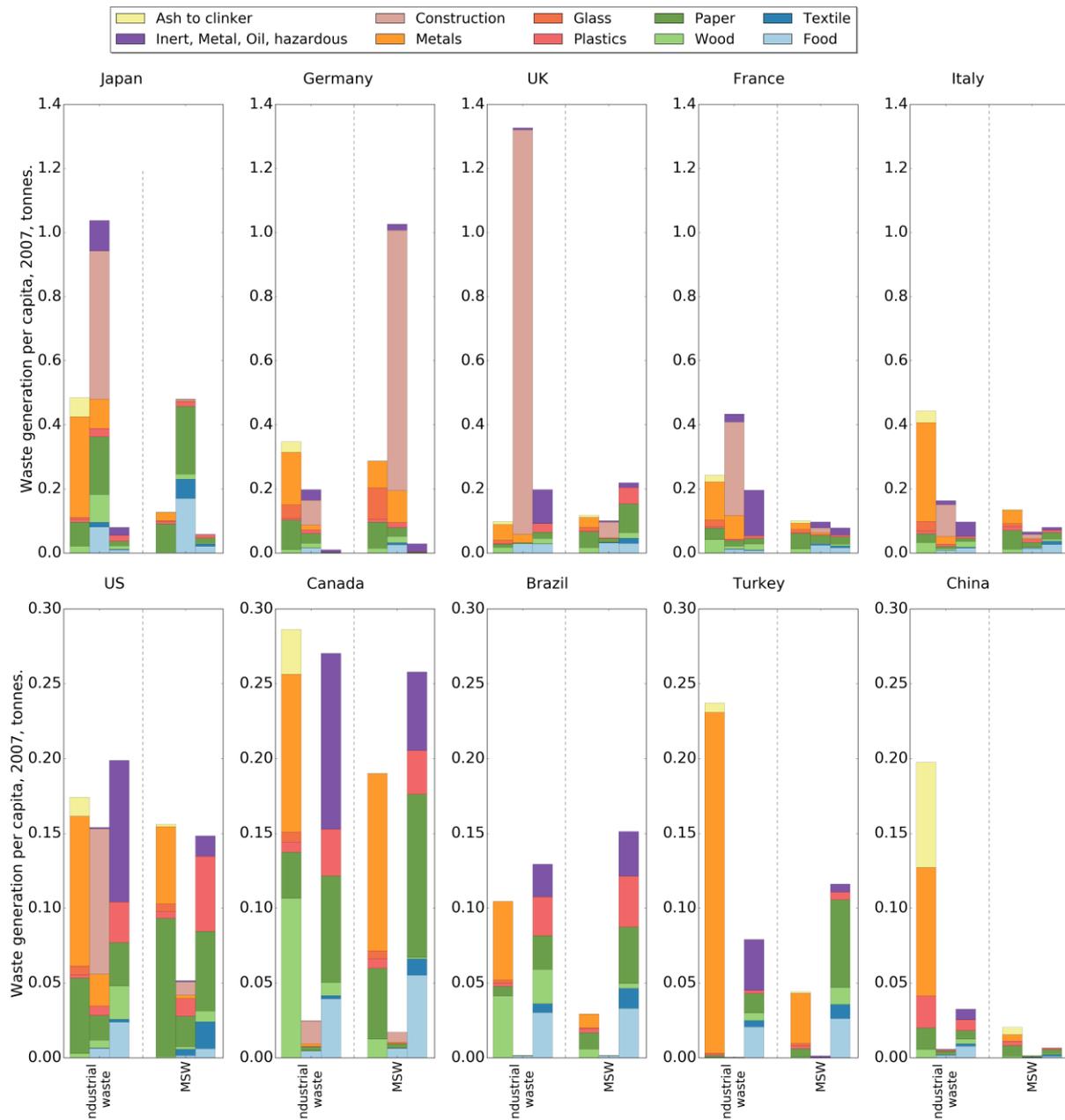
**Figure 2:** EXIOBASE2 accounts of waste supply per capita, by aggregated economic sectors for a selection of countries (all regions are available in the Supplement S1). MSW (municipal solid waste) consists of waste generated by final demands and service sectors. Industrial waste is solid waste generated 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

299  10% by 2030 (European Commission 2015a, 2015b). In 2007, only 29% of MSW was recycled, and

300  the recycling of an additional 97 Mt (megatonnes) of MSW would be needed to reach the goal set by

301  the European Commission (table 1, detailed table for all EU countries can be found in Supplement

302  S1). According to the SUT, however, the part of the 2007 MSW that shows potential for recycling[5] in

303  the EU was just about 56 Mt, meaning that a level of recycling of 65% of MSW would not have been

304  possible in 2007, as only two third of the required additional 97 Mt to be recycled were actually

305  recyclable waste. The share of landfilling would have to be reduced by another 9 percentage points

306  (33 more Mt) in order to reach the goal set for 2030 at the 2007 waste generation levels.

