Methodology and Indicators of Economy-wide Material Flow Accounting

State of the Art and Reliability Across Sources

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Summary

This contribution presents the state of the art of economy-wide material flow accounting. Starting from a brief recollection of the intellectual and policy history of this approach, we outline system definition, key methodological assumptions, and derived indicators. The next section makes an effort to establish data reliability and uncertainty for a number of existing multinational (European and global) material flow accounting (MFA) data compilations and discusses sources of inconsistencies and variations for some indicators and trends. The results show that the methodology has reached a certain maturity: Coefficients of variation between databases lie in the range of 10% to 20%, and correlations between databases across countries amount to an average R^2 of 0.95. After discussing some of the research frontiers for further methodological development, we conclude that the material flow accounting framework and the data generated have reached a maturity that warrants material flow indicators to complement traditional economic and demographic information in providing a sound basis for discussing national and international policies for sustainable resource use.

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Introduction

Economy-wide material flow accounting[1] (EW-MFA, shortened here to MFA) is finally approaching conceptual and methodological maturity, and a range of data sets and international databases are publicly accessible and available for analysis and for comparison with other data. This article brings together key authors from the research institutions that have been responsible for developing this methodology, to jointly present its state of the art.

Material flow accounting is a fairly young discipline. For countries, it generates indicators of a similar generality as does economic accounting, energy accounting, or demographic accounting. All these accounting systems are built up from and can be broken down into much more detailed information, but one of their strengths is their ability to generate highly aggregate information. This same strength may also be considered a weakness: Because of its reductionist character, the meaning of aggregate indicators derived from these accounting systems is often questioned. Conversely, comprehensive and compact information has a high practical value.[2] Energy (flow) accounting has a long tradition (Martinez-Alier 1987; Cleveland et al. 2000), and the International Energy Agency (IEA) provides regular monitoring of socioeconomic energy flows at a global scale. The amount of energy used by socioeconomic systems is accepted as a relevant measure; nevertheless, the environmental impact use of this depends on energy sources and conversion technologies, and the social and economic impact depends on access, prices, and safety. There has been an ongoing debate over energy accounting and the appropriate indicators, such as total primary energy supply (TPES); emergy (available energy, as used by H. Odum [1991] for the analysis of ecological systems); exergy (the amount of useful energy put to work; see Ayres et al. 2003); and primary energy input, including, beyond TPES, food and feed (domestic energy consumption [DEC]; see Haberl 2001)—and how to accumulate and use them. With materials, mass (e.g., tonnes[3]) is a physically meaningful unit that indicates certain common features. Mass is a very robust measure, immutable across time and space in classical physics; it can be measured with simple technical means and requires very little explanation to comprehend. MFA indicators in mass units can be applied on various levels of aggregation, and on each level different lessons can be learned. The interpretation of MFA indicators in terms of environmental pressures depends on the material groups accounted for and is a matter not just of mass flows per unit of time (Bringezu et al. 2003) but also of their quality.

MFA is an accounting framework building on a consistent database that can be used for various policy-oriented analyses of economy-environment interactions. MFA-based indicators provide background information in aggregated form on the composition of and changes to the physical structure of socioeconomic systems. Considering the gross domestic product (GDP) of a country alongside its material use enables countries to monitor their progress in decoupling resource use from economic growth (see, e.g., EUROSTAT 2009). With time series data for material use available, it is possible to perform historical analyses on the development of certain environmental pressures for particular countries or the world economy (see, e.g., Steger and Bleischwitz 2009; Schandl and West 2010). It can be shown, for example, that economic growth is associated not only with rising use of materials but also with a shift from using renewable to using more nonrenewable resources (Krausmann 2009). Metabolic transitions—that is, changes in the scale and composition of material use over time—can be tracked and related to socioeconomic developments (Krausmann et al. 2008). Another important application of MFA data is their use in economic models that allow the incorporation of environmental and resource use aspects in evaluations of economic strategies in trade or employment (Giljum 2006; Schandl and Turner 2009). With the help of generic models, national material consumption can be investigated in a global context. Adding the physical dimension of trade delivers information on world resource supply and demand, the scale of resource flows between country groups, and resource dependencies (Dittrich and Bringezu 2010). Another application of material flow analysis is the combination of data on material use with data on the use of other natural resources, such as water, land, or energy, or the interlinkage with outputs, such as emissions to air, water, and waste (Moll and Watson 2009). In recent years, research has increasingly focused on the question of how to combine quantitative information stemming from MFA with data on the environmental impact of specific materials originating from life cycle analysis (LCA) accounts (e.g., Van der Voet et al. 2005).

We present a brief outline of the history of material flow accounting in the next section. The following section is devoted to system definitions, key methodological assumptions, and indicators. Next, we discuss existing data, their reliability and comparability, and the uncertainties involved. Across multinational databases, we demonstrate results for some key indicators, globally and for particular national economies. Finally, we summarize what has been achieved so far in economy-wide material flow accounting and suggest areas where further development and standardization of the method are required.

The Historical Development of Material Flow Accounting

In 1969, Robert Ayres, a physicist, and Allen Kneese, an economist, presented the first version of what—much later, in the 1990s—would become material flow analysis of national economies. Their core argument was an economic one: The economy draws heavily on priceless environmental goods, such as air and water—goods that are becoming increasingly scarce—and this precludes Pareto-optimal allocations in markets at the expense of those free common goods. They claimed that "the common failure (of economics) . . . may result from viewing the production and consumption processes in a manner that is somewhat at variance with the fundamental law of the conservation of mass" (Ayres and Kneese 1969, 283). Thus, they proposed to "view environmental pollution and its control as a *materials balance problem* for the entire economy" (Ayres and Kneese, 1969, 284, emphasis added). "In an economy which is closed (no imports or exports) and where there is no net accumulation of stocks (plant, equipment . . . or residential buildings), the amount of residuals inserted into the natural environment must be approximately equal to the weight of basic fuels, food, and raw materials entering the processing and production system, plus oxygen taken from the atmosphere" (284).

On the other side of the Cold War divide, in the Soviet Union, Gofman and colleagues (1974) articulated an analogous critique against the state-planned economy. They attempted a comprehensive material flow analysis of the Russian economy, including raw materials, air, and water flows, and they produced some very plausible figures (see Fischer-Kowalski et al. 2007). At around the same time, apparently without any knowledge of similar approaches in the United States, Gofman came up with a theoretical economic solution that became known as "internalizing externalities" (Cobb and Daly 1989) but applied to state planning. The theoretical solutions have barely progressed since Gofman's writings, and the practical solutions (namely actually internalizing externalities), to be blunt, rarely happen. So Ayres and Kneese (1969) as well as Gofman and colleagues (1974) can still be considered pioneers of the idea of adjusting the economy to address environmental concerns, and little change has occurred in practice.

