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RESEARCH AND ANALYSIS

Analysis of the development and structural drivers of raw-material use in Germany

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Abstract

In orderto reduce the negative consequences of raw-material extraction, it is necessary to accurately report raw-material use and to understand its drivers in society. In this study, we conduct a multi-regional environmentally extended input–output analysis of Germany's past raw-material use. We then perform a two-stage structural decomposition analysis (SDA) of the development of material use in order to identify the main drivers. Although input-based indicators of Germany's raw-material use, which also include the material footprint of exports, show slight upward trends between 1995 and 2011, consumption-based indicators have remained relatively steady in that time frame. On the one hand, this suggests a relative decoupling of Germany's domestic consumption from material use. On the other hand, exports, which contribute significantly to Germany's value-added creation, have driven up input-based indicators. The first stage of the SDA reveals that the material intensity of raw-material provision would have by itself decreased Germany's raw-material consumption (RMC), whereas changes in the structure of the global economy and in Germany's final demand would have increased it. The second stage of the decomposition reveals that the positive contributions to Germany's RMC are in large part due to shifts toward internationally sourced intermediate and final goods and an overall increase in the level of final demand in Germany.

KEYWORDS
decomposition analysis, economy-wide material flow analysis (EW-MFA), input–output analysis (IOA), material consumption, multi-regional, structural change

1 | INTRODUCTION

Over the past century, global material use has increased by a factor of eight (Schaffartzik, Eisenmenger, Krausmann, & Weisz, 2014). This development is accompanied by a shifting away from the age-long dominance of renewable biomass as the primary material input of human activity to non-renewable materials comprising non-metallic minerals, metal ores, and fossil fuels, which together make up the majority of global material use today (Krausmann et al., 2009; Schaffartzik et al., 2014, 2016). Current global material extraction amounts to over 70 billion metric tons per year (Giljum, Dittrich, Lieber, & Lutter, 2014; Schandl et al., 2017) and may reach 180 billion metric tons in 2050 (Hatfield-Dodds et al., 2017). Wealthy countries, such as Germany, play a major role in global material extraction since their continuously growing demand for products induces material extraction across the globe. When taking used and unused extraction (e.g., overburden) into account, our calculations reveal that Germany's domestic consumption of goods and services in 2011 induced about 6% of global material extraction. This was more than 5% share of Germany's GDP in the world total (United Nations, 2019). Between 1995 and 2011, the share of imports, measured in raw material equivalents (RME—the sum of all raw materials required along global supply chains of goods and services finally consumed in a given place) in Germany's overall material demand, has increased from 42% to 63%. These imports are increasingly sourced from remote places, specifically East as well as South and Southeast Asia, with implications for transport and local conditions of raw-material extraction.

Raw-material extraction is often accompanied by vast impacts on the ecosystem and associated environmental issues, including local emissions of toxic substances and global GHG emissions (Ayres, 1997; Giegrich, Liebich, Lauwigi, & Reinhardt, 2012; Norgate & Haque, 2010; Nuss & Eckelman, 2014). These environmental issues are reinforced by declining ore grades, which result in increased specific energy demands and environmental pressures (Calvo, Mudd, Valero, & Valero, 2016; Frenzel, Kullik, Reuter, & Gutzmer, 2017; van der Voet, van Oers, Verboon, & Kuipers, 2018). In addition, many extraction activities create social problems, such as the exploitation of the local workforce, or the financing of political conflicts (Gandenberger, Glöser, Marscheider-Weidemann, Ostertag, & Walz, 2012; Manhart, 2007). The continued extraction of finite resources also raises issues of intergenerational equity, as these resources may not be available anymore to future generations.

In light of these problems, Germany, among other countries, has developed strategies to reduce raw-material use, mostly in the form of material efficiency measures (e.g., Bundesregierung, 2016; Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, 2016). In order to put these strategies into practice, it is necessary to be able to accurately determine material use for individual geographical regions. In Germany, raw-material use is officially reported in the environmental–economic accounts of the German Statistical Office (Destatis, 2018) and in different reports of the German Environment Agency (cf., Lutter, Giljum, Gözet, Wieland, & Manstein, 2018; Kaumanns & Lauber, 2016). However, these publications do not systematically take the structure of the global production and consumption system and its development over time into account.

One way of taking this structure into account when determining the material use of countries is environmentally extended multi-regional input–output (EE-MRIO) analysis. EE-MRIO is an extension of standard (normally monetary) input–output analysis (cf., Leontief, 1936; Miller & Blair, 2009), which portrays the supply and use structure of different industries located in multiple countries/world regions and includes various types of environment-related information. Time series of EE-MRIO data can further be used to study changes in material use resulting from changes in underlying technical, economic, and demographic factors, which is usually done with some form of decomposition analysis.

The body of literature on the material use of countries and world regions is very large. An increasing number of studies employ large EE-MRIO databases for such analyses, allowing them, inter alia, to differentiate between production- and consumption-based metrics of direct and indirect material use.[1] Some of these studies make the case for attributing material extraction to final demand as the ultimate driver of all economic activity and thus speak of "material footprints" in analogy to the concept of carbon footprints (Wiedmann et al., 2015). These analyses are conducted with different geographical foci, some adopting a global perspective (e.g., Bruckner, Giljum, Lutz, & Wiebe, 2012; Giljum, Bruckner, & Martinez, 2015; Wiedmann et al., 2015), while others focus on country groups, such as the European Union (e.g., Giljum et al., 2016), or individual countries (e.g., Schaffartzik et al., 2014).

A similar differentiation can be made for studies employing decomposition analyses in order to identify the drivers of change in material use. Many studies adopt a global focus, with partial reporting of regional or national results (e.g., Plank, Eisenmenger, Schaffartzik, & Wiedenhofer, 2018; Pothen and Schymura, 2015; Pothen, 2017), while there are also country-specific studies (Hoffrén, Luukkanen, & Kaivo-oja, 2000; Weinzettel & Kovanda, 2011; Wenzlik, Eisenmenger, & Schaffartzik, 2015; Wood, Lenzen, & Foran, 2009). Decomposition methodologies are also used for comparisons of different MRIO databases (Giljum et al., 2019; Owen, Steen-Olsen, Barrett, Wiedmann, & Lenzen, 2014).