307      The EU27 performs worse than the other developed economies (except Japan) in terms of the share

308  of MSW recycled. Australia, Canada, and the US have much higher recycling shares than the EU, but

309  also their MSW fraction going to landfill sites is more than twice as high as in the EU. In absolute

310  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.

312 **Table 1:** Overview of municipal solid waste (MSW) and landfilled waste flows in different developed countries and world

313 regions, 2007. The shares of MSW recycled and landfilled, and the share of MSW in total solid waste are shown. The table

314 also shows how much additional MSW needs to be recycled and diverted from landfill sites to meet the EU Circular

315 Economy directive targets. The rightmost column shows the total landfilled solid waste.

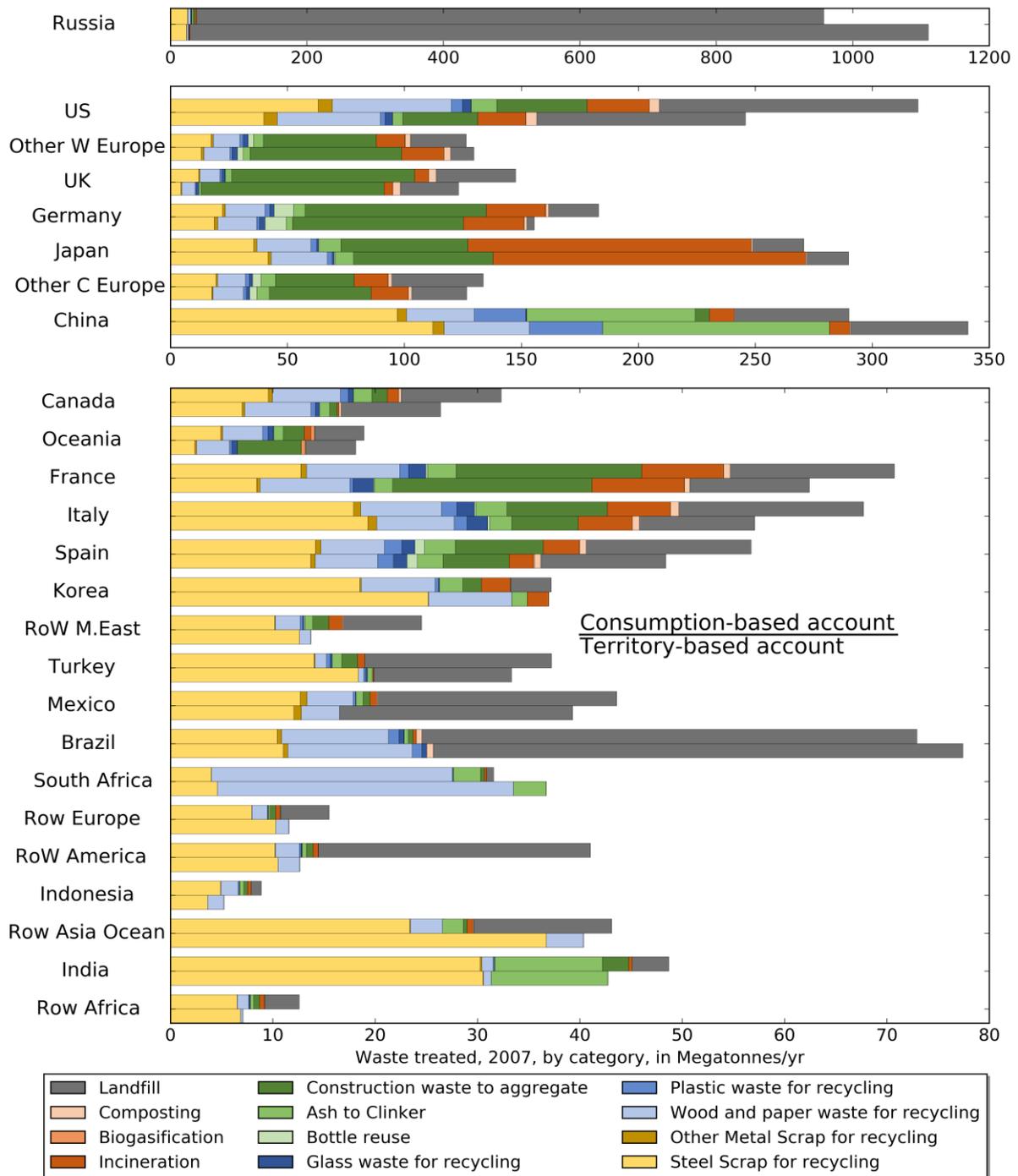| Country/Region | Share of municipal waste recycled (%) | Share of municipal waste landfilled (%) | Share of MSW in total solid waste (%) | Additional MSW to be recycled (Mt) | Additional MSW to be diverted from landfilling (Mt) | Total landfilled waste (Mt) |
|---|---|---|---|---|---|---|
| **EU Target 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 |