Another 20 years passed before these earlier achievements bore fruit. In the 1990s, more or less simultaneously but at first independently, an empirically productive strain of MFA research emerged: at the National Institute for Environmental Studies (NIES) in Japan, at the Wuppertal Institute (WI) in Germany, and at the Institute for Social Ecology (SEC) in Austria. All three institutions had good linkages with their national statistical agencies and produced first material flow data for their respective countries in the early 1990s (e.g., Japan Environment Agency 1992; Steurer 1992; Bringezu 1993). A step forward was attained with a major initiative to establish a research network on material flows, financed by a European grant. Under the name ConAccount, this network held its first two workshops in Leiden and Wuppertal in 1997 (Bringezu et al. 1998a; Bringezu et al. 1998b), and later, without external funding, the group continued to organize biannual workshops all over Europe.[4] This intensive international exchange allowed for an integration of the Japanese and European scientific communities (see Moriguchi 2002) and helped to improve conceptual and methodological standards. Beyond Europe and Japan, inspired by a Scientific Committee on Problems of the Environment workshop in Wuppertal, the World Resources Institute (WRI), a U.S.-based nonprofit organization, joined the cooperation and agreed to publish the first systematic comparison of material inputs to four industrialized national economies, including the United States (Adriaanse et al. 1997). Three years later, the WRI published, with a somewhat broader country base, another volume on the material outflows of national economies (Matthews et al. 2000). This volume also outlined important details of the methodology. Meanwhile, reviews on the intellectual history of social metabolism and MFA appeared, helping to sharpen the specifics of the approach, imbed it in wider traditions, and recognize the heritage from the above-mentioned earlier efforts (Fischer-Kowalski 1998; Fischer-Kowalski and Hüttler 1998; Moriguchi 2007).

At this stage, Eurostat, the statistical office of the European Union, started to play a major role. It forged a path toward including MFA data in its standard program of environmental information. A methodological guide was published in 2001, as well as a first preliminary account of material flow indicators for the EU-15[5] (1980–1997) as an outcome of contracts with the WI (Eurostat 2001a; Eurostat 2001b). The Vienna SEC produced a revised and extended version of material flow indicators for the EU-15, which became part of Eurostat's environmental statistics (Eurostat 2002). On the basis of better data subsequently obtained from national statistical offices, including new European Union (EU) member states, and again on the basis of a collaboration with SEC in Vienna and WI in Wuppertal, a practical guide and an updated series of MFA indicators (1970–2004) were published in the second half of the decade (Eurostat 2007a, 2007b). Only recently, a revision of the guide and an updated data set have been made available from Eurostat, and the EU is preparing to institute obligatory reporting of MFA data by its member states as a module within the System of Environmental Economic Accounting (SEEA). In addition to Eurostat, the Organisation for Economic Co-operation and Development (OECD) also became active in material flow research in recent years. It adopted a first council recommendation on MFA in 2004 (OECD 2004), and with a series of workshops and publications (OECD 2008a, 2008b, 2008c) contributed to the advancement and international harmonization of material flow accounting methods.

This created a need for a reliable global MFA database, even for use in understanding national or regional flows; consequently, several research institutions undertook efforts to create such a database. Most important was the success of the Sustainable Europe Research Institute (SERI) in gaining funding from the European Research Program for the project MOSUS, which yielded a first global multinational database for material extraction (Behrens et al. 2007; www.mosus.net/) that is regularly updated (SERI 2009). European research funding continues to play a major role in the advancement of MFA methods and data collection, in particular with the projects MATISSE (www.matisse-project.net/projectcomm/) and EXIOPOL (still ongoing as of May 2011; www.feem-project.net/exiopol/).

The increasing availability of comparable multinational MFA data triggered a series of scientific publications dealing with their analysis, probing their utility, and trying to link them to other environmental information, such as land use, energy, and environmental impacts (e.g., Wagner 2002; Bringezu et al. 2004; Haberl et al. 2004; Van der Voet et al. 2005; Weisz et al. 2006; Russi et al. 2008; Bringezu et al. 2009; Schandl and West 2010; Steinberger et al. 2010). It became increasingly clear that material flows in a country were highly interwoven, through trade, with material flows in the rest of the world, and in particular linked to energy-intensive and material-intensive raw material extraction processes that were not adequately reflected in national material flow data (e.g., Fischer-Kowalski and Amann 2001; Bringezu et al. 2004; Giljum 2004; Giljum and Eisenmenger 2004; Schütz et al. 2004; Giljum and Muradian 2007). The same insight also invoked substantial research in Japan (Kondo et al. 1998; Seo and Taylor 2003; Hashimoto et al. 2004; Nakamura and Nakajima 2005).

Efforts to understand the material flows in industrial countries and their interdependence with material flows in the rest of the world stimulated methodological development, in particular of physical and hybrid input-output analysis, which emerged as a major research topic in the field (e.g., Lenzen et al. 2004; Suh 2005; Huppes et al. 2006; Moll and Acosta 2006; Weisz and Duchin 2006; Weisz 2007; Suh 2010).

System Definition, Key Methodological Assumptions, and Indicators

Methodological Foundations

According to the first law of thermodynamics, matter can be neither created nor destroyed in any physical transformation process.[6] Material inputs into a system must therefore always equal material outputs plus net accumulation of materials in the system (*material balance principle*). Material that flows into the system builds up and maintains the system's material compartments (stocks). Conversely, all materials required to maintain a system compartment or stock must be considered part of the system's relevant material flows. This principle applies for systems, such as a national economy, as well as for any subsystem, such as an economic sector, a company, a city, or a household.

For material flow analysis of socioeconomic systems, system boundaries need to be defined. The first is the boundary between the socioeconomic system—for example, a national economy—and the natural environment from which materials are extracted and to which emissions and wastes are discarded. The second is the (political) frontier to other economies, with imports and exports as input and output flows. Only flows that cross these system boundaries on the input side or the output side are accounted for. All other flows within the system are considered as internal transfers and do not show up with the standard MFA indicators.

Among the researchers developing this methodology, consensus has been reached on how the compartments and stocks for MFA of national economies should be defined (Fischer-Kowalski and Hüttler 19981; Matthews 2000). The most important "stock" is the human population: The metabolic activity of the socioeconomic system can be interpreted as maintaining and reproducing a certain human population at a certain level of material comfort. The second stock compartment is composed of the "built environment (infrastructure and buildings) and artefacts (machinery and durable consumer goods)" (OECD 2011) that together comprise all manmade and maintained structures and durable goods.[7] This component has a particular importance, as it determines the largest flows in highly industrial economies.

A third compartment is livestock and other domestic animals: All biomass uptake by those animals is accounted for as system inputs, whereas livestock products, such as milk or meat, are dealt with as internal transfers. Agricultural plants are not defined as a compartment of the socioeconomic system. This implies that the respective system input is the harvest ("harvest approach"), not the water, carbon dioxide (CO_2), and nutrients that plants take up to grow ("ecosystem approach"). The same harvest approach is applied to forestry and fishing, with the exception of fish from aquaculture, which are treated as an internal transfer.