To the best of the authors' knowledge, Germany's material use and its drivers have not been analyzed in great detail in relation to the global production and consumption system. This paper attempts to fill this gap by performing an EE-MRIO analysis of Germany's material use in the time frame from 1995 to 2011. The drivers of changes in Germany's material use are then analyzed with the help of structural decomposition analysis (SDA) for the consumption-based indicator rawmaterial consumption (RMC).

The paper continues in Section 2 with a description of the database and the methodologies employed for calculating material use indicators and performing the SDA. Section 3.1 provides an overview of the development of different indicators for Germany and the geographical origin of the embodied materials. The drivers of this past material consumption are identified and discussed in Section 3.2. Section 4 closes with a discussion and conclusions.

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[1] See Eurostat (2018) for a comprehensive description of economy-wide material flow indicators and metrics.

2 | METHODS

2.1 | EE-MRIO analysis and EXIOBASE

Input–output (IO) analysis is an analytical framework with which the interdependence of industries and final demand in an economy can be analyzed (see Miller & Blair, 2009 for a thorough introduction). In environmentally extended input–output (EEIO) analysis, environment-related information (emissions, raw-material extraction, etc.) is attached to IO tables in the form of coefficients, which represent the amount of environmental effect per unit of gross output of each sector. Underlying this is the assumption that the environmental effects caused by the production of a sector are proportional to the output of that sector (Leontief, 1970; Tukker & Jansen, 2006). EEIO models are thus based on "a comprehensive accounting framework covering all economic activities" (Tukker, Huppes, van Oers, & Heijungs, 2006, pp. 9), through which economic and environmental data is brought together in a consistent and systematic way, which ensures compatibility with established systems of national economic and environmental accounting (Schaffartzik et al., 2014). Multi-regional versions of these models, that is, EE-MRIO models, extend this by portraying international consumption–production systems, linking countries and world regions, and the environmental impacts associated with their economic activities. EE-MRIO analysis thus constitutes a transparent and holistic method of accounting for the material inputs of the global economic system, which allows for the precise allocation of direct and indirect material use to national economic activities at the sectoral level.

Formally, to arrive at the absolute environmental burden $\boldsymbol{M}$, the environmental coefficient matrix $\boldsymbol{E}$ is multiplied with the gross output vector $\boldsymbol{x}$, which is calculated by multiplying the Leontief inverse with the final demand vector $\boldsymbol{y}$[2]:

$$\begin{aligned} \boldsymbol{M} &= \boldsymbol{Ex} \\ &= \boldsymbol{E}(\boldsymbol{I}-\boldsymbol{A})^{-1}\boldsymbol{y} \\ &= \boldsymbol{ELy}. \end{aligned} \tag{1}$$

However, IO models in general rely on a number of (partly restrictive) assumptions, including linear-limitational production functions, which imply that all production factors (intermediate deliveries and primary inputs) are in a constant, proportional relationship to each other and to the output of a respective sector. In addition, each sector is assumed to produce one homogeneous product that it sells to all sectors without differentiation. Furthermore, monetary and physical flows are assumed to be proportional, implying that the monetary deliveries sold from one sector to all other sectors always have the same physical content per monetary value (Miller & Blair, 2009; Suh, 2004; Weisz & Duchin, 2006). Finally, EE-MRIO tables in particular generally date back some years due to high data collection and harmonization requirements.

The calculations in this paper are performed with the EE-MRIO database EXIOBASE, which has been developed as part of various projects within the European Commission's 6th and 7th framework programmes, including EXIOPOL, DESIRE, CREEA, and Carbon-Cap (Stadler et al., 2018; Tukker et al., 2009, 2013; Wood, Hawkins, Hertwich, & Tukker, 2014; Wood et al., 2015). Among the available MRIO databases with environmental extensions, including the World Input–Output Database (WIOD) (Dietzenbacher, Los, Stehrer, Timmer, & de Vries, 2013), EORA (Lenzen, Moran, Kanemoto, & Geschke, 2013) and the Global Trade Analysis Project (GTAP) (Peters, Andrew, & Lennox, 2011), EXIOBASE is especially well suited for an analysis of material use due to its comparatively high sectoral resolution and detailed environmental extensions. In this paper, the latest public release of EXIOBASE (version 3.4) is used, which contains yearly IO and base tables as well as environmental and primary factor extensions for the time frame from 1995 to 2011. The IO tables used for this paper are the product-by-product version with 200 product categories and 49 countries and world regions.[3] The energy and material use extension contains 217 entries for used extraction and 223 entries for unused extraction.[4] The majority of the entries comprise biomass, while 12 metal ores and 8 non-metallic minerals are distinguished.[5] Since v.3.4 of EXIOBASE, fossil fuels are aggregated into one combined category (Stadler et al., 2018). For the subsequent analysis, the raw materials are clustered into these four categories (biomass, metals, minerals, and fossil fuels) in line with the environmental–economic accounts of the German Statistical Office (Destatis, 2018; Kaumanns & Lauber, 2016).

2.2 | Structural decomposition analysis

The SDA is performed for the indicator RMC, which encompasses all raw materials required along the supply chains of the goods and services demanded in Germany for final consumption. RMC thus comprises total domestic extraction and imports in RME, minus exports in RME (Eurostat,

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[2] The notation throughout the paper follows the conventions of matrix algebra, where matrices are denoted as bold upper-case letters, vectors as bold lower-case letters, and elements as simple lower-case letters.

[3] The product-by-product tables in EXIOBASE have been constructed using the industry technology assumption. Next to 44 countries that are portrayed individually, the remaining countries are clustered, respectively, within the five world regions—Asia and Pacific, America, rest of Europe (other than EU28), Africa, and Middle East (cf. Stadler et al., 2018).

[4] Unused extraction categories are almost identical to the used extraction categories but exclude honey and beeswax in the agricultural category, but differentiate between different types of coal, oil, and gas in the fossil fuel category.

[5] For simplicity, these categories are subsequently referred to as biomass, metals, minerals, and fossil fuels.