316

317 <heading level 2> Global Supply Chain effect on CE

318 According to the EXIOBASEv2 database, Russia is the largest generator of waste, followed by

319 China, the US, the larger Western European Economies, and Japan (figure 3). This ranking does not

320 change substantially if one takes a consumption-based perspective. China's waste footprint is about

321 15% smaller than its territorial waste account, while the waste footprint of the North American and

322 Western European countries is up to 25% higher than their territorial account.

323 The relative shares of different waste treatment processes vary by region (figure 3). Russia, Brazil,

324 Mexico and Canada rely mainly on landfill sites, whereas Japan has the highest share of incineration.

325 Those regional differences may be explained, at least partly, by the size and population density of the

326 country: Russia, Brazil, Mexico and Canada are among the largest countries in the world and

327 therefore are not as constrained by space as some other regions when disposing of waste. Japan, on

328 the other hand, has a high population density and thus incineration is of high institutional priority

329 (Nakamura and Kondo 2002).

330 Not all regions show the same coverage of waste types. High income countries usually have more

331 comprehensive waste accounts than low and middle income countries. Low and middle income

332    countries have only a few waste types for which data are available, and in particular, they do not seem

333    to report incineration or landfilling at all, which is clearly the result of poor coverage of often

334    unregulated landfill sites in official statistics and informal dumping and burning. Due to this apparent

335    data gap the solid waste footprints are to be seen as first estimates that need to be improved in the

336    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).

342   The possible correlation between affluence and waste generation is investigated using the full

343   country resolution of EXIOBASEv2 (48 regions) in order to have the maximum number of data points

344   (figure 4).

345   As income per capita increases, a country's waste management industry tends to rely more on

346   recycling, although a clear relationship is hard to establish because of differences in economic

347   structure among countries and insufficient data coverage ($R^2 = 0.46$, figure 4, left). The coupling

348   becomes stronger when adopting a consumption perspective. One possible explanation is that with

349   increasing income, consumers tend to purchase products with higher level of fabrication, which

350   involve more industrial processes with waste generation. With increased income countries and regions

351   tend to rely on foreign recycling activities to supply their consumption more than on domestic

352   recycling activities, because the consumption-based income elasticities of waste generation are higher

353   than the territorial elasticities ($\varepsilon = 1.31$ for consumption-based instead of $\varepsilon = 1.15$ for territorial-based).

354   Recovery waste (figure 4, middle) shows a particularly high income elasticity ($\varepsilon = 2.22$ and $2.12$

355   respectively for consumption-based and territory-based accounts). One possible explanation could be

356   the combination of increasing waste flows due to affluence and better access to technical knowledge

357   and investment required for recycling and recovery assets. The landfilled waste regression (figure 4,

358   right) must be interpreted cautiously, as the correlation result ($\varepsilon = 1.53$, $R^2 = 0.56$) might be biased

359   because of incomplete data for lower income countries, as already seen in figures 2 and 3. Even so,

360   waste footprints appear to rise faster than income for landfilled waste.

361
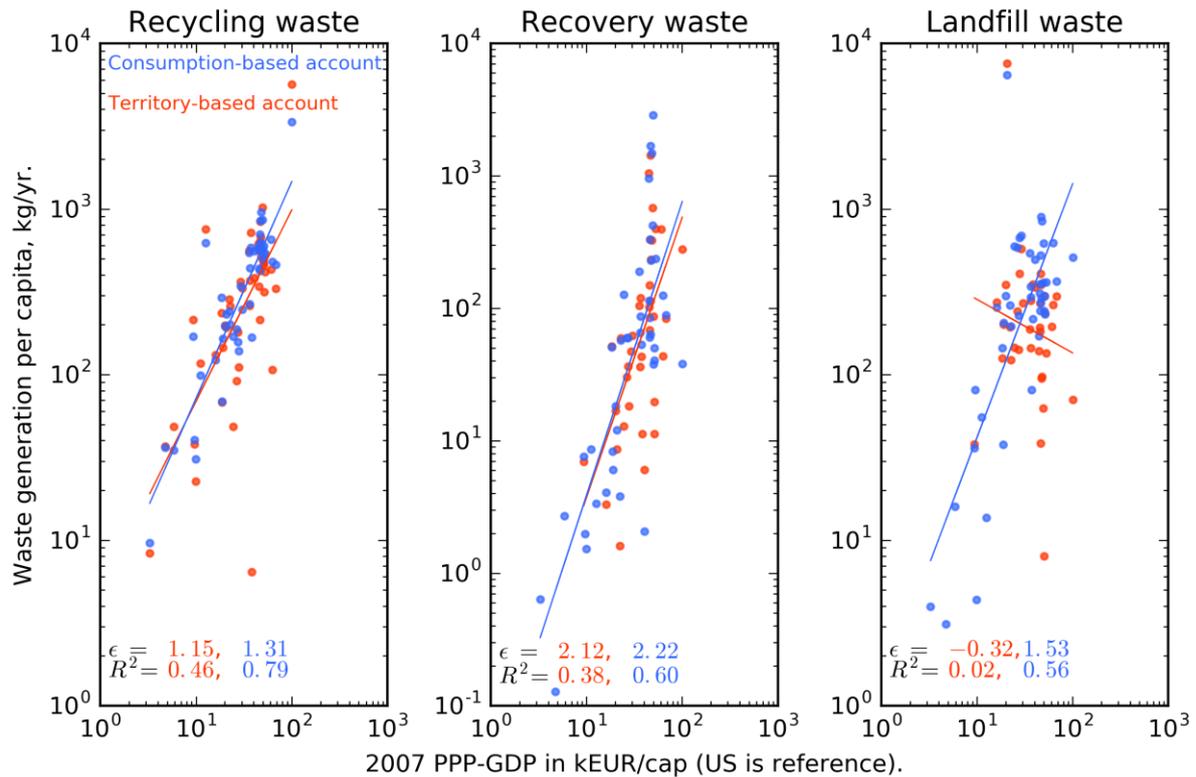
**Figure 4**: Per capita waste generation over per capita PPP-GDP. **Red plot** for territorial-based accounting and **blue plot** for consumption-based accounting of waste. Same broad treatment categories as in figure 1: re-processing or re-used waste (**left plot**); waste that is potentially utilized 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.