The convention finally accepted is seen to comply best with the various and partly contradictory requirements for a material flow accounting system. Three requirements need to be respected: (1) feasibility of compiling the accounts at sufficient quality in a cost-efficient way: (2) a nonperverse, directional interpretation of the derived aggregated indicators; and (3) compatibility with the system boundaries of the System of National Accounts (SNA). Although the third requirement provides arguments in favor of the ecosystem approach, the other two requirements speak strongly against it.[8] Data quality would suffer substantially, as observed data would have to be weighed by highly uncertain coefficients, which would completely change the order of magnitude of the numbers accounted for. The interpretation of indicators would be distorted, as the extraction of CO_2 from the atmosphere would be accounted for as socioeconomic resource consumption.[9]

Physical flows can be distinguished into three main classes: materials, water, and air. As water and air flows, in general, exceed all other physical flows by an order of magnitude, guidebooks (EUROSTAT 2007; OECD 2008b) recommend presenting water and air separately from

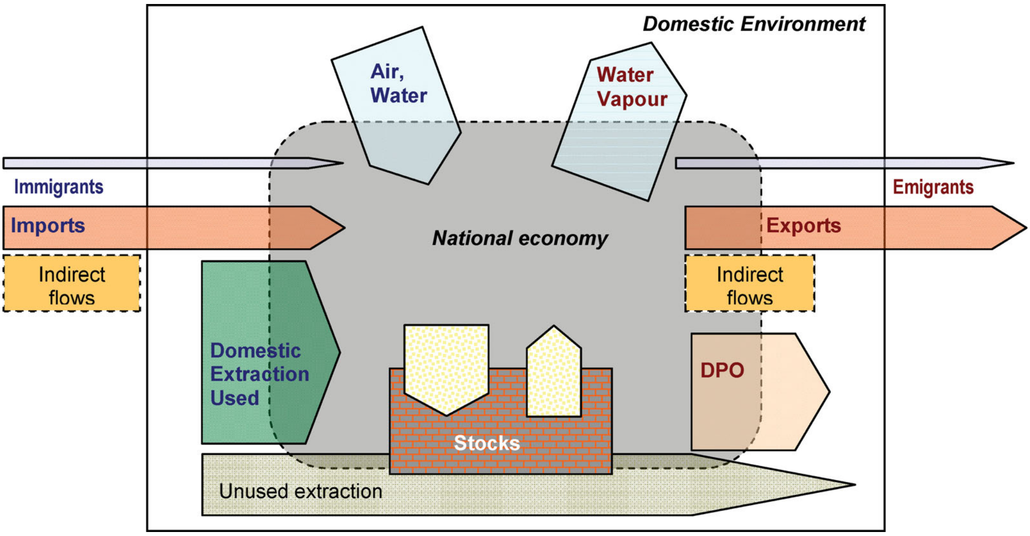

Figure 1 The economy-wide material balance model. Indirect (or embedded) material flows upstream of imports (and exports) can be expressed as raw material equivalents (RME). Definitions and interrelations between the indicators (as used in this figure and throughout the article): DE = domestic extraction used (amount of materials extracted from national territory for direct use); Imports = direct material input from trade (weight at border); Exports = material amounts exported (weight at border); DMI = direct material input = DE + Imports; DMC = domestic material consumption = DE + Imports – Exports; total material requirement (TMR) = DE + unused (domestic) extraction + Imports + unused extraction in country of origin; total material consumption (TMC) = TMR – exports – unused extraction of exports. DPO = domestic processed output, consisting of wastes, emissions, dissipatively used materials, and deliberate deposition (e.g., fertilizers); Balancing items = air and water contained in materials that evaporate during production processes respectively. that are drawn into commodities during production (e.g., oxygen in combustion); Immigrants and emigrants = flows of people who increase or decrease the population stock in this country.

materials, and they are not part of the standard indicators. For the calculation of consistent material balances, though, at least some of them must be included (see figure 1). Primary materials, at the highest level of aggregation, are classified into biomass, fossil fuels, industrial minerals and metal ores, and bulk materials for construction.[10]

From its beginning, the conceptual structure of MFA accounting was developed under the perspective of a possible broader integration into a comprehensive economic-environmental accounting framework, together with the national accounting matrix with environmental accounts (NAMEA; Eurostat 2008), SEEA (United Nations 2003), and the United Nations Framework Convention on Climate Change (UNFCCC) systems. Harmonizing system boundary definitions remains a major issue, however, and, as argued above, this question might not be resolved easily, because each of those accounting systems also has its own rationality and policy application. It should be noted, though, that in other aspects there are promising attempts for integration. Most important is the ongoing attempt to develop methods to disaggregate material inputs by economic sectors. In our view, this effort should be the next step in further developing MFA toward being a fully integrated part of a wider family of economic-environmental accounting tools.

Material Flow Indicators

Although traditional indicators for environmental pressures focus almost entirely on outflows, the most frequently used material flow indicators are input indicators. The complete MFA model accounts for both inputs and outputs (see figure 1), but indicators for input flows can be constructed empirically much more easily, both because the categories of raw materials to be accounted for are not so diverse and because economic statistics can be used that give a fairly complete picture of resource inputs into the national economy (at least in monetary terms). Output flows are accounted for in trade statistics (namely as exports), on the one hand, and there they are complete and consistent. The outflows to the natural environment, on the other hand, are registered in environmental waste and emissions statistics, but these are rarely complete in terms of mass balance.

With input flows, two important distinctions are made. One distinction is between *used* and *unused materials*. Used materials are defined as the amount of extracted resources entering the economic system for further processing or consumption. Used materials acquire the status of a commodity and have an economic value. Unused materials refer to materials that are extracted from the earth's crust or from ecosystems but never enter the economic system for further use. Unused materials comprise overburden and other extraction waste from mining, by-catch, and wood harvesting losses from biomass extraction and soil excavation, as well as dredged materials from construction activities (EUROSTAT 2007; OECD 2008a). Global data availability and quality regarding unused extraction are still unsatisfactory.

Another distinction that needs to be drawn is between *direct* and *indirect material flows*. Direct flows refer to the actual mass of the material or product and thus do not consider accumulative material requirements along production chains. Indirect flows indicate all materials required along a production chain to manufacture a product. In MFA, these indirect flows are also referred to as "hidden flows" or "embodied materials."[11] Indirect flows may comprise both used and unused materials. The upstream material requirements of used extraction are termed "raw material equivalents" (RMEs; EUROSTAT 2001). Several projects are currently targeted toward developing and testing methodologies to account for indirect material flows of traded products, applying coefficient approaches from life cycle assessment, input-output techniques, or hybrid approaches combining the two (e.g., Weisz 2007; Hertwich and Peters 2009; Munoz et al. 2009; Weinzettel and Kovanda 2009). A standard approach to how indirect flows should best be calculated still needs to be developed.