2018). For a given country, it can be calculated by multiplying the coefficients representing used raw-material extraction within the environmental coefficient matrix with gross output, which is in turn the product of the multi-regional Leontief inverse and final demand of that country (see Equation 1). RMC is thus the product of three factors, and the change in German RMC between 1995 and 2011 can be attributed to changes in either of these three factors, namely changes in material coefficients, the structure of the global economy (as portrayed by the multi-regional Leontief inverse), or the level and composition of final demand for goods and services in Germany. In order to investigate the contributions of these factors, decomposition analysis is a suitable tool.

SDA is an intuitive and proven method based on the IO framework to assess the contributions of the aforementioned factors to the total change in environmental impacts—in the present case RMC (cf. Dietzenbacher & Los, 1998; Hoekstra & van den Bergh, 2002, 2003; Su & Ang, 2012; Weinzettel & Kovanda, 2011). SDA results in complete decompositions without unexplained residuals, can handle zero values and allows for two-stage decompositions, in which further structural changes can be analyzed (Su & Ang, 2012). One form of SDA is additive decomposition, in which the changes in individual factors are summed to get the total change. When additively decomposed, Equation (1) thus turns into:

$$\Delta \boldsymbol{M} = \underbrace{\Delta \boldsymbol{E}\boldsymbol{L}\boldsymbol{y}}_{\text{Material coefficient change}} + \underbrace{\boldsymbol{E}\Delta \boldsymbol{L}\boldsymbol{y}}_{\text{Structural change}} + \underbrace{\boldsymbol{E}\boldsymbol{L}\Delta \boldsymbol{y}}_{\text{Final demand change}} . \tag{2}$$

For simplicity, Equation (2) does not contain time indices. However, when comparing two years as in the present case, either one can be used as the respective reference value for the decomposition terms. Depending on which reference year is chosen, the individual terms have different values, even though the overall value for $\Delta \boldsymbol{M}$ remains the same. This yields a number of equally valid complete decomposition variants, none of which is conceptually strictly preferable to the other ones (Baiocchi & Minx, 2010; Dietzenbacher & Los, 1998; de Haan, 2010; Miller & Blair, 2009). The variants of the above decomposition are shown in Equation (S1) in Supporting Information S1 of this paper.

Despite potentially large deviations between the decomposition variants, it is useful to calculate the average of all decomposition variants for each decomposition term in order to get an overview of its contribution to total RMC change (Dietzenbacher & Los, 1998; Guan, Hubacek, Weber, Peters, & Reiner, 2008; Peters, Weber, Guan, & Hubacek, 2007). According to Hoekstra, Michel, and Suh (2016), the average is equivalent to a decomposition formula originally proposed by Sun (1998), which is based on a growth path between two discrete points (see Equations (S2) to (S4) in Supporting Information S1). Calculating the averages of the decomposition variants in this way reduces the computational burden. Unless stated otherwise, these equations are used in the subsequent decomposition analysis.

As Wood & Lenzen (2009) have shown, in analyses utilizing monetary flow data, price fluctuations can lead to misleading conclusions regarding material intensities of sectoral production and therefore have to be corrected for. The intermediate deliveries and final demand matrices are therefore transformed into constant 2005 prices before conducting the decomposition calculations. For this, country- and product-specific price indices from Stadler et al. (2018) are used, with which the nominal values of the intermediate deliveries and final demand matrices are multiplied element-wise.

We employ a two-stage decomposition in which the contributions of changes in the three decomposition factors calculated in the first stage are further split up into separate effects in the second stage. These sub-decompositions of each factor are explained in the following subsections.

2.2.1 | Sub-decomposition of material intensities

Material intensities of sectoral production can either change domestically or abroad. In order to differentiate between domestic and foreign changes, a sub-decomposition is performed in which first only the material coefficients of German production $\boldsymbol{E}_{\text{dom}}$ and subsequently the coefficients of all other countries in the MRIO system $\boldsymbol{E}_{\text{RoW}}$ are changed:

$$\Delta \boldsymbol{E} = \Delta \boldsymbol{E}_{\text{dom}} + \Delta \boldsymbol{E}_{\text{RoW}}. \tag{3}$$

2.2.2 | Sub-decomposition of the global production structure

The change of the global production structure can be interpreted as stemming from changes in international sourcing patterns on the one hand, and changes in the technology mixes of national production systems on the other hand. Even though these effects ultimately accrue to the multi-regional Leontief inverse $\boldsymbol{L}$, they can first be isolated within the multi-regional technical coefficient matrix $\boldsymbol{A}$. The details of how the changes in $\boldsymbol{A}$ relate to changes in $\boldsymbol{L}$ are explained in Section S2.2 of Supporting Information S1.

$\boldsymbol{A}$ can thus be split into one matrix representing the total input requirements of each industry in each country/region $\boldsymbol{A}^*$ and one matrix representing the import shares for each industry in each country/region $\boldsymbol{C}$, where $\boldsymbol{A}$ is the Hadamard product of $\boldsymbol{C}$ and $\boldsymbol{A}^*$ (Hoekstra et al., 2016, Eq. S4):

$$\boldsymbol{A} = \boldsymbol{C} \otimes \boldsymbol{A}^*. \tag{4}$$

Changes in international sourcing patterns can be further differentiated by splitting the import shares matrix $\boldsymbol{C}$ into different sub-matrices and analyzing the effects on Germany's RMC separately. Here, we differentiate between (a) solely domestic changes, that is, German sourcing of German intermediates (by only using $\boldsymbol{C}_{\text{dom}}$ for the decomposition calculation), (b) changes in German sourcing of foreign intermediates (by only using $\boldsymbol{C}_{\text{imp}}$), and (c) changes in the sourcing between the countries of the rest of the world, including intermediates from Germany (by only using $\boldsymbol{C}_{\text{RoW}}$). The construction logic of each of these sub-matrices is explained in Section S2.2 of Supporting Information S1.

