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Analysis

Global patterns of materials use: A socioeconomic and geophysical analysis

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A B S T R A C T

Human use of materials is a major driver of global environmental change. The links between materials use and economic development are central to the challenge of decoupling of materials use and economic growth (dematerialization). This article presents a new global material flow dataset compiled for the year 2000, covering 175 countries, including both extraction and trade flows, and comprising four major material categories: biomass, construction minerals, fossil energy carriers and ores/industrial minerals. First, we quantify the variability and distributional inequality (Gini coefficients) in international material consumption. We then measure the influence of the drivers population, GDP, land area and climate. This analysis yields international income elasticities of material use. Finally, we examine the coupling between material flows, and between income and material productivity, measured in economic production per tonne material consumed. Material productivity is strongly coupled to income, and may thus not be suitable as an international indicator of environmental progress — a finding which we relate to the economic inelasticity of material consumption. The results demonstrate striking differences between the material groups. Biomass is the most equitably distributed resource, economically the most inelastic, and is not correlated to any of the mineral materials. The three mineral material groups are closely coupled to each other and economic activity, indicating that the challenge of dematerializing industrial economies may require fundamental structural transformation. Our analysis provides a first systematic investigation of international differences in material use and their drivers, and thus serves as the basis for more detailed future work.

1. Introduction

Global materials extraction has been estimated to range between 47 and 59 billion tonnes per year at the turn of the 21st century, and it is growing rapidly (Krausmann et al., 2008). Human use of materials is one of the major drivers of global environmental change. Environmental problems occur during the extraction of resources, the processing of raw materials and finally when emissions and wastes are returned to the natural environment after the materials have been used. The links between materials use and economic development are central to the debate on whether or not a decoupling of materials use and economic growth (dematerialization) can be achieved (Commission of the European Communities, 2005; OECD, 2008). The process of decoupling is generally considered to be necessary for sustainable development strategies such as the factor 4 or factor 10 reduction in resource use (Weizsäcker et al., 1997), as well as greenhouse gas emissions. Recently, concerns regarding the sufficient and secure supply of resources, their global distribution and access have re-entered the debate on sustainable development. Resource scarcity is no longer seen as a remote threat.

Material flow accounting and analysis (MFA) has emerged as one of the key tools to quantify and monitor human use of natural resources. MFA seeks to measure the physical counterpart of the monetary economy, in mass units. The concepts and methods of MFA have been increasingly standardized are applied by statistical offices in many industrial countries (Eurostat, 2001, 2007). Aggregate material flow indicators have become an integral part of environmental reporting systems (e.g., EEA, 2007). Different materials have vastly different environmental implications, often exemplified by comparing one tonne of sand with one tonne of plutonium. The indicators of MFA thus report on the aggregate scale of the physical economy — not on specific environmental consequences thereof.

Since the seminal studies of Kneese et al. (1970) and the World Resources Institute (Adriaanse et al., 1997) our knowledge about the size, structure and development of materials use in national economies has grown considerably. In recent years, numerous studies have covered the materials use in individual countries (among the most recent studies are for example Gonzalez-Martinez and Schandl (2008) and Schandl et al. (2008). Some have also compared material use in several or many countries (Weisz et al., 2006; Kovanda and Hak, 2008; Russi et al., 2008). There is moreover a fairly good empirical database on global resource extraction (Schandl and Eisenmenger, 2006; Behrens et al., 2007; SERI, 2008).

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Globally, huge variations in the sizes and structure of materials use exist between countries. These differences are certainly related to economic development, but, as Weisz et al. (2006) have shown, material consumption per capita varies significantly between industrialized countries with similar levels of income, and a host of factors apart from income may have measurable influences. At the global scale the differences are even larger, but, to date, little research has been done to identify the most important related socioeconomic and geophysical factors. Knowledge of these factors is, however, key to the understanding of the dynamics of materials use and the interpretation of headline indicators derived from economy wide material flow accounts.

The goals of this article are the following: (1) to quantify variability and distributional inequality in international material consumption, (2) to measure the influence of population, GDP, land area and climate on material consumption and trade, alone and in combination, (3) to examine the coupling amongst material flows. The analysis is conducted for total material flows and the four major material groups: biomass, construction minerals, fossil energy carriers and ores/industrial minerals. Our analysis thus attempts a first systematic investigation of cross country differences in material use and their drivers, and hopefully provides the basis for more detailed future work.

In the next section, we introduce the data sources and estimation procedures used to compile the material flow database (Section 2); this is followed by a brief description of our statistical methods (Section 3). The results (Section 4) begin with a discussion of international variability and distribution (Gini coefficients) of materials use, then turns to univariate and multivariate analysis of major socioeconomic and geophysical drivers of material consumption: population, GDP, land area and climate. This is followed by an investigation of correlations among the four main material groups and their trade flows. The implications of our results for material productivity as an international indicator are then discussed in Section 5. We end with conclusions and next research steps (Section 6).