All these indicators may be shown as summary accounts, and in this *extensive* form they represent the *metabolic scale* of the national economy (or aspects of it). They may also be shown as *intensities*. For international comparisons, the most common way is to show them as annual flows per capita population (e.g., "domestic material consumption" [DMC]/cap ∗ year) and thus express the average amount of material associated with sustaining one individual during a year (*metabolic rate*). Another form is to express a country's material flows in relation to its monetary flows (e.g., "direct material input" [DMI]/$ GDP ∗ year), thus creating an indicator of *material productivity* (or, conversely, *material intensity*). Finally, one may relate material flows to the size of the territory (e.g., "domestic extraction" [DE]/hectare ∗ year), thus creating a crude indicator for the *material burden on the domestic environment* and *resource availability*. For the definition and interrelations between the indicators, see figure 1.

Beyond the indicators described in figure 1 and its caption, further indicators are used, such as *physical trade balances* (PTBs) and *net additions to stock*. PTBs express whether resource imports exceed resource exports and help to explain the extent to which domestic material consumption is based on domestic resource extraction or depends on imports. Net additions to stock balance inputs and outputs from stock and thus give an indication of changes in the size of the system compartments that will have to be maintained by material flows in the future. Finally, efforts are made to define various *recycling rates* for the system (see, e.g., Hashimoto and Moriguchi 2004).

Most existing compilations of MFA indicators at the country level focus on direct inputs of used materials, in particular on DE, imports, exports, and the derived indicators DMI, DMC, and PTB. A mature methodology and a number of data sets exist for these indicators, which allow researchers to compile comparable countrywise data for a large number of countries. These are the data sets we refer to for a first systematic check of the reliability of key MFA indicators, as we undertake in the next section.

It is both a strength and a weakness of MFA that it minimizes value judgments. MFA is an analytical accounting tool that provides information about amounts and kinds of physical flows through socioeconomic systems. It does not convey opinions on whether these flows are justified by the benefits provided, nor does it judge the size of unwanted environmental impacts. One might say that all MFA does is translate economic activity into physical terms. Whatever follows from this requires additional assumptions, be they assumptions about the thermodynamics of closed systems, about the scarcity of resources, about the energy requirements of moving mass, or about the proportionality between certain mass flows and ecosystem disturbances, to name a few. MFA can therefore support very different approaches of environmental governance or, more broadly speaking, of sustainability policies, the current emphasis on enhancing resource productivity and achieving a decoupling between economic and physical growth being only one of them (cf. European Commission 2005; Yoshida et al. 2007). In this latter context, though, MFA has been recognized as a key approach to assess the material base, the material throughput, and the resource productivity of national economies both for Europe and at the international level (cf. European Commission 2003; OECD 2004, 2008c).

Data Reliability and Uncertainties Across Different Multinational Data Sets

Multinational Data Sets

In recent years, a large number of national and, more recently, also multinational (regional and global) MFA data sets have been compiled, and data on used extraction of materials and also on physical amounts of trade have been made accessible to the public. It is beyond the scope of the article to assess the quality of all existing national and regional MFA data sets; we focus on comprehensive sets of global and European Union data. Table 1 gives a brief overview of the data sets available for comparison.

A compilation of MFA data for all countries globally was provided in 2006 by Schandl and Eisenmenger, who published a data set for domestic extraction for 2000 based on the methodological principles of the Eurostat (2001a) handbook. In this data set, data for construction minerals were estimated at the regional scale only, not at the country level. Krausmann and colleagues (2008a) published a global MFA data set for 2000 that also includes trade flows according to the most recent guidelines of Eurostat (2007b). SERI maintains a country-by-country database containing annual data on material extraction for the period 1980 to 2007 (at the time of writing) for almost all countries globally. This database has been frequently revised and is annually updated.[12] Steinberger and colleagues (2010) have published a revised version of the data set by Krausmann and colleagues (2008b), referring to the latest methodological achievements and including a new estimate for construction minerals based exclusively on physical data. The trade data in this data set are identical to those in the work of Krausmann and colleagues (2008a). In 2009, Krausmann and colleagues published time series data for global materials extraction covering the period 1900 to 2005; however, their data only show the global aggregate and are not available for individual countries. Furthermore, two data sets provide data on domestic extraction and trade for EU member states: Weisz and colleagues (2007) compiled data for the EU-15, and Eurostat (2009) compiled data for the EU-27. An updated version of this data set was published after we performed the analysis for this article. Other multinational data sets include an analysis for several Latin American countries by Russi and colleagues (2008) and recently published data for the Asian Pacific region (Schandl and West 2010), but these were not available for the analysis presented here. All of these data sets are consistent with respect to the system boundaries applied and the basic accounting principles. They do comply with the standards explained in the previous section, but they also reflect the gradual evolution of methodology and were compiled to address different research questions. Table 1 presents these data sets in chronological

Table 1 Overview of multinational material flow accounting (MFA) data sets used for comparison: Coverage, data sources, and estimation procedures

Reference	*Schandl and Eisenmenger (2006)*	*Krausmann and colleagues (2008)*	*SERI (2009)*	*Krausmann and colleagues (2009)*	*Steinberger (2010)*	*Weisz and colleagues (2007)*	*Eurostat (2009)*
Country coverage	173 countries	176 countries	203 countries	Global aggregate	176 countries	15 EU members	29 European countries
Time coverage	2000	2000	1980–2006	1900–2005	2000	1970–2004	2000–2005
Flow coverage	DE	DE, Im, Ex	DE	DE	DE, Im, Ex	ED, Im, Ex	DE, Im, Ex
Biomass data sources	FAO; *e: global coeff.*	FAO; *e: country-specific coeff.*	FAO; *e: coeff. derived from Eurostat (2007)*	FAO; *e: global coeff. variable across time*	FAO; *e: country-specific coeff.*	National statistics; FAO; *e: European coeff.*	National statistics; FAO; *e: Eurostat (2007)*
Ores and industrial minerals data sources	USGS; *e: regional coeff.*	USGS; UNICPS; *e: national coeff.*	BGS, USGS, UNICPS; WMD, national data; *e: statistic national coeff.*	USGS, *e: global coefficients variable across time*	USGS *e: national coeff.*	National statistics; UNICPS; *e: European coeff.*	National statistics; *e: Eurostat (2007)*
Fossil energy carriers data sources	IEA	IEA; UN statistics	IEA	IEA; UN statistics	IEA; UN statistics	National statistics; IEA	National statistics; IEA
Construction minerals data sources	*e: development status; only for country groups*	*Combines information from statistical sources with a GDP-based estimate using PPPs*	*Combines information from statistical sources with a GDP-based estimate using const. prices*	*Physical estimate global aggregate only; no country data*	*Revised version of Krausmann and colleagues (2008). Physical estimate of construction minerals without using GDP*	*Reporting based on statistical sources; for some countries estimated on the basis of GDP*	*Reporting based on statistical sources; for some countries estimated on the basis of physical data*

Note: DE = domestic extraction; Im = imports; Ex = exports; FAO = Food and Agricultural Organisation; USGS = U.S. Geological Survey; BGS = British Geological Survey; UNICPS = United Nations Industrial Commodity Production Statistics; IEA = International Energy Agency; WMD = World Mining Data; UN = United Nations; *e = estimate based on*; *coeff.* = coefficients; GDP = gross domestic product; const. = construction.