The change in the technology mix represents a change in the overall production technology employed in a given country as represented by $\boldsymbol{A}^*$, regardless of the geographical origin of the intermediates. In this case, it may also be of interest whether the technology mix changes domestically or abroad, the latter of which has indirect effects on German RMC. We thus differentiate between a change in Germany's overall production technology (by using the sub-matrix $\boldsymbol{A}^*_{\text{dom}}$) and a change in the overall production technologies of all other countries and world regions in the MRIO system (by using $\boldsymbol{A}^*_{\text{RoW}}$). The construction of these matrices is also explained in Supporting Information S1. Equation (4) can thus be decomposed into:

$$\boldsymbol{A} = \left[\boldsymbol{C}_{\text{dom}} + \boldsymbol{C}_{\text{imp}} + \boldsymbol{C}_{\text{RoW}}\right] \otimes \left[\boldsymbol{A}^*_{\text{dom}} + \boldsymbol{A}^*_{\text{RoW}}\right] \tag{5}$$

This sub-decomposition of $\boldsymbol{A}$ can then be used to assess the effects of partial changes to $\boldsymbol{L}$ on German RMC. The subsequent calculation steps are outlined in Section S2.2 of Supporting Information.

2.2.3 | Sub-decomposition of German final demand

Germany's final demand $\boldsymbol{y}$ can be further decomposed in a similar fashion. It is possible to distinguish between changes in the international sourcing of final demand, in its composition, and in its level. In order to assess this, the final demand vector for Germany can first be split up into a sub-vector representing the international sourcing of German final demand $\boldsymbol{f}$ and one representing total final demand irrespective of its origin $\boldsymbol{y}^*$, where $\boldsymbol{y}$ is the Hadamard product of $\boldsymbol{f}$ and $\boldsymbol{y}^*$:

$$\boldsymbol{y} = \boldsymbol{f} \otimes \boldsymbol{y}^*. \tag{6}$$

The final demand sourcing vector can be further split up into a domestic $\boldsymbol{f}_{\text{dom}}$ and a foreign part $\boldsymbol{f}_{\text{RoW}}$. In order to distinguish between composition and level effects of German final demand, the total final demand vector can be further split into a composition vector $\boldsymbol{b}$ and a scalar representing the sum of final demand in Germany y. Equation (6) thus turns into (Hoekstra et al., 2016, Eq. S7):

$$\boldsymbol{y} = [\boldsymbol{f}_{\text{dom}} + \boldsymbol{f}_{\text{RoW}}] \otimes [\boldsymbol{b} \cdot y]. \tag{7}$$

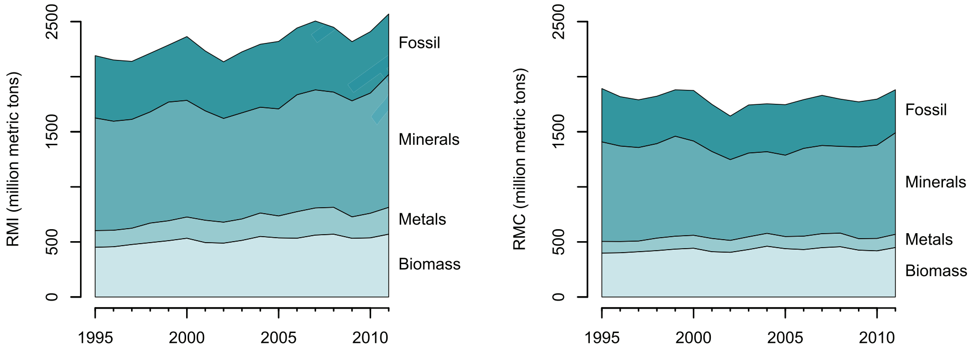
This sub-decomposition of $\boldsymbol{y}$ can then be used to assess the individual contributions of sourcing, composition, and level changes of final demand to German RMC. The subsequent calculation steps are outlined in Section S2.3 of Supporting Information S1.

3 | RESULTS

3.1 | Development of material flow indicators between 1995 and 2011

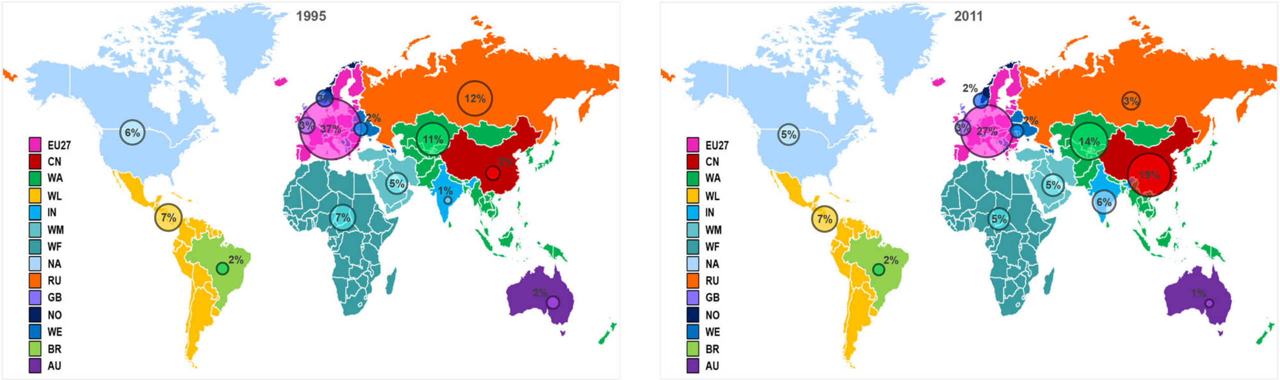
This section provides an overview of Germany's material use in the time frame from 1995 to 2011 based on our calculations with EXIOBASE v.3.4 along two input- and consumption-based indicators taking only used extraction into account (raw material input [RMI] and RMC) and two such indicators also taking unused extraction into account (total material requirement [TMR] and total material consumption [TMC]; see Eurostat (2018) for a definition of the indicators). In addition, an overview of the geographical origin of Germany's imports in RME in 1995 and 2011 is provided.

Overall, RMC has remained relatively steady in the time frame from 1995 to 2011, while RMI has increased by close to 20% (see Figure 1). The majority of both RMI and RMC is made up of minerals, followed by biomass and fossil fuels. Metals make up the smallest fraction in both cases.