# Discussion

## 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.

378    While incineration and other forms of energy recovery are certainly helpful in reducing waste

379    tonnage and greenhouse gas emissions from landfill sites, they also preclude recycling, for example of

380    paper or plastics. In this group, which accounts for 0.7 Gt globally, or 15 % of the total global waste

381    generation, lies another potential to reduce material loss and the dependency on virgin resources, as at

382    least 0.2 Gt thereof are potentially recyclable materials (wood, paper, glass, plastics, and metal).

383    Finally for the recycling and re-use flows, the EXIOBASE pSUT lists 1 Gt. The resolution of the

384    SUTs does not allow us to assess the quality of the recycled materials, but from other, more detailed

385    studies it is known that quality loss is a major issue during the recycling process, especially for metals

386    like aluminum that are sensitive to tramp elements (Løvik et al. 2014; Cullen and Allwood 2013).

387    Waste accounts like the one presented here allow for a first rough estimate of the maximum

388    potential for increased recycling and recovery. It is well established that the actual potential is lower,

389    due to economic reasons (price), physical reasons like contamination with tramp elements (metals) or

390    organic waste (paper, plastics), or system-wide trade-offs  between energy costs and material recovery

391    (What is the energy cost of recovering the material from waste compared to primary production?).

392    The waste accounts allow policy makers to identify hotspots of waste generation. They provide a

393    quantitative basis for estimating which of the many circular economy strategies proposed may have an

394    impact on the large scale and which do not.

395    In the EU, MSW represents only of 37% of total waste flows. In 2007, a recycling rate of 65% of

396    MSW might not have been possible, because the EXIOBASE waste account shows that the wood,

397    metal, plastics, glass, and paper fraction, which is potentially recyclable, in the non-recycled MSW

398    (recovered and landfilled MSW) was too small (about 56 Mt, but about 100 Mt would have been

399    needed to meet the target). CE policies need to target industrial waste, too, as this waste fraction

400    shows a potential for additional recycling (wood, metal, plastics, glass, and paper content) of about 55

401    Mt in the EU, and about 350 Mt globally. As industrial waste never goes through the use phase, it

402    should be eliminated at source as much as possible or be directly recycled on site.

## The relation between international trade and the circular
economy

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

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

413    ## Data quality and reliability of results

414    The EXIOBASE2 waste accounts are not complete, as the sum total of waste generation equals the
415    sum total of reported waste treatment, for which no consistent and complete global statistics are
416    available. Figure 2 and the territorial accounts in figure 3 show that some regions, including the
417    "RoWs" ("Rest of the World"), Indonesia, India and South Africa, report only a few different waste
418    types, most of them waste for recycling. There is an underestimation of the total amount of waste
419    treated in these and probably also in other regions, as data on dumping and landfilling in low income
420    countries are not available in official statistics. In the reports about data gathering it is recognized that
421    waste data stem from many different sources and that "Waste has often no economic value, is
422    composed of different fractions frequently mixed together, reused in industrial processes or illegally
423    dumped" ((Merciai et al. 2013), p. 20). These facts exacerbate the compilation of complete and
424    coherent waste accounts for all regions. The possible gaps in the data might come from either: (i)
425    legal dumping or other treatment that is not recorded and therefore not captured by the SUT tables;
426    (ii) illegal dumping or other treatment, thus also not captured by the tables; and (iii) direct reuse at the
427    households or industries of origin (e.g., food waste composted or used as feed without market
428    transactions involved). Hoornweg and Bhada-Tata (2012b) estimate that Africa and south Asia have