Table 2 Estimates of indicators of global (used) extraction (DE, extensive) in 2000 by main material groups (in billion tonnes [10^9 t])

Reference	*Biomass*	*Fossil energy carriers*	*Ores and industrial minerals*	*Construction minerals*	*Global material extraction*
Schandl and Eisenmenger (2006)	16.9	9.6	3.5	19.0	48.8
Krausmann and colleagues (2008)	18.4	10.0	3.8	26.5	58.7
Krausmann and colleagues (2009)	17.7	10.0	4.5	17.5	49.6
SERI (2009)	18.2	9.7	7.1	15.3	50.3
Steinberger and colleagues (2010)	17.6	10.1	4.9	16.3	48.9
M	17.7	9.9	4.7	18.9	51.3
SD	0.6	0.2	1.4	4.5	4.2

Note: t = tonnes.

order, first the global data sets and then the data sets for the European countries only.

Data on domestic extraction are available from all multinational MFA data sets listed in table 1. Import and export data are only reported in the two European Union data sets and, in identical form, in two global data sets. Other indicators (net additions to stock, domestic processed output) are not yet available from multinational data sets. Thus, our analysis of multinational MFA data and their reliability across data sets focuses on domestic extraction. We first probe into the results for the global level, using 2000 as a reference year, and investigate the reliability of measuring material extraction[13] by its four main aggregates (see table 2 and figure 2). We then focus on country-level data (again for 2000) and provide checks on the reliability of DE from individual countries (see table 3 and figure 2). Finally, we cross-check global trends in DE across time (see figure 3). Differences between multinational MFA data sets can be a result of deviations in the used primary data sources and the way these primary data are processed in material flow accounts. But, above all, differences between data sets may be due to variations in the procedures and coefficients used to estimate flows not covered in statistical sources: At the global scale, between half and two-thirds of the total mass flow of DE is estimated. It has to be noted, however, that our analysis does not take into consideration any uncertainties stemming from the primary data used to compile MFA data.

Estimates for Global Material Extraction and Use

Table 2 shows the estimates of global material extraction to be fairly consistent across all five global data sets. In particular, the estimates at the global scale for biomass and fossil energy extraction only minimally deviate from the mean across data sets of 17.7 and 9.9 billion tonnes, respectively. The situation is somewhat different for mineral materials. Both for ores and industrial minerals and for construction minerals, one of the five data sets stands out. In the case of ores and industrial minerals, the SERI global estimate is significantly higher than the other four, whereas in the case of construction minerals, Krausmann and colleagues' (2008) data deviate from the rest. The most likely reasons for these deviations are (1) differences in the coefficients used to estimate gross ores and the allocation of specific minerals to either industrial minerals or construction

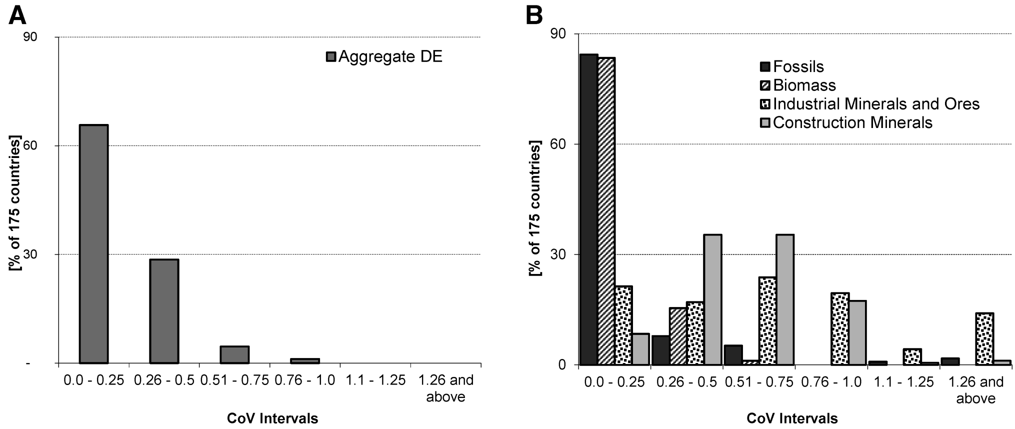

Figure 2 Coefficients of variation (CoV = standard deviation/mean) for domestic extraction (DE) between data sets. Figure 2a: for aggregate DE; Figure 2b: for main material groups.

minerals in the case of the SERI estimate and (2) the use of GDP in purchasing power parities to estimate construction minerals in Krausmann and colleagues' (2008) data set. Values given for total global DE range between 48.8 billion tonnes in the work of Schandl and Eisenmenger (2006) and 58.7 billion tonnes in the work of Krausmann and colleagues (2008), whereas the global average across data sets is at 51.3 billion tonnes.

On a per capita basis, global metabolic rates average at 8.5 tonnes (8.1 to 9.7 t/capita/yr), and roughly 1.8 t/ha of materials are extracted per year. Global material productivity ranged between US$481 and US$577 (in 1990 dollars) per tonne in 2000 (see table 4). All in all, the various estimates for used global extraction (DE) of materials are remarkably consistent, with standard deviations mostly below 10% of global means (see table 2). Thus, estimates for global material extraction and use have an uncertainty of about +/− 10%, somewhat less for biomass and fossil fuels and somewhat more for industrial and construction minerals.

Table 3 Correlations between data sets by countries, for aggregate domestic extraction (DE) in 2000, according to each of the studies cited

	Total DE			
Reference	*Steinberger (2010)*	*SERI (2009)*	*Weisz and colleagues (2007)*	*Eurostat (2009)*
Krausmann and colleagues (2008)	**0.97**	0.95	**0.99**	0.95
Steinberger (2010)		**0.96**	0.92	0.87
SERI (2009)			**0.99**	**0.96**
Weisz and colleagues (2007)				0.93

Note: All coefficients of determination are significant at the 1% level. Coefficients of determination (R^2) of log log regressions; $R^2 > 0.96$ are in boldface.

