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Analysis

The Distribution of Material Footprints in Germany[☆]

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ABSTRACT

This study investigates the within-country heterogeneity of material footprints implied by households' consumption in Germany. Material footprints are defined as the amount of biomass, minerals, and fossil fuels extracted to produce the goods that households consume. Combining input-output data with households' consumption expenditures from the German sample survey of income and expenditure (EVS), we present the first comprehensive study on the distribution of material footprints among households, highlighting hot spots of unsustainable consumption patterns by household groups. Households in the quartile with the highest consumption expenditures have material footprints three times as large as those in the quartile with the lowest expenditures. We use a microeconomic model to study households' consumption behavior using EVS data. The results suggest that price-based instruments can reduce material footprints of luxury consumption such as leisure and private transport without imposing large burdens on less affluent households. The material footprints caused by energy consumption do not react sensitively to price changes, which suggests that non-price policies are more effective to reduce them.

1. Introduction

In 2011, the European Commission introduced its flagship initiative "A resource-efficient Europe" (EU Commission, 2011a) as part of the Europe 2020 growth strategy. It aims at "[developing] our wealth and well-being, while reducing the levels and impact of our resource use" (EU Commission, 2011b). The EU's ambitions are shared by a number of countries, including Japan and China, which strive to use materials more efficiently or to reduce the level of material use altogether (Bahn-Walkowiak and Steger, 2015). These goals are motivated by the local and global pollution caused by the extraction and processing of materials (Dudka and Adriano, 1997; Csavina et al., 2012; Rooney et al., 2012; Brandt et al., 2014) as well as by the notion that humanity's material use as a whole has reached unsustainable levels (Hoekstra and Wiedmann, 2014). Another motivation are concerns about disruptions of the supply of economically important raw materials (U.S. Department of Energy, 2011; EU Commission, 2014a).

From a sustainability perspective, the material footprint (MF), also known as raw material consumption (RMC), is an advantageous indicator to inform decision makers about material use. It is defined as the sum of all materials extracted to produce a country's or household's final demand along the supply chain, irrespectively of where the materials have been used.[1] Unlike indicators of direct material use, such as the domestic material consumption (DMC), which records domestically extracted plus imported minus exported materials, the MF does not falsely indicate dematerialisation if a country offshores material-intensive production. This property is particularly important for resource-poor countries which depend heavily and increasingly (Wiedmann et al., 2015) on direct as well as indirect imports of materials. Acknowledging these properties, the EU Commission proposes GDP divided by the material footprint as an indicator for resource productivity (EU Commission, 2014b).

Discouraging households in wealthy nations from consuming

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[1] A country's MF is usually computed by combining monetary input-output tables with material extraction data in physical units (Lutter et al., 2016).

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material-intensive goods can contribute to reducing the ecological damages caused by the extraction and processing of raw materials. Designing the corresponding policies requires data on the amount of biomass, minerals, and fossil fuels used to produce commodities for final consumption and also evidence on how households' material footprints react to incentives, in particular prices. While the existing literature provides estimates for countries' material footprints (Muñoz et al., 2009; Schoer et al., 2012; Arto et al., 2012; Bruckner et al., 2012; Wiebe et al., 2012; Kovanda and Weinzettel, 2013; Schaffartzik et al., 2014; Wiedmann et al., 2014; Giljum et al., 2015; Wiedmann et al., 2015; Ivanova et al., 2015; Wenzlik et al., 2015; Giljum et al., 2016)[2], evidence on the heterogeneity of households' MF within a country is scarce and, furthermore, either focused on "exotic" materials such as neodymium (Shigetomi et al., 2015, 2016) or based on very small samples (Kotakorpi et al., 2008; Lettenmeier et al., 2012).[3]

This study makes two contributions to a better understanding of households' material footprints. First, it estimates the distribution of material footprints among German households, highlighting hot spots of material-intensive consumption. It considers 36 household groups distinguished by socio-economic characteristics as well as 10 consumption categories. To our knowledge, it constitutes the first comprehensive study on the within-country distribution of households' material footprints.

The second contribution of this study is to estimate how households' material footprints react to changes in prices and affluence. Data on material footprints' responsiveness to price changes indicates whether price-based instruments such as taxes can effectively curb material footprints. Considering different household groups, furthermore, enables policy-makers to design policies that avoid undesirable burdens for low-affluence households. This study is the first to quantify how households' MF react to price and affluence.

Our research is conducted in two steps. First, we estimate material footprints per monetary unit of consumption by using the Exiobase global multi-region input-output model (Tukker et al., 2013; Wood et al., 2014) and link them to households' consumption expenditure data from the German sample survey of income and expenditure (Einkommens- und Verbrauchsstichprobe, EVS).[4] Expenditures, thus, serve as the measure of affluence in this study.