(a) Raw material input (b) Raw material consumption

FIGURE 1 Time series of raw material input (a) and raw material consumption (b), own calculation based on EXIOBASE v.3.4. Underlying data used to create this figure can be found in Supporting Information S2



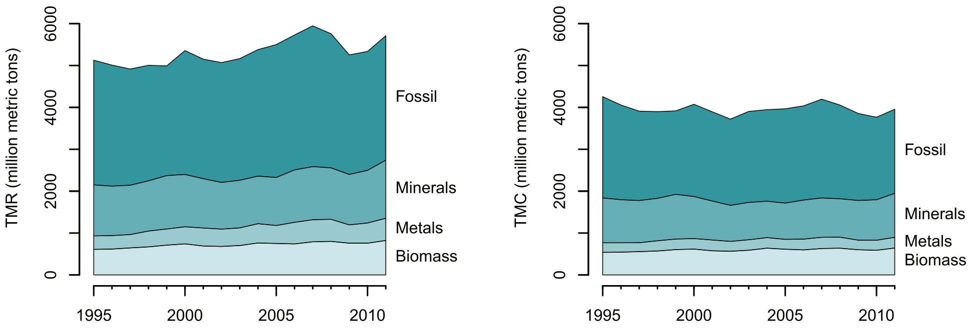
(a) 1995 (b) 2011

FIGURE 2 Import shares of German RMC in 1995 (a) and 2011 (b), own calculation based on EXIOBASE v.3.4; countries in ISO 3166-1 Alpha-2 codes, world regions as in Stadler et al. (2018) with the following adaptations: WA = RoW Asia and Pacific + JP, KR, TW, ID; WL = RoW America + MX; WF = RoW Africa + ZA; WE = RoW Europe + CH; WM = RoW Middle East + TR; NA = USA + Canada. Underlying data used to create this figure can be found in Supporting Information S2

The increase in RMI is mainly driven by metals, followed by biomass and—to a lesser extent—minerals. In contrast, the RMI of fossil fuels has slightly decreased (see Figure 1a). As Figure 1b shows, RMC was at approximately the same level in 2011 as it was in 1995. However, internal shifts between the material categories within RMC took place. The consumption of metals has increased by 14% in the period from 1995 to 2011 and that of biomass by 13%. The use of minerals has remained relatively steady, while fossil fuel consumption has decreased by almost 20% in the same period.

Since RMI includes exports in RME whereas RMC does not, the difference in growth between these two indicators implies that the material requirements for the production of German exports must have driven the increase in RMI. A look at the geographical origins of Germany's RMI and consumption also reveals an overall increase in imports in RME. The share of imports in Germany's RMC has risen from 42% in 1995 to 63% in 2011. As Figure 2 illustrates, while the other countries of the EU27 plus Great Britain remain the main foreign suppliers of (embodied) raw materials, their share of total imports in RME decreased from close to 40% in 1995 to close to 30% in 2011. In the same time frame, imports from China rose almost tenfold from 2% to 17% of total imports in RME, while those of India displayed a similarly dramatic increase from 1% to 6%. The rest of Asia and the Pacific region provided another 15% of imports in 2011 (up from 12% in 1995). In contrast, the imports from Russia decreased by two thirds to merely 3%, which is mainly due to a reduction in fossil fuel imports.

If unused extraction is added to the above indicators, the picture changes mostly with respect to the composition of the contributing material categories. As Figure 3 shows, the majority of TMR and TMC is made up of fossil fuels, in particular lignite from domestic extraction. This is due to the large amounts of unused material in lignite mining activities. The main driver of the growth in TMR (+13% from 1995 to 2011) are again exports, mostly in the form of metals and to a lesser extent biomass. In the same time frame, overall TMC has actually decreased by about 7%, mainly due to a reduction in fossil fuel use. However, similar to the case of RMC, the TMC of metals and biomass has increased in this time period.



(a) Total material requirement (b) Total material consumption

FIGURE 3 Time series of total material requirement (a) and total material consumption (b), own calculation based on EXIOBASE v.3.4. Underlying data used to create this figure can be found in Supporting Information S2

3.2 | Results of the structural decomposition analysis

3.2.1 | Overview of results

This section provides an overview of the results of the first stage of the SDA as described in Section 2.2. In this first stage, the contributions of changes in material coefficients, the multi-regional Leontief inverse, and final demand to changes in Germany's RMC are analyzed (see Equation 2). While the overall RMC change is small, the changes attributable to the three decomposition components are larger and partly counteract each other. Overall, material coefficient changes had a negative[6] impact on German RMC while the structural change in the global economy (as represented by changes in the multi-regional Leontief inverse) as well as the development of Germany's final demand had a positive impact.

Figure 4 shows the decomposition results for the four material categories. Whiskers are added to the bars in order to indicate the maximum and minimum values of the decomposition variants described in Section S1 of Supporting Information S1. When summed over all material categories, the average contribution of the material coefficient changes is the highest with a hypothetical RMC reduction of over 700 million metric tons, followed by a final demand driven hypothetical RMC increase of close to 450 million metric tons. The structural changes in the global economy had the smallest average contribution with a hypothetical RMC increase of about 250 million metric tons.

At the level of the individual material categories, it can be observed that the contribution of material coefficient changes is negative for all material categories except minerals, where a slight increase in RMC would have taken place if only the coefficients had changed. The opposite is true for structural changes of the global economy, which would have led to an increase of Germany's RMC for all material categories except minerals. Only the change in final demand uniformly has a positive impact across all material categories and represents the main driver of the hypothetical RMC increases for three of the four categories except fossil fuels.

The whiskers show a relatively wide spread for each decomposition term in each material category, indicating a high sensitivity of the results to the choice of decomposition equation. Considerable variation can for instance be observed for fossil fuels and minerals, with the largest absolute variation for fossil fuels. It is also noteworthy that in a number of cases, the extremes as indicated by the whiskers would lead to effects with opposite signs, such as the material coefficient change in the metals and minerals category, as well as the structural change of the economy in the biomass, metals, and minerals category. Only the final demand change is consistently accompanied by hypothetical RMC increases across all decomposition variants.

3.2.2 | Results of the sub-decompositions

As outlined in Section 2.2.1, the three components—material coefficients, multi-regional Leontief inverse, and final demand—can be further decomposed in order to gain a better understanding of the mechanisms leading to changes in Germany's RMC. For clarity, the results of this second stage of the decomposition are summed over the four material categories and are summarized in Figure 5.