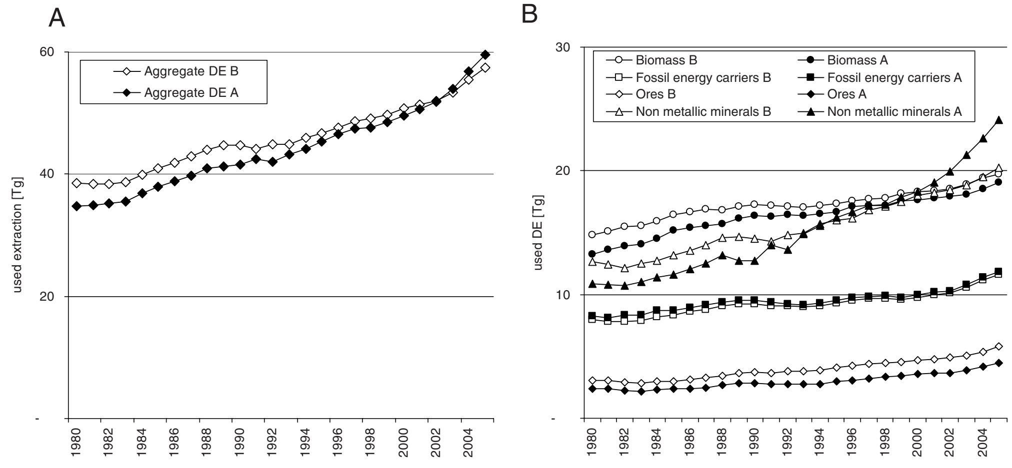

Figure 3 Trends of global material extraction in the period from 1980 to 2005. Figure 3a: aggregate domestic extraction (DE); Figure 3b: DE by main material groups. Comparison of estimates by Krausmann and colleagues (2009) (dataset A, white markers) and SERI (2009) (dataset B, black markers). One teragram (Tg) = 10^9 kilograms (kg, SI) = 10^6 tonnes (t) ≈ 1.102 × 10^6 short tons. Source: Our own calculations, based on the work of Krausmann and colleagues (2009) and SERI (2009).

Countrywise Estimates of Domestic Material Extraction

If we compare the data for total DE from the six data sets at the country level, we find correlations between individual data sets for total DE correlations to range between 0.93 and 0.99 (see table 3). This is quite a satisfactory result.[14]

The apparent consistency is also supported by relatively small coefficients of variation (standard deviation by mean) between data sets for individual countries: According to figure 2, a high standard of consistency has been reached for biomass and fossil energy carriers. For more than 80% of countries, the standard deviation between data sets amounts to less than 25% of the mean, and for more than 90% it amounts to less than 50%. For mineral materials, congruence is much lower: Only 34% and 38%, for ores and industrial minerals and for construction minerals, respectively, of all countries show a coefficient of variation of less than 0.5, and for some countries deviations from the mean are very large. For aggregate DE, the results are, nevertheless, satisfactory: Sixty-five percent of all countries show a coefficient of variation below 0.25, and around 95% are below 0.5. For individual countries, data reliability is lower: For total DE, uncertainty is somewhere between +/— 20%; again, for biomass and fossil fuels it is lower and for industrial and construction minerals higher than that.

Table 4 Estimates of intensive indicators (DE/x*yr) of global material extraction in 2000

Indicator	*Unit*	*Average*	*Minimum*	*Maximum*	*SD*
Global metabolic rate	[t/cap*yr]	8.5	8.1	9.7	7
Global pressure on land	[t/ha*yr]	1.8	1.7	2.1	0.1
Material productivity	[US$/t*yr]	552.9	480.5	577.4	41.1

Note: DE = domestic extraction; t = tonne; cap = capita; yr = year; one hectare (ha) = 0.01 square kilometers (km^2, SI) ≈ 0.00386 square miles ≈ 2.47 acres.

Global Trends in Material Extraction and Use

Two data sets provide information on global material extraction in time series and allow for trends to be compared over time. Figure 3 shows the changes in global material extraction in the period from 1980 to 2005, as estimated by Krausmann and colleagues (2009) and SERI (2009). It appears that the two timelines for global DE have come very close in the past decade, and they display very similar oscillations, but, overall, the growth rate of global DE in Krausmann and colleagues' data set is steeper than in the data from SERI.

In line with what has been observed so far, data for the extraction of fossil energy carriers and biomass are remarkably similar in the two data sets. Differences in the estimates for biomass, in particular in the early years, are most likely due to Krausmann and colleagues' (2009) use of dynamic coefficients to estimate grazed biomass and harvested crop residues, whereas the SERI (2009) data set is based on static coefficients derived from Eurostat (2007) for industrial countries at the turn of the 21st century. For ores, there is a significant difference in the overall amount, but the trends over time are very similar. The deviation is most likely due to differences in the coefficients applied to estimate gross ore from metal content and assumptions on coupled production. Differences are largest for the "nonmetallic minerals" category, which is dominated by construction materials and includes industrial minerals.[15] The two data sets are based on different estimation procedures for construction materials. Krausmann and colleagues (2009) used physical data (cement production, concrete consumption, asphalt production, and road networks) to estimate construction minerals, whereas SERI (2009) combined data available from national MFAs and statistical sources with an estimate based on per capita income. Although both estimates arrive at a quite similar volume of global extraction of nonmetallic minerals, Krausmann and colleagues' (2009) estimate shows a steeper increase than the one from SERI (2009). Although Krausmann and colleagues (2009) arrive at a lower estimate for the early years, their final estimate exceeds that of SERI (2009) from 2002 onward and ends 5% higher in 2005.

Indicator Reliability Across Sources

Biomass and fossil energy carriers are the material groups for which global estimates are most consistent. This is unsurprising for fossil energy carriers (one-fifth of global DE), because they comprise a comparatively small number of materials of high economic significance. The economic importance of energy has led to the institutionalization of the IEA, which maintains an internationally accepted database of high quality. If deviations occur, they are due to minor differences in the way data on extraction are reported in primary sources, country coverage of primary sources, and applied conversion factors to convert from energy content to mass. The high degree of consistency is also not surprising for biomass (one-third of global DE). Providing reliable information on food and nutrition is an important public policy issue that is internationally monitored by the Food and Agriculture Organization, which has a long tradition in the collection of data on agriculture, forestry, and fishing (FAOSTAT). On the one hand, all data sets use FAOSTAT as a primary source for harvested crops and wood. These data are of high quality, although minor deviations may occur due to the conversion of volume to mass (wood) and assumptions on water content (fodder crops). On the other hand, significant biomass flows, such as used crop residues and grazed biomass, are not covered by statistical sources and have to be estimated. These flows account for roughly 50% of global biomass extraction. For both flows, standardized estimation procedures have been developed (Wirsenius 2003; Krausmann et al. 2008; Eurostat 2009) that make assumptions on the ratio of grain to straw (harvest indexes) and roughage intake by livestock. Although all data sets have essentially based their estimates on these procedures, no standardized coefficients (species-specific feed intake, harvest indexes) exist that take into account regional and historic differences. Variations in these assumptions are the reason for the observed differences of estimated biomass extraction.