2. Material Flow Data

We present a thoroughly revised version of the global material flow dataset, an initial version of which was presented in Krausmann et al. (2008) and is available online (see note 8.1). Up to date this is the only publicly available MFA dataset containing data on both used extraction and trade flows (imports and exports) which allows for a calculation of domestic material consumption (apparent national consumption, DMC). It contains data on material flows for up to 175 countries for the year 2000 by four main material categories: biomass, construction minerals, fossil energy carriers and ores/industrial minerals. The compilation of material flow data followed the general principals of economy wide material flow accounting as outlined for example in the handbook issued by the European Statistical Office (Eurostat, 2007). It is important to note that all data on the extraction and trade of materials contained in our dataset are independent of GDP and population; the primary data compiled in the used international data sources are fully based on surveys (e.g. agricultural censuses, mining statistics, trade records) of national and international statistical organizations or on estimation procedures based exclusively on physical input variables from similar sources. The compilation of the dataset has been described in some detail in Krausmann et al. (2008), and we limit ourselves to outline the basic characteristics of the data and the revisions we have made.

2.1. Used Domestic Extraction (DE)

Data on domestic extraction of biomass include harvest of 165 different primary crops, used amount of crop residues, wood fellings including bark, grazed biomass and fish catch. These data are based on a detailed survey of global biomass flows (Krausmann et al., 2008) and were converted from dry weight into fresh weight or for some items air dry weight (wood, grazed biomass) according to MFA standards.

Data on the extraction of fossil energy carriers (coal, petroleum, natural gas and peat) come from the database of the International Energy Agency (IEA, 2007a,b) and were supplemented with data from the UN energy statistics yearbook (United Nations, 2004) for approximately 40 countries not included in the IEA database.

Data on the extraction of metal ores/industrial minerals were taken from the database of the United States Geological Survey (USGS, 2008). MFA standards require data on ore extraction to be accounted for in terms of gross ore. In cases where metal content was reported we used information on country specific ore grades to extrapolate gross ore mass and on coupled production to avoid double counting.

Data on the extraction of bulk minerals used predominantly for construction (sand and gravel, crushed stone, limestone etc.) are poorly reported in statistical sources. Existing global estimates usually mix reported data with crude estimates based on income (per capita GDP) (Behrens et al., 2007; Schandl and Eisenmenger, 2006; Krausmann et al., 2008). The quality and comparability of these estimates is unsatisfying for the purposes of this study. In order to enhance cross country comparability and to arrive at data independent of GDP, we introduced an estimate of bulk minerals used for construction which is based on physical input data only. We used information on cement production (USGS, 2008) to estimate limestone extraction for cement assuming a ratio of limestone to cement of 1.25 (Josa et al., 2004). We estimated sand and gravel used in concrete on the basis of national cement consumption (USGS, 2008; United Nations Statistical Division, 2008) assuming a ratio of cement to sand and gravel of 6 in concrete. To encompass at least some of the sand and gravel used in road construction and maintenance we extrapolated sand and gravel demand for asphalt production by combining bitumen consumption (IEA, 2007a,b; United Nations, 2004) and the ratio of bitumen to sand and gravel of 20 in asphalt. In order to correct for an underestimation of this fraction in countries with a high share of gravel roads we used information on the share of gravel roads of total road network (The World Bank Group, 2007). And finally, we used the share of rural to urban population to correct for underestimation of construction mineral consumption in rural regions. Our estimate of construction minerals is conservative and underestimates the total use, although we cannot fully exclude double counting if recycled concrete or slugs are used. Based on comparison with countries were reasonable statistical data exist, we assume it covers roughly two thirds of all used natural aggregates. The amount of clay or dimension stone in construction has not been estimated. We assume that in most countries the amount these materials is small compared to sand and gravel. The advantages of this approach are that the estimate of these large mass flows is comparable across countries, entirely based on biophysical input data of comparatively high quality, and does not rely on GDP. These advantages are crucial requirements for the socioeconomic cross-country analysis of this article.

2.2. Trade

Data on physical imports and exports were compiled from different sources: trade with raw materials and products from agriculture and forestry (biomass) was taken from FAO (2005). Data on trade with fossil energy carriers and derived products was taken from the (IEA, 2007a,b; United Nations, 2004), and trade with industrial minerals, ores and derived products was taken from United Nations Statistical Division (2008) trade database (UNCOMTRADE). UNCOMTRADE data were used at the three digit level according to SITCrev.1 classification. Items only reported in monetary units have been converted into mass by using the average global unit price calculated from all importing and exporting countries where both monetary and physical values were reported. The amount of estimated items was, however, small and accounts for only around