As described above, the largest part of the hypothetical change to Germany's RMC in absolute terms is caused by a reduction in the material intensity of sectoral production, that is, through a decrease in material coefficients (left-hand side of Figure 5). These results largely match with those of similar studies at the national (Plank et al., 2018; Pothen & Schymura, 2015) and global level (Pothen, 2017). When differentiating by

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[6] Throughout the paper, the contributions of the decomposition components are reported as "positive" and "negative" in the mathematical sense, that is, leading to increases and decreases in RMC, respectively.

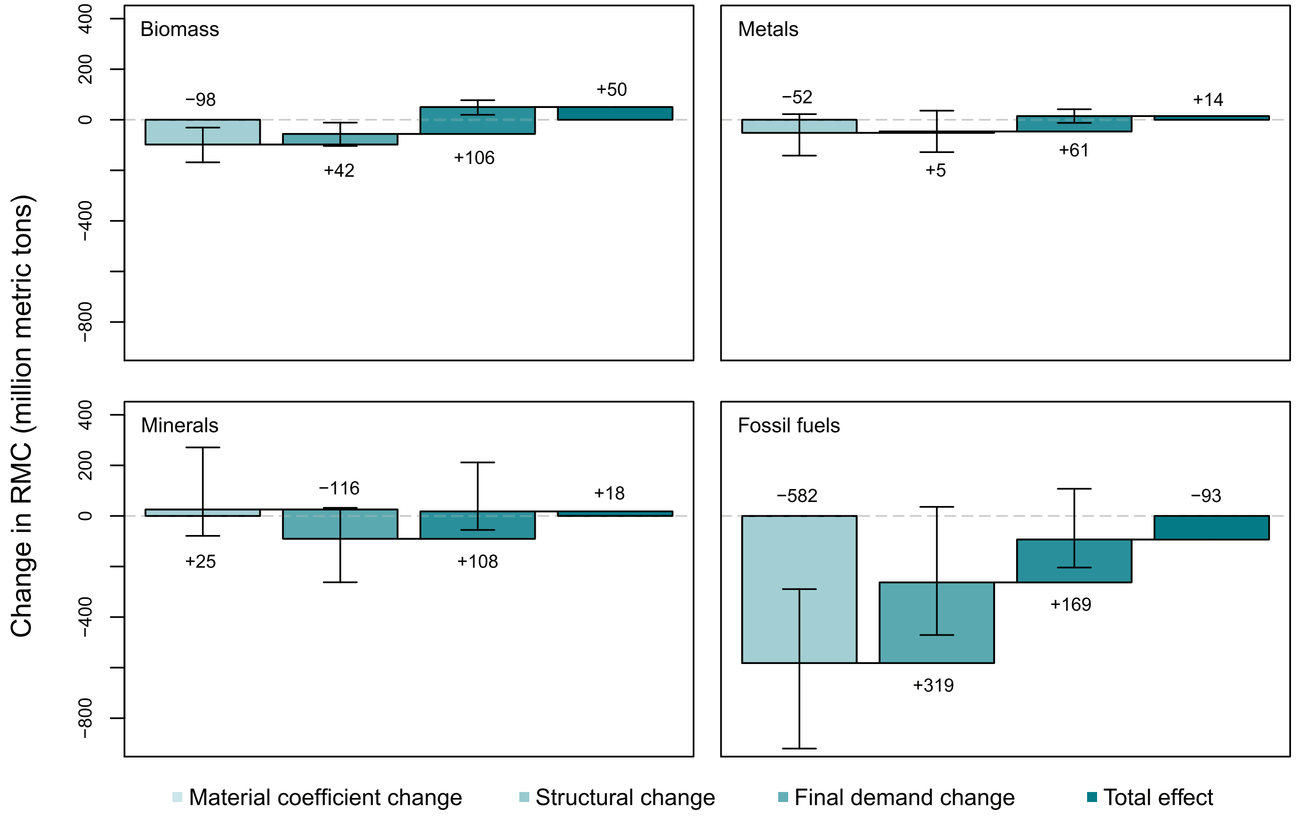

FIGURE 4 Decomposition of RMC change between 1995 and 2011, own calculation based on EXIOBASE v.3.4. Underlying data used to create this figure can be found in Supporting Information S2

geographical location of the coefficient changes (cf., Equation 3), less than one third (approximately 31%) of this effect can be attributed to changes in domestic material coefficients. The majority of the effect is therefore due to reductions in material coefficients abroad. This reduction in the physical inputs per monetary output of foreign raw-material processing sectors affects German RMC through a reduction of the materials embodied in German imports.

International structural changes, that is, shifts in sectors' direct and indirect structures of production as portrayed by the multi-regional Leontief inverse, would by themselves have led to an overall increase in German RMC. Thus while the specific use of material inputs per unit of output of the material processing sectors has been reduced (material coefficient change), the global inter-industry demand for products in which these raw materials are embodied has changed in such a way that Germany's material consumption would be higher in 2011 than in 1995. In order to disentangle some of the effects at play, a sub-decomposition of the changes in the multi-regional Leontief inverse was carried out. The results are summarized in the middle part of Figure 5, where the changes of the five components of Equation (5) are portrayed by the five bars in the center ("Change in multi-regional L-matrix"). Whereas the first three bars of this group refer to changes in the geographical origins of intermediate inputs, the last two refer to shifts in the production technologies employed in Germany and the rest of the world, respectively.

Despite the overall positive effect of global structural change on German RMC, there have been shifts in the relative amounts of domestically sourced intermediate inputs with a negative effect on RMC. While not all shares of domestically sourced intermediates decreased between 1995 and 2011, on average less domestic intermediate inputs were used, which would have decreased German RMC by close to 100 million metric tons. The concurrent increase in the shares of internationally sourced intermediates and the changes in their distribution across supplier countries would in contrast have led to a much larger increase of German RMC of close to 300 million metric tons ("Imports" in Figure 5). On average, input demand thus shifted from less material intensive national supply to more material intensive international supply. This effect is compounded by a similar development in the rest of the world, where intermediate input shares ("Trade RoW" in Figure 5) also shifted toward a more material intensive sourcing pattern of goods finally consumed in Germany. Even though Germany is only indirectly affected by this, these changes in the rest of the world would nonetheless have driven up German RMC by 50 million metric tons.