In contrast, our analysis has shown that consistency of estimates for mineral materials is somewhat disappointing. In particular, the observed differences at the country level are considerable. Ores and industrial minerals, which amount to 10% of global DE, are a very large and heterogeneous group of materials. A variety of sources exist that provide data on mineral materials (e.g., U.S. Geological Survey, United Nations Industrial Commodity Production Statistics [UNICPS], British Geological Survey [BGS]), but reporting standards (e.g., units), data quality, and coverage concerning materials and countries vary considerably across databases, which is one of the causes for deviations across material flow accounts. The major source of variation is, however, the translation of extracted metals into gross ores, as required by MFA methodology. Statistical sources present data for ores mostly in metal content but in some cases also as concentrates or gross ores. Often it is not easy even to identify what exactly is reported in the source. Conversely, reliable country-specific statistics concerning average ore grades and coupled production are difficult to obtain as they are highly variable across mines and over time (see, e.g., the comprehensive work of Mudd [2009] for Australia).

Construction minerals are a very large flow amounting to more than one-third of global material extraction. Within the group of construction minerals, sand, gravel, and crushed stone are the most important components. They are very poorly covered in international statistical databases. Many countries report only part of the materials extracted, and some countries report none at all. In effect, data published by countries are not comparable internationally and over time, and they are not consistent across sources. International data sets therefore usually apply estimates, sometimes in combination with data reported in national statistical sources or derived from national MFAs. Different estimation procedures have been suggested, but in general two types are used: One type of estimate assumes a certain relation between income and per capita extraction of construction minerals. This relation does exist, but it is not as robust as one might wish. In particular, the relation is not necessarily linear: There seems to be a link between early phases of economic growth and enhanced use of construction materials. Apart from the question of robustness of this relation, building assumptions about a relationship between GDP and material flows a priori into estimates of material flows preclude the analysis of physical and monetary flows as statistically independent variables. The other type of estimate builds on information on the production and use of concrete and asphalt as major applications of natural aggregates. This strategy may fail to capture some of the historical and countrywise variability of this relation. So far, no acceptable standardization of methods has been achieved, and as long as national data are so badly reported and standardized, it is hard to achieve a major breakthrough at the international level. The uncertainty over estimates for construction minerals also affects figures for aggregate DE.

So far, only a few multinational data sets include data on imports and exports—too few to analyze their reliability. Very few data sources are available that provide multinational data on physical trade flows. The most prominent sources are the United Nations' UNCOMTRADE and the European Union's COMEXT databases; other sources, such as FAOSTAT and IEA, only provide trade data for specific material groups (e.g., biomass, fossil energy carriers). A major problem concerning the integration of physical trade data into MFA accounts and, hence, a potential source for deviations and uncertainty is the lack of standardized procedures to handle the manifold data gaps and flaws in the primary data (see, e.g., Eurostat 2009; Dittrich and Bringezu 2010). A second unresolved issue is the question of how to classify and aggregate trade flows recorded by international trade classification systems in a way that is consistent with the requirements of MFA classification systems. Although this is more or less straightforward for primary materials and most semimanufactured products, it is difficult for manufactured products that comprise a whole range of different materials.

Apart from these apparent weaknesses, global MFA data have been demonstrated to be fairly reliable, with differences and uncertainties that remain within a reasonable range that does not preclude sound analysis and interpretation of results. Nevertheless, a further harmonization of conventions and estimation procedures is needed, in particular for metal ores and nonmetallic minerals used for construction. Estimation procedures applicable for the developing countries, where statistical data are often lacking, must be improved. A transparent set of region-specific and time-specific conversion coefficients should be compiled and made accessible.

Conclusions, and Some Directions for the Future

The methodology for material flow accounting has evolved over the past 2 decades, built on strong theoretical foundations laid in the late 1960s. How mature it may be considered today needs to be questioned on three levels: the conceptual level, the level of standardization of measures and estimates, and the level of reliability of data attained by this methodology. Concerning the conceptual level, researchers learned very early on to discuss system boundaries carefully and to strive for high systemic consistency, both internally among the physical indicators and externally with monetary systems of national accounts. Much effort has been invested in achieving consensus about system definitions, both among academic institutions and with statistical agencies, to the effect of achieving a certain maturity on the conceptual level. As far as maturity of measurement and estimation methods is concerned, there has been a healthy balance between competition and cooperation, within academia and among statistical agencies of various countries and levels, to warrant a process of gradual standardization and harmonization. As of today, maturity has been achieved as far as direct material inputs are concerned. A number of research efforts have been directed toward achieving material balances between inputs and outputs and accounting for indirect flows, but these efforts have not yet been internationally harmonized. This has implications for the third level, the level of data reliability: Only measurements of direct material inputs have been reported for a sufficient number of cases to probe into the reliability of these data. We have undertaken to address this problem in our analysis, to the effect of concluding that material input flow data today appear mature enough to deliver reasonably reliable results in time series across many decades and for all countries of the world. The situation is even rapidly improving: Meanwhile, a considerable number of mostly industrialized countries have incorporated this information into their standard statistical information systems (e.g., Austria, Germany, Japan), and at the European Union level, a legal base to make MFA data reporting obligatory is under preparation, as part of the international efforts at creating an SEEA.

Still, a number of issues remain unresolved. Scientific as well as political discussions have revealed that indicators referring to indirect flows (e.g., raw material equivalents [RMEs]) and unused flows (e.g., total material consumption [TMC]) are required to reveal possible shifts of environmental burden through international trade. Several approaches for assessing indirect material flows of traded products have been developed and are currently being tested (Weisz 2007; Giljum et al. 2008; Buyny 2009; Schaffartzik et al. 2011). A harmonization of these approaches is a next key step toward the inclusion of indirect material flows in MFA accounts. Also, data availability on unused flows is still lower than for used flows, although not necessarily less important (Bringezu et al. 2009).

To tailor material flow data for economic policy, researchers would require further disaggregation of the current information by economic sectors. There have been several attempts to do so based on physical input-output tables (PIOT) for the whole economy (Stahmer et al. 1997; Pedersen 1999; Giljum and Hubacek 2004; Suh 2004; Dietzenbacher 2005; Hoekstra and Van den Bergh 2006; Weisz and Duchin 2006). The PIOT approach usually involves a much higher degree of data work than other accounts do, which often results in a large time lag before data can be supplied for policy analysis and policy planning. To avoid such delays, a less complex approach to PIOT may be warranted that focuses on those industries that are receiving the primary materials—that is, the first step of material conversion (Lennox et al. 2005).

Another research frontier is the actual closing of the material balance of national economies. This involves establishing a consistent link between resource inputs and outputs in terms of materials discarded from economic processing. In comparison with inputs, MFA researchers have invested much less effort so far on outputs, although the core idea of material balancing paves a path toward an integrated systemic approach. In the course of research projects such as EXIOPOL (Tukker et al. 2009) or FORWAST (http://forwast.brgm.fr/), significant progress toward filling these gaps is being made; however, further research is needed to increase methodological harmonization.

Finally, approaches for modeling and scenarios of material flows will gain importance for assessing alternative futures of resource use in relation to policy alternatives (see UNEP panel for Sustainable Resource Management, Fischer-Kowalski et al. 2011; Schandl et al. 2008).