Second, we employ the Exact Affine Stone Index (EASI, Lewbel and Pendakur, 2009) demand system to model households' consumption behavior. It represents consumption decisions as a system of equations which depend on prices, consumption budgets, and observed as well as unobserved household characteristics. We employ the EASI demand system because it extends previous models of household demand (Deaton and Muellbauer, 1980; Banks et al., 1997) by allowing for a non-linear relationship between budget and demand. This flexibility is advantageous in the light of the close and potentially non-linear relationship between affluence and material footprints found on the country-level (Pothen and Welsch, 2017). Demand systems have been used to study households' energy use and carbon emissions (Baker et al., 1989; Creedy and Sleeman, 2006; Labandeira et al., 2006; Pashardes et al., 2014; Sommer and Kratena, 2017; Tovar Reaños and Wölfing, 2018) but, to our knowledge, this is the first study employing a demand system to investigate material footprints. It is, furthermore, the first to use the EASI demand system to study sustainable consumption. We obtain the household expenditure data we use from EVS waves from 1993 to 2013, which contain 122,500 observations. We investigate Germany, the world's fourth-largest economy, in this study because it depends on material imports and its government has implemented the target of doubling material productivity by 2020 compared to 1994 (Bundesregierung, 2002; Bahn-Walkowiak and Steger, 2015).

Our results suggest a right-skewed distribution of MF among households in Germany. One per cent of them have a material footprint that exceeds 100 t. The quartile of households with the lowest expenditures has material footprints one third the size of those in the quartile with the highest expenditures. While transport, leisure, and appliances are particularly responsable for high-affluence households' MF, food, housing, and energy account for a substantial share of all households' material footprints. Price-based instruments can effectively reduce material footprints; equity issues, however, should also be considered. While price increases for housing and food can lead to substantial reductions in MF, they are likely to impose a disproportional burden on low-affluence households. The results in this paper are presented for materials aggregated according to their physical mass. We, furthermore, provide detailed results for 45 individual materials. These enable researchers to study footprints of specific materials or to use alternative aggregating schemes (Fang and Heijungs, 2014), such as monetary measures of environmental damage, to weigh materials. The results for the individual materials are available in the online appendix. We present the material footprint of copper as an example in Appendix B.

The paper proceeds as follows. Section 2 presents the methodological approach. The results are shown in Section 3. Section 4 discusses the policy implication of our results. Section 5 concludes.

2. Methodology

2.1. Computing the Material Footprints

This subsection outlines how $\mathbf{MF}_h$, the matrix of the material footprints of household h, is estimated. Each of its elements $MF_{m,c,h}$ records the amount of material m extracted to produce h's demand for consumption purpose c. Household surveys, like the German sample survey of income and expenditure (EVS), record expenditures on functionally defined consumption purposes such as transport. We index these consumption purposes c and cc throughout the paper. The vector f_h quantifies households' consumption expenditures. Its elements $f_{c,h}$ record the expenditures of household h on consumption purpose c. $\mathbf{MF}_h$ is computed according to Eq. (1).

$$\mathbf{MF}_h = \mathbf{E}{\cdot}\mathbf{L}{\cdot}\mathbf{V}{\cdot}\mathbf{K}{\cdot}f_h \tag{1}$$

$\mathbf{E}$ is the matrix of material intensities. Its elements $E_{m,i,r}$ record how many kilograms of material m are extracted to produce one euro worth of product i in region r. $\mathbf{L}$ is the Leontief inverse. Each element $L_{i,r,j,s}$ records how many euros worth of product i from region r are used to manufacture one euro of product j in region s. The Leontief inverse accounts for all inputs to product i from region r over the whole supply chain. It is computed as $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$, where $\mathbf{A}$ denotes the matrix of direct input coefficients and $\mathbf{I}$ the identity matrix of appropriate size.

We use the Exiobase product-by-product GMRIO table (Wood et al., 2014; Tukker et al., 2013) to compute $\mathbf{L}$. It differentiates between 200 products and 48 regions. 43 thereof represent individual countries; the

[2] Utilising between-country heterogeneity, studies find affluence, measured as income or final demand, to be the principle driver of material footprints (Wiedmann et al., 2015; Pothen, 2017; Pothen and Welsch, 2017).

[3] The energy footprint of households, also known as energy requirements, has been estimated since the 1970s (Herendeen, 1978; Herendeen and Tanaka, 1976). Other studies on energy and carbon footprints of households include Wier et al. (2001) for Denmark, Weber and Matthews (2008) for the USA, Druckman and Jackson (2009) and Baiocchi et al. (2010) for the UK, Girod and De Haan (2010) for Switzerland, Steen-Olsen et al. (2016) for Norway, and Lenzen et al. (2006) for Australia, Brazil, Denmark, India as well as Japan. Hertwich (2005) provides an overview.

[4] Due to higher data quality, the MF only considers materials which enter consumption and production processes. Unused extraction, such as overburden in mining, is not considered.