The changes in the production technologies employed are also decomposed into a domestic ("Domestic technology") and a foreign ("Foreign technology") component. The former refers to the overall production technology employed by Germany irrespective of the origin of the intermediate inputs, the latter to that of each of the other countries in the MRIO system. As Figure 5 illustrates, the domestic production technology change

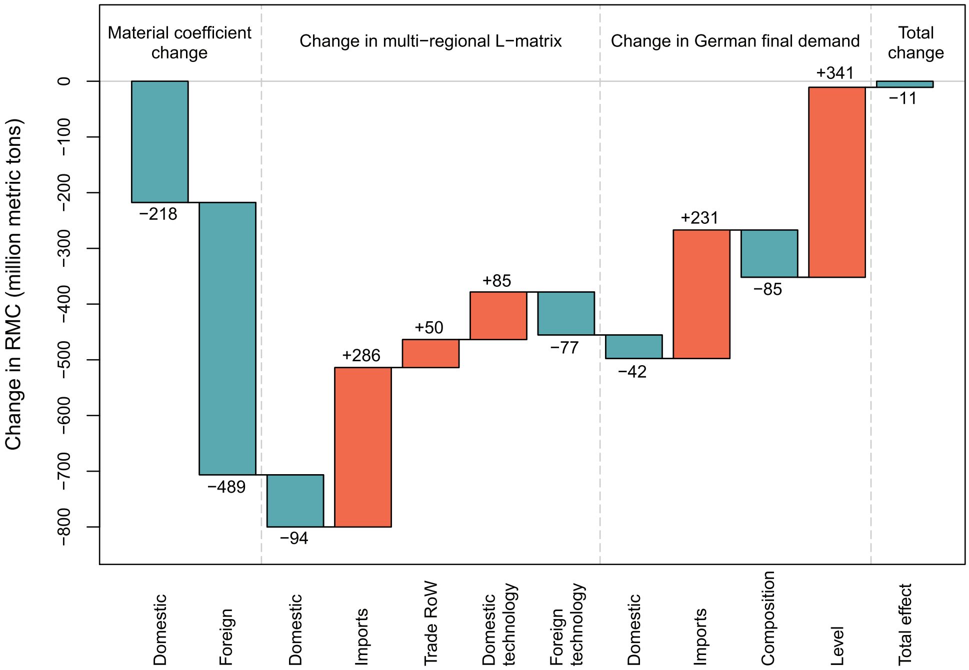

FIGURE 5 Summary graph of decomposition results, own calculation based on EXIOBASE v.3.4. Underlying data used to create this figure can be found in Supporting Information S2

would by itself have increased Germany's RMC by 85 million metric tons. This implies that Germany's industry in 2011 relied on a technical input structure with an overall higher embodied material content than in 1995. In contrast, the production structure in the rest of the world changed in such a way that the products finally consumed in Germany had a lower embodied material content, thereby hypothetically reducing Germany's RMC by close to 80 million metric tons.

These results are somewhat in contrast with those of Plank et al. (2018) and Pothen and Schymura (2015) regarding the overall contribution of structural changes, which they found to have an overall negative effect on German RMC. However, Plank et al. (2018), similar to the present study, further differentiate between a "production recipe," which equals the overall production technology, and an "import structure" effect, which they however construct from the import structure effects of intermediate inputs and final demand. The change of the production recipe has a negative effect, whereas the change of the import structure has a positive effect on German RMC.

The overall changes in final demand would have by themselves driven up Germany's RMC by the highest amount, which is in line with the findings of similar studies (Plank et al., 2018; Pothen & Schymura, 2015; Pothen, 2017). As shown in Figure 4, the effect of final demand changes is also positive across all decomposition variants. Hence, it appears that the development of final demand in Germany unambiguously led to an RMC increase between 1995 and 2011. While the absolute effect appears plausible in a growing economy, there may have been changes in the geographical sourcing and composition of final demand that could have countered this development.

In order to investigate this, the effect of the final demand change can be further decomposed into four separate effects, consisting of changes in the share of domestic sourcing, the share of international sourcing as well as the structure and the level of German final demand (see Equation 7). These four components are portrayed by the four bars on the right-hand side of Figure 5. The sub-decomposition reveals that the change in the share of domestically sourced final demand would by itself have reduced RMC by approximately 40 million metric tons. Similar to the case of intermediate inputs, the changes in sectoral shares of domestically sourced final demand on average reflect a shift to less material intensive sourcing of final demand. However, the concurrent changes in the shares of imported final products from various supplier countries again represent a kind of overcompensation of this shift regarding their embodied material content. They would have accordingly increased German RMC by approximately 230 million metric tons.

The change in the composition of Germany's final demand ("Composition" in Figure 5) would by itself have led to a reduction of German RMC by 85 million metric tons, indicating that consumption preferences changed toward products with less embodied materials. All of these structural effects on final demand are, however, outweighed by the effect resulting from the absolute increase in the level of final demand in Germany between 1995 and 2011. This is the largest positive driver of Germany's RMC in that time frame and would have by itself increased it by over 340 million metric tons.

4 | DISCUSSION

The analysis revealed that material consumption in Germany, both excluding and including unused extraction, has remained relatively steady from 1995 to 2011. In the same time frame, the RME of exports have increased noticeably for both used and unused extraction. Therefore, while Germany's own consumption of (embodied) raw materials does not follow a growth trend in the considered time frame, even when taking the RME of imports into account, its exports do. Whereas the former may at first glance be interpreted as a positive development from the perspective of resource conservation, the latter may prove problematic for an economy that heavily depends on exports, such as Germany's. In fact, exports accounted for almost 40 % of German GDP in 2016 (Destatis, 2017a, 2017b).

The raw materials embodied in the products finally consumed in Germany are increasingly extracted outside of Germany and Europe, specifically in different parts of Asia. This implies that transport—whether of the raw materials themselves or of the products in which they are embodied—and its environmental impacts have become more important. Moreover, local environmental and social conditions of mining activities in Asia have historically been worse than in Europe (cf., Burke, 2006). A continuation of these trends, driven by Germany's demand for final goods and services, may thus exacerbate environmental and social problems in Asia and other parts of the globe.