Beyond these MFA-specific methodology issues, MFA data lend themselves for a wide variety of questions to be explored. Meanwhile, several databases are freely accessible (see, e.g., www.materialflows.net, www.uni-klu.ac.at/socec/inhalt/1088.htm, www.cse.csiro.au/forms/form-material-flows.aspx, or http://epp.eurostat.ec.europa.eu/portal/eurostat/home) to deal with, for example, the interrelations between carbon flows and other resource flows, the links between materials and energy and land use on various scale levels, the link between resource flows and environmental impacts, the relationships between stocks and flows and between infrastructures and current resource consumption, the connection between resource use density per area and biodiversity, the quantitative opportunities of resource substitution, and scenarios of dematerialization and international equity. Increasingly, a number of policies directed at reducing environmental pressures and impacts make use of MFA indicators, such as the EU Thematic Strategy on the Sustainable Use of Natural Resources (2005), the OECD Strategy for Sustainable Materials Management (2004), Japan's "3 R" (Reduce, Reuse, Recycle) Strategy (2005), China's Law on Circular Economy (2008), and Korea's "Green Growth Policy for Sustainable Development in a Low Carbon Society" (2008). The achievements in material flow accounting to date suggest that this framework adds important information to the leading aggregates, such as population, GDP, income, employment, and consumption, and will therefore challenge the traditional economic information for national policy making in the context of sustainable development.

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Notes

1. The acronym "MFA" often is also spelled out as "material flow analysis." Between the more descriptive term ("accounting") and the more theoretically demanding term ("analysis"), no well-defined distinction can be drawn. In this contribution, we use the terms interchangeably. Economy-wide MFA is one of six major types of material flow analysis (Bringezu and Moriguchi 2002).
2. One of the early ways to convey such comprehensive information was the so-called IPAT formula by Ehrlich and Holdren (1972). It expressed *I* (environmental impact) as a function of *P* (population numbers), *A* (affluence, i.e., gross domestic product/population), and *T* (technology, i.e., the particular ways affluence is generated). Meanwhile, this formula has seen a number of modifications and specifications (e.g., by York et al. 2003); in particular, the *T* has received a number of interpretations. It has, for example, been operationalized as energy intensity of the economy and could as well be operationalized as material intensity.
3. One tonne (t) = 10^3 kilograms (kg, SI) $\approx$ 1.102 short tons. All mass units in this article are metric.
4. Finally, in 2008, under the presidency of Fischer-Kowalski, ConAccount became Material Flow Analysis–ConAccount, a formal section of the International Society of Industrial Ecology (ISIE). The first ConAccount meeting under ISIE was held in Tokyo in 2010.
5. The EU-15 refers to the members of the European Union that had joined before 1995. The EU-27 encompasses all countries that are members as of 2011, including all accession countries from Central and Eastern Europe that joined the Union before 2007.
6. Strictly speaking, it can be created or destroyed (e.g., with nuclear fission)—however, the sum of material and energy remains constant.
7. This complies with "fixed assets" as defined in System of National Accounts (SNA).
8. There is an ongoing debate between the MFA community (researchers and statisticians) and the SEEA community about this issue, which was also

addressed by the reviewers of this article. SEEA advocates often argue that an ecosystem approach complies better with the SNA. From an MFA perspective, the ecosystem approach has serious drawbacks: With the harvest approach, roughly one-third of the plant biomass is captured. This—with some standardization of water content—is the amount actually collected, transported, processed, and transformed into economic value. Accounted for in such a way, biomass amounts to about one-quarter of all material input of industrial economies. By an ecosystem approach, one would have to account not only for the mass of the whole plant (including unharvested parts) but also for the plants' gross primary production—that is, all the CO_2 uptake of the plant in its lifetime. These operations would lead to a multiplication of the "harvested" materials by a factor of about 6. If, furthermore, the lifetime water consumption (and evaporation) of the plant were taken into account, the total mass would again multiply by about 100 (strongly dependent on plant and climate). In effect, the material volume, from an ecosystem approach, would be about 600 times the amount of the actually harvested biomass. On the economic side, farmers pay neither for the belowground fraction of their plants that remains in the soil after harvest, nor for the CO_2 extracted from the atmosphere, nor for the rainfall. All they pay for, besides (sometimes) irrigation water, is fertilizers and pesticides, which play hardly any role in terms of plant biomass at the time of harvest. By an ecosystem approach, one would increase the share of biomass to 80% (without water) or even 99.5% (if water is included) of the total material input of industrial societies, and one would reduce overall resource productivity (dollars per kilogram) by two orders of magnitude by adding a lot of mass and no value. The required estimates, which would have to be made on the basis of very general coefficients, would result in very large uncertainties of MFA indicators. Thus, a consequent ecosystem approach would largely destroy the information value of MFA.

9. There is a certain inevitable asymmetry between material flows and economic flows, already addressed by Ayres and Kneese (1969), as referred to above. Framed slightly differently, this asymmetry occurs because physical flows cross the border between the environment and the economy, whereas monetary flows do not. Monetary flows circulate only within the economy. Understanding this difference requires recognizing that socioeconomic systems are closed with regard to monetary flows but open with regard to physical flows. In addition, each crossing requires a conversion. When materials are converted to commodities, this physically means losses (wastes or heat are created as a byproduct), whereas economically this means gains (value is created). This explains in a very fundamental way why SNA, which is based on monetary principles, and MFA, which is based on physical principles, never can be completely symmetrical.
10. Efforts are ongoing to use the same system definitions and stock and flow distinctions for computing energy and water balances for socioeconomic systems. For energy, a consistent approach has already been formulated and applied to a number of national economies (see Haberl et al. 2006; see also the so-called material and energy flow accounting [MEFA] approach; Haberl et al. 2004). For water, the question is more complicated because of the numerous recycling flows that play a much larger role than with materials, but efforts are ongoing (see, e.g., Hoekstra and Chapagain 2008).
11. If the black box of economy-wide material flow accounting is opened up and intraeconomy flows are investigated (e.g., in an input-output framework), indirect flows can also be assessed within the domestic economy. For possible distinctions among "hidden," "embodied," and "indirect" flows, see the work of OECD (2008, vol. 1, p. 43).
12. See www.materialflows.net. For the cross-country comparison, we accessed the database in December 2009.
13. On the global level, material extraction (DE) equals materials use (DMC), because trade flows equal out.
14. The picture changes at the level of material groups, however: Although coefficients of determination for biomass and fossils are still generally very high (between 0.84 and 0.99 for fossils and between 0.92 and 0.99 for biomass), consistency is lower for mineral materials (see the supporting information available on the JIE Web site).
15. A consistent separation of industrial minerals and construction minerals was not possible for the time series data; therefore, we have chosen to show aggregates for ores, on the one hand, and nonmetallic minerals, on the other.

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Supporting Information

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

Supporting Information S1: This supporting information has correlations between data sets by countries comparing five recent academic studies, for domestic extraction of biomass, fossil energy carriers, construction materials, and industrial materials.