429    the lowest collection rates of solid waste (46 and 65% respectively), while OECD countries together

430    have a collection rate of 98%. Even for high income countries, like the US, estimates of waste

431    disposal rate can be underestimated: Powell et al. (2016) revised the estimate of the landfill disposal

432    rate from 122 to 262 million tonnes per annum in the US in 2012. The really high flow of landfilled

433    wastes in Russia is based on statistical sources (Perelet and Solovyeva 2011) and it is acknowledged

434    that Russia generates 1.5 times more waste that the EU, which is unexpectedly high given the

435    population of the country (UNECE 2012). In table S6 in the Supplement S1 we indicate the

436    completeness and reliability of the waste statistics from which the accounts are derived. The

437    incomplete coverage of waste flows in poorer regions affects the consumption-based accounting of

438    waste in higher income regions, as Figure S6 in the SI shows that high-income regions 'consume' 50-

439    80% of the exports of embodied waste from low-income regions. As such the solid waste footprints

440    presented here are a first estimate, and more resources are needed to complete the waste accounts to

441    better understand the effect of global supply chains on waste generation and to properly address the

442    issue of waste embodied in trade in CE and waste policies.

443    ## Directions for future work

444    Decisions on waste management at the country level have traditionally been informed by material

445    flow cost accounting and life cycle assessments (LCA) of waste treatment technologies, where

446    assessments of given technologies on the small scale were scaled up to the levels of actual waste

447    generation in different countries (Tukker 1999; Morrissey and Browne 2004; Parkes et al. 2015). As

448    shown by Nakamura and Kondo (2002), Kondo and Nakamura (2005) and Chen and Ma (2015),

449    global input-output models that include waste treatment like the one presented here, can provide

450    additional insights into how waste management and material efficiency could be optimized, for

451    example, by coupling these models to linear programs. The WIO model (Nakamura and Kondo

452    (2002)) allows for studying networks of waste generation and treatment, where different policies can

453    be modelled through the choice of the waste allocation matrix $S$ (see equation 1). Kondo and

454    Nakamura (2005) use a linear program (LP) to identify optimal waste management and recycling

455    strategies, which can provide policy-relevant advice for making material cycles more sustainable.

456    The WIO model could be linked to LCA studies of specific waste treatment routes thus extending

457    their system boundary. Since the WIO model covers waste flows at scale it overcomes a typical

458    limitation of LCA, the focus on small units of consumption.

459    Chen and Ma (2015), for example, use a WIO model of Taiwan to unravel industrial waste and by-

460    product flows between industries and identify over- or under-supply of wastes/by-products.

461    Performing similar analysis at the country or regional level could help to understand how to enhance

462    industrial symbiosis (IS) and how to improve industry-wide material efficiency by favoring inter-

463    industry waste exchanges and by diverting waste from down-cycling, recovery or landfill processes. A

464    global scenario for enhanced IS could be estimated by determining optimal sector specific bilateral

465    waste flows using a modified version of the World Trade Model with Bilateral Trade[6] (Duchin 2005;

466    Strømman and Duchin 2006).

467    Direct bilateral trade of waste is not yet included explicitly in the database. Adding traded waste to

468    the SUTs would allow for studying the downstream treatment of waste that is sent abroad for

469    treatment or reuse (Nakamura et al. 2014). The tracing of domestically generated waste might be

470    relevant for policy makers as it would allow them to estimate the losses of secondary resources and

471    related environmental impacts. Trade of waste also plays an important role in redistributing secondary

472    resources across the world.

473    Multiregional pSUTs have another important application for studying the circular economy, as

474    they allow for assessing the material efficiency of industrial production across different countries by

475    estimating how much material is turned into scrap in fabrication processes, recycled, or lost in landfill

476    sites. pSUTs are also the basis for IO models with a byproduct technology or product substitution

477    construct that allow us to study the potential and impacts of substitution of virgin by recycled

478    material. The application of multiregional physical transaction tables to study sustainable material

479    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.

480

## Supporting information available

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

483 **Supplement S1:** Contains the details of the EXIOBASE and WIO model classification and aggregation,

484 the construct used to build the WIO model, and additional results.

485 **Supplement S2:** Contains the waste accounts for 48 and 25 regions for 11 types of solid waste and 12

486 waste treatment processes for the year 2007.

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# References

Anupam, K., M. Takanori, M. Takashi, and M. Tohru. 2012. Decoupling and Environmental Kuznets Curve for Municipal Solid Waste Generation: Evidence from India. *International Journal of Environmental Sciences* 2(3): 1670–1674.

Ayres, R.U. and A. V Kneese. 1969. Production, Consumption, and Externalities. *American Economic Association* 59(3): 282–297.