A look at the underlying structural factors of the development of Germany's RMC provided additional insights. Our analysis showed that the material intensity of sectoral production had a negative effect on German RMC while the structure of the global industrial system and final demand in Germany had positive effects.

The negative effect of material coefficient changes on Germany's RMC indicates that less physical input was needed in 2011 than in 1995 to produce a given monetary amount of output in the raw-material processing sectors. Since the monetary transactions in the input–output tables used in the present study have been transformed into constant prices, this development cannot be explained by price hikes and concurrent steady material inputs. Thus, raw-material processing sectors must have reduced their material intensities. In the case of metals, this apparently happened despite declining ore grades for some metal ores (cf., Calvo et al., 2016; Frenzel et al., 2017; van der Voet et al., 2018). However, it is unlikely that this development will continue indefinitely as intensity reductions have physical limits. Since Germany's RMC was kept at a relatively constant level between 1995 and 2011 mostly because of such intensity reductions, RMC can be expected to increase in the future in the absence of counteracting changes in production structures or final demand.

In contrast to the intensity reductions, the changing structure of the global economy had an overall positive effect on German RMC. This effect was found to be dominated by changes in the import shares of intermediate inputs into German production and their distribution across supplier countries, while changes in sourcing patterns in the rest of the world and the overall production technology employed in Germany added to it.

A closer look at Germany's production technology reveals that its change between 1995 and 2011 is most notably characterized by an increase in the total share of intermediate inputs across the majority of sectors and a concurrent decrease in the share of value added. This development is a result of continuously increasing innovation dynamics as well as cost pressures (Bundesverband der Deutschen Industrie, 2016). The increased intermediate inputs and their embodied materials are sourced from a variety of sectors, including a few raw-material processing ones as well as a range of manufacturing and some service sectors. This development is accompanied by increased shares of imported intermediate inputs, mainly from China, South and Southeast Asia, with higher contents of embodied materials.

The additional materials are also embodied in Germany's exports, which have grown at approximately double the average growth rate than domestic consumption (Destatis, 2014). The sectors for which exports displayed the highest growth rates are manufacturing as well as some service sectors, which are also the main beneficiaries of the increased intermediate inputs from global supply chains. Much of the (embodied) raw material imports have thus been re-exported, which explains the growth in the RME in exports in contrast to a relatively steady domestic material footprint.

These positive effects on Germany's RMC were slightly counteracted by changes in domestic shares of intermediate inputs and changes in production technologies in the rest of the world, which had a negative effect. However, overall it can be concluded that a shift toward more globalized and material intensive supply networks took place, which was in turn a significant positive driver of German RMC. The likely future development of global production structures is more difficult to assess than potential limits to material intensity reductions, especially in the wake of historical breaks such as the current COVID-19 pandemic. However, if global supply networks continue to develop in the same way as in the considered time frame and despite calls for their (partial) re-regionalization, they will likely lead to future increases in German RMC.

The changes in the final demand for goods and services in Germany were found to be the largest positive driver of Germany's RMC. The main effect results from the absolute increase in final demand, while a considerable contribution is also made by the increased share of imports in the sourcing of final demand. In contrast, Germany's RMC would have slightly decreased based on changes in the domestic shares and the composition of final demand. The composition effect points toward the conclusion that the consumption preferences in Germany changed toward generally less material intensive types of goods and services in the time frame between 1995 and 2011. However, since the sourcing of these goods changed at the same time toward a higher share of international suppliers with more material intensive supply chains, the composition effect is considerably outweighed. Taken together, this suggests that material consumption does not follow the pattern suggested by the environmental Kuznets curve (EKC) because not only the types of products but also their origins determine their environmental impact. The EKC describes the relationship between affluence and environmental pressure as an inverted U, where environmental pressure first increases with rising affluence but then decreases again as even higher levels of affluence induce people to place more value on environmental aspects of their consumption (cf., Grossman & Krueger, 1991). Germany, with its relatively high level of affluence, is conceptually placed on the right-hand side of the EKC, implying that consumption preferences have been changing in such a way that environmental impacts are reduced. However, the evidence of material use in industrialized countries following such a pattern is weak (cf. Canas, Ferrão, & Conceição, 2003), specifically when embodied materials are taken into account (cf., Bringezu, Schütz, Steger, & Baudisch, 2004; Pothen & Welsch, 2019), other than in the form of short-term effects (cf., Steinberger, Krausmann, Getzner, Schandl, & West, 2013). The results of this paper are in line with these findings.

The growing demand for goods and services in Germany is thus expectedly accompanied by a growth in RMC. Highly developed countries such as Germany are often assumed to dampen the growth in RMC through various forms of material efficiency. However, our analysis indicates that these may prove futile in light of a growing internationalization of supply networks and final demand. The growing internationalization also implies that Germany experiences decreasing control over the material implications of its own final demand. This suggests that the effects of domestic material-related efforts will be marginal and the policy focus may have to shift toward the rest of the world. For instance, Germany is currently discussing a supply chain law, which is mainly intended to ensure social standards in global supply chains, though other criteria could be added. Other options are policies aiming at the re-organization of global supply networks, including options for re-regionalization, and a more prominent role of new generations of bio-based materials that are not in competition with food production. Recent efforts at furthering the circular economy on the European level may contribute to this re-organization, starting with the re-use of functional units and components and ending with substance-level recycling.

The employed EE-MRIO methodology is well suited to provide a broad account of the development and drivers of raw material use in Germany. However, due to its broad scope, the methodology suffers from several drawbacks, including lack of detail and data uncertainties. Since the time series only go up to 2011, more recent trends in raw material use in Germany cannot be captured. The results of the structural decomposition variants display a relatively wide range, indicating a high sensitivity to methodological choices. Future research could thus perform more detailed and up-to-date case studies of critical areas relating to raw material use in Germany, such as the material intensity reductions of individual raw material processing sectors and the globalization of specific supply chains.

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CONFLICT OF INTEREST

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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