Banerjee, O., M. Cicowiez, M. Horridge, and R. Vargas. 2016. A Conceptual Framework for Integrated Economic-Environmental Modeling. *The Journal of Environment & Development* 25(3): 276–305. http://jed.sagepub.com/cgi/doi/10.1177/1070496516658753.

Beylot, A., B. Boitier, N. Lancesseur, and J. Villeneuve. 2016. A consumption approach to wastes from economic activities. *Waste Management*. http://linkinghub.elsevier.com/retrieve/pii/S0956053X1630023X.

Beylot, A., S. Vaxelaire, and J. Villeneuve. 2015. Reducing Gaseous Emissions and Resource Consumption Embodied in French Final Demand: How Much Can Waste Policies Contribute? *Journal of Industrial Ecology* 0(0): n/a-n/a. http://dx.doi.org/10.1111/jiec.12318.

Bruckner, M., S. Giljum, C. Lutz, and K.S. Wiebe. 2012. Materials embodied in international trade - Global material extraction and consumption between 1995 and 2005. *Global Environmental Change* 22(3): 568–576.

Caneghem, J. Van, C. Block, H. Van Hooste, and C. Vandecasteele. 2010. Eco-efficiency trends of the Flemish industry: Decoupling of environmental impact from economic growth. *Journal of Cleaner Production* 18(14): 1349–1357.

Chen, P.-C. and H. Ma. 2015. Using an Industrial Waste Account to Facilitate National Level Industrial Symbioses by Uncovering the Waste Exchange Potential. *Journal of Industrial Ecology* 0(0): 1–13.

Court, C.D. 2012. Enhancing U. S. hazardous waste accounting through economic modeling. *Ecological Economics* 83: 79–89.

Court, C.D., M. Munday, A. Roberts, and K. Turner. 2014. Can hazardous waste supply chain "hotspots" be identified using an input-output framework? *European Journal of Operational Research* 241: 177–187.

Cullen, J.M. and J.M. Allwood. 2013. Mapping the global flow of aluminium: from liquid aluminium to End-Use goods. *Environmental Science & Technology* 47(7): 3057–3064. http://www.ncbi.nlm.nih.gov/pubmed/23167601.

Duchin, F. 2005. A world trade model based on comparative advantage with m regions, n goods, and k factors. *Economic Systems Research* 17(2): 141–162. http://www.tandfonline.com/doi/abs/10.1080/09535310500114903.

Ellen MacArthur Foundation. 2015. *Circularity Indicators - An Approach to Measuring Circularity*. Cowes, UK. https://www.ellenmacarthurfoundation.org/programmes/insight/circularity-indicators.

European Commission. 2011. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Roadmap to a Resource Efficient Europe , COM(2011) 571 final.

European Commission. 2015a. *Closing the loop - An EU action plan for the Circular Economy*. *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS*.

European Commission. 2015b. DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2008/98/EC on waste.

Fry, J., M. Lenzen, D. Giurco, and S. Pauliuk. 2015. An Australian Multi-Regional Waste Supply-Use Framework. *Journal of Industrial Ecology* 0(0): 1–11.

Georgescu-Roegen, N. 1971. *The Entropy Law and the Economic Process*. Cambridge, MA: Harvard University Press.

Ghisellini, P., C. Cialani, and S. Ulgiati. 2015. A review on circular economy: the expected transition

555      to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*.
556      http://linkinghub.elsevier.com/retrieve/pii/S0959652615012287.

557    Goodall, C. 2011. *"Peak Stuff"-Did the UK reach a maximum use of material resources in the early*
558      *part of the last decade? Carbon Commentary*.

559    Haas, W., F. Krausmann, D. Wiedenhofer, and M. Heinz. 2015. How Circular is the Global
560      Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the
561      European Union and the World in 2005. *Journal of Industrial Ecology* 0(0): 1–13.
562      http://doi.wiley.com/10.1111/jiec.12244.

563    Hellweg, S. and L.M.I. Canals. 2014. Emerging approaches, challenges and opportunities in life cycle
564      assessment. *Science* 344(6188): 1109–1113.
565      http://science.sciencemag.org/content/344/6188/1109.full.

566    Hoornweg, D. and P. Bhada-Tata. 2012. What a waste: a global review of solid waste management.
567      *World Bank, Washington DC*: 9.
568      http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-
569      1334852610766/What_a_Waste2012_Final.pdf.

570    Jackson, T. 2009. *Prosperity without growth? The transition to a sustainable economy*.
571      http://www.sd-commission.org.uk/data/files/publications/prosperity_without_growth_report.pdf.

572    Jensen, C.D., S. Mcintyre, M. Munday, and K. Turner. 2013. Responsibility for Regional Waste
573      Generation: A Single-Region Extended Input-Output Analysis for Wales. *Regional Studies*
574      47(6): 913–933. http://dx.doi.org/10.1080/00343404.2011.599797.

575    Kagawa, S., H. Inamura, and Y. Moriguchi. 2004. A Simple Multi-Regional Input–Output Account
576      for Waste Analysis. *Economic Systems Research* 16(1): 1–20.
577      http://dx.doi.org/10.1080/0953531032000164774.

578    Kagawa, S., S. Nakamura, H. Inamura, and M. Yamada. 2007. Measuring spatial repercussion effects
579      of regional waste management. *Resources, Conservation and Recycling* 51: 141–174.
580      http://www.sciencedirect.com/science/article/pii/S0921344906001856.

581    Kondo, Y. and S. Nakamura. 2005. Waste input–output linear programming model with its
582      application to eco-efficiency analysis. *Economic Systems Research* 17(4): 393–408.
583      http://dx.doi.org/10.1080/09535310500283526.

584    Lee, C.H., P.C. Chen, and H.W. Ma. 2012. Direct and indirect lead-containing waste discharge in the
585      electrical and electronic supply chain. *Resources, Conservation and Recycling* 68: 29–35.
586      http://dx.doi.org/10.1016/j.resconrec.2012.07.007.

587    Lenzen, M. and C.J. Reynolds. 2014. A Supply-Use Approach to Waste Input-Output Analysis.
588      *Journal of Industrial Ecology* 18(2): 212–226. http://dx.doi.org/10.1111/jiec.12105.

589    Leontief, W. 1972. Air pollution and the economic structure: Empirical results of input-output
590      computations. In *Input-Output Techniques*, ed. by A Brody and A P Cater. Amsterdam: North-
591      Holland.

592    Liao, M., P. Chen, H. Ma, and S. Nakamura. 2015. Identification of the driving force of waste
593      generation using a high-resolution waste input–output table. *Journal of Cleaner Production* 94:
594      294–303. http://www.sciencedirect.com/science/article/pii/S0959652615001067.

595    Lieder, M. and A. Rashid. 2015. Towards Circular Economy implementation: A comprehensive
596      review in context of manufacturing industry. *Journal of Cleaner Production*.
597      http://linkinghub.elsevier.com/retrieve/pii/S0959652615018661.

598    Løvik, A.N., R. Modaresi, and D.B. Müller. 2014. Long-term strategies for increased recycling of
599      automotive aluminum and its alloying elements. *Environmental Science and Technology* 48(8):
600      4257–4265.

601    Majeau-Bettez, G., R. Wood, and A.H. Strømman. 2014. Unified Theory of Allocations and
602      Constructs in Life Cycle Assessment and Input-Output Analysis. *Journal of Industrial Ecology*
603      18(5): 747–770.

604    Mazzanti, M. 2008. Is waste generation de-linking from economic growth? Empirical evidence for
605      Europe. *Applied Economics Letters* 15(4): 287–291.
606      http://dx.doi.org/10.1080/13504850500407640.

607    Mazzanti, M., A. Montini, and F. Nicolli. 2012. Waste dynamics in economic and policy transitions:
608      decoupling, convergence and spatial effects. *Journal of Environmental Planning and*
609      *Management* 55(5): 563–581.

Mazzanti, M. and R. Zoboli. 2008. Waste generation, waste disposal and policy effectiveness. Evidence on decoupling from the European Union. *Resources, Conservation and Recycling* 52: 1221–1234.

Mazzanti, M. and R. Zoboli. 2009. Municipal Waste Kuznets curves: Evidence on socio-economic drivers and policy effectiveness from the EU. *Environmental and Resource Economics* 44(2): 203–230.

Merciai, S., J.H. Schmidt, R. Dalgaard, S. Giljum, S. Lutter, A. Usubiaga, J. Acosta, H. Schütz, D. Wittmer, and R. Delahaye. 2013. *CREEA — Report and data Task 4.2 : P-SUT*. http://creea.eu/download/public-deliverables.

Morrissey, A.J. and J. Browne. 2004. Waste management models and their application to sustainable waste management. *Waste Management* 24(3): 297–308.

Nakamura, S. and Y. Kondo. 2002. Input-output analysis of waste management. *Journal of Industrial Ecology* 6(1): 39–63.

Nakamura, S., Y. Kondo, S. Kagawa, K. Matsubae, K. Nakajima, and T. Nagasaka. 2014. MaTrace: tracing the fate of materials over time and across products in open-loop recycling. *Environmental Science & Technology* 48(13): 7207–14.

National People's Congress. 2008. *Circular Economy Promotion Law of the People's Republic of China*.

Nicolli, F., M. Mazzanti, and V. Iafolla. 2012. Waste Dynamics, Country Heterogeneity and European Environmental Policy Effectiveness. *Journal of Environmental Policy & Planning* 14(4): 371–393.

OECD. 2011. *Resource Productivity in the G8 and the OECD - A report in the framework of the Kobe 3R Action Plan*. http://www.oecd.org/environment/waste/47944428.pdf.

Pagotto, M. and A. Halog. 2015. Towards a Circular Economy in Australian Agri-food Industry: An Application of Input-Output Oriented Approaches for Analyzing Resource Efficiency and Competitiveness Potential. *Journal of Industrial Ecology* 0(0): n/a-n/a. http://doi.wiley.com/10.1111/jiec.12373.

Parkes, O., P. Lettieri, and I.D.L. Bogle. 2015. Life cycle assessment of integrated waste management systems for alternative legacy scenarios of the London Olympic Park. *Waste Management* 40: 157–166. http://dx.doi.org/10.1016/j.wasman.2015.03.017.

Pauliuk, S., G. Majeau-Bettez, and D.B. Müller. 2015. A General System Structure and Accounting Framework for Socioeconomic Metabolism. *Journal of Industrial Ecology* 19(5): 728–741. http://doi.wiley.com/10.1111/jiec.12306.

Perelet, R. and S. Solovyeva. 2011. *Analysis for European Neighbourhood Policy (ENP) Countries and the Russian Federation on social and economic benefits of enhanced environmental protection – Russian Federation Country Report*.

Peters, G.P. 2008. From production-based to consumption-based national emission inventories. *Ecological Economics* 65(1): 13–23. http://linkinghub.elsevier.com/retrieve/pii/S0921800907005162.

Powell, J.T., T.G. Townsend, and J.B. Zimmerman. 2016. Estimates of solid waste disposal rates and reduction targets for landfill gas emissions. *Nature Climate Change* 6(2015): 162–165.

Reynolds, C.J., J. Piantadosi, and J. Boland. 2014. A Waste Supply-Use Analysis of Australian Waste Flows. *Journal of Economic Structures* 3. http://link.springer.com/article/10.1186/s40008-014-0005-0.

Salemdeeb, R., A. Al-tabbaa, and C. Reynolds. 2016. The UK waste input – output table : Linking waste generation to the UK economy. *Waste Management & Research*: 1–6.

Schmidt, J.H., S. Merciai, R. Delahaye, J. Vuik, R. Heijungs, A. de Koning, and A. Sahoo. 2012. *CREEA - Recommendation of terminology, classification, framework of waste accounts and MFA, and data collection guideline. CREEA - Compiling and Refining Environmental and Economic Accounts Recommendation*. Vol. D4.1. http://creea.eu/download/public-deliverables.

Steinberger, J.K., F. Krausmann, and N. Eisenmenger. 2010. Global patterns of materials use: A socioeconomic and geophysical analysis. *Ecological Economics* 69(5): 1148–1158.

Strømman, A.H. and F. Duchin. 2006. A world trade model with bilateral trade based on comparative advantage. *Economic Systems Research* 18(3): 281–297. http://dx.doi.org/10.1080/09535310600844300.

665 Tsukui, M., S. Kagawa, and Y. Kondo. 2015. Measuring the waste footprint of cities in Japan- a
666     interregional waste input–output analysis.pdf. *Journal of Economic Structures* 4(18): 1–24.
667     http://dx.doi.org/10.1186/s40008-015-0027-2.
668 Tukker, A. 1999. Life cycle assessments for waste, part I: Overview, methodology and scoping
669     process. *The International Journal of Life Cycle Assessment* 4(5): 275–281.
670 Tukker, A., T. Bulavskaya, S. Giljum, A. de Koning, S. Lutter, M. Simas, K. Stadler, and R. Wood.
671     2014. *The Global Resource Footprint of Nations. Carbon, water, land and material embodied in*
672     *trade and final consumption calculated with EXIOBASE 2.1*. Leiden/Delft/Vienna/Trondheim.
673 Tukker, A., A. de Koning, R. Wood, T. Hawkins, S. Lutter, J. Acosta, J.M. Rueda Cantuche, et al.
674     2013. EXIOPOL – Development and Illustrative Analyses of a Detailed Global MR-EE
675     SSUT/IOT. *Economic Systems Research* 25(1): 50–70.
676     http://www.tandfonline.com/doi/abs/10.1080/09535314.2012.761952.
677 UNECE. 2012. The Environment Impact of Waste Generation and Waste Management.
678     http://www.unece.org/news/waste_statistics.html. Accessed September 21, 1016.
679 Wiedmann, T.O., H. Schandl, M. Lenzen, D. Moran, S. Suh, J. West, and K. Kanemoto. 2013. The
680     material footprint of nations. *Proceedings of the National Academy of Sciences of the United*
681     *States of America* 112(20): 9–10.
682 Wood, R., K. Stadler, T. Bulavskaya, S. Lutter, S. Giljum, A. de Koning, J. Kuenen, et al. 2015.
683     Global Sustainability Accounting - Developing EXIOBASE for Multi-Regional Footprint
684     Analysis. *Sustainability* 7(1): 138–163.
685 World Bank. 2015. GDP (current US$). *World Bank*.
686     http://databank.worldbank.org/data/reports.aspx?source=2&type=metadata&series=NY.GDP.M
687     KTP.CD. Accessed November 3, 2015.
688