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Material Flow Accounting: Measuring Global Material Use for Sustainable Development

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Abstract

The growing extraction of natural resources and the waste and emissions resulting from their use are directly or indirectly responsible for humanity approaching or even surpassing critical planetary boundaries. A sound knowledge base of society's metabolism, i.e., the physical exchange processes between society and its natural environment and the production and consumption processes involved, is essential to develop strategies for more sustainable resource use. Economy-wide material flow accounting (MFA) is a framework that provides consistent compilations of the material inputs to national economies, changes in material stocks within the economic system, and material outputs to other economies and the environment. We present the conceptual foundations of MFA and derived indicators and review the current state of knowledge of global patterns and trends of extraction, trade, and use of materials. We discuss the relation of material use and economic development and the decoupling of material use from economic growth in the context of sustainable resource use policies.

Contents

1. INTRODUCTION

Materials extracted from the biosphere and the lithosphere are the physical basis of human society (1). With industrialization, the use of materials has drastically increased. In the past century alone, the flow of key natural resources has grown by one or more orders of magnitude (**Figure 1**). The extraction of fresh water multiplied from 580 to 4,400 billion m^3/year (2), the consumption of

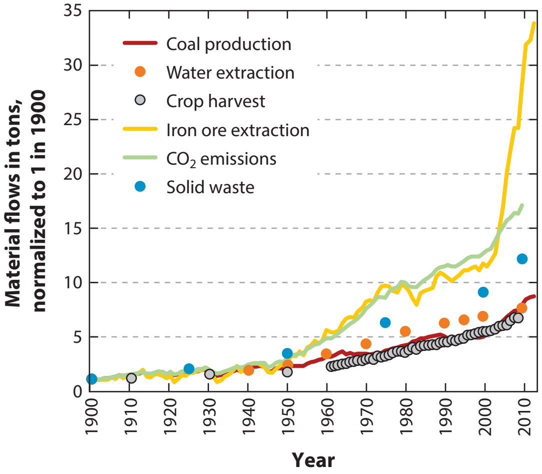

Figure 1

Growth of global resource flows in the twentieth century. All flows are in metric tons per year and normalized to 1 in the year 1900. Data for coal, crops, and iron ore are provided by Reference 3; for water, by Reference 2; solid waste, by Reference 5; and CO$_2$ emissions from fossil fuels, by Reference 4.

coal grew from 0.9 to 8 Gt/year (1 Gt $= 10^{15}$g $=$ 1 Pg), the harvest of crops increased from 1 to 7.5 Gt/year, and the extraction of iron ore rose from 0.09 to 2 Gt/year (3). All materials that enter the economic system are disposed of into nature at the end of their service lifetime, and as a consequence the amount of waste and emissions has also surged. Global CO_2 emissions from burning fossil fuels have risen from 0.5 to 10 Gt/year (4), and the production of municipal waste is estimated to have multiplied from 0.3 to 3.9 Gt/year (5).

Figure 1 indicates that growth in the physical size of the economy has accelerated in the twenty-first century. Socio-economic flows of materials have already reached a level that effectively alters global biogeochemical cycles, thus justifying the concept of a new geological era, the Anthropocene (6). The increase in atmospheric CO_2 concentration and the consequent impact on the global climate system are just two of the many consequences of increasing material use that challenge global sustainability. At the beginning of the twenty-first century humans appropriate roughly 25% of the annual global net primary production to provide food, feed, fiber, and fuel (7); economic activities have doubled the amount of reactive nitrogen in the biosphere (8); and the amount of key metals (e.g., copper) accumulating in stocks-in-use or in landfill is at the same order of magnitude as that of known reserves (9, 10). Most global and regional sustainability problems are a direct or indirect consequence of the use of materials and the corresponding wastes and emissions. The growing use of materials is pushing humanity beyond a "safe operating space" and crossing planetary boundaries (11, 12). A sound knowledge base of the material exchange processes between society and its natural environment; the production and consumption processes involved; and the relation between material use, economic development, and human well-being are therefore essential to develop strategies for more sustainable use of natural resources.

A valuable conceptual approach to study the biophysical basis of human societies is the concept of socio-economic metabolism. It is widely applied in interdisciplinary research fields such as industrial ecology and ecological economics to study resource flows and to understand the link between economic processes and environmental pressures (13, 14). A particular method derived from the socio-economic metabolism framework is economy-wide material flow accounting (MFA) (15, 16). MFA applies a mass balance approach and traces the flow of materials through socio-economic systems from their extraction in agriculture, forestry, and mining to their end-of-life discharge to the environment as waste and emissions. In recent years economy-wide MFA research has greatly advanced. A large body of empirical research has become available and researchers have drawn a comprehensive picture of global, regional, and national material flows. MFA-derived indicators are used prominently in environmental reporting (17, 18) and provide the backbone for the development of sustainable resource use strategies and their monitoring (19, 20).

In this review, we present recent research in economy-wide MFA and discuss its policy relevance. We introduce the concept of socio-economic metabolism and the method of MFA. We discuss the scientific evidence for a global metabolic transition and provide a brief overview of the state of knowledge of current patterns of global material use and their trajectories over time, including outlooks on future material use. We review the decoupling of material use and economic development and discuss the relevance of the MFA approach for sustainable resource use policy.

2. MATERIAL FLOW ACCOUNTING

2.1. A Brief History of the Concept

The concept of socio-economic metabolism (SEM, sometimes also known as social or industrial metabolism) is a holistic approach to investigate the biophysical patterns and dynamics of socio-economic material and energy flows, as well as their underlying drivers (13, 14). The origin of the concept can be traced back to the works of Karl Marx (21, 22); the modern concept mainly

In-use stocks: materials that have accumulated in buildings, infrastructures, and durable goods (manufactured capital)

originates from the works of Robert U. Ayres (23). In 1969, Ayres & Kneese (24) introduced a material balance approach that was revolutionary in environmental and economic thinking at that time (25). They argued that the economy is at odds with the first law of thermodynamics, that materials cannot be "consumed" and that to reduce wastes and emissions a reduction in material inputs would be required. SEM emphasizes that socio-economic systems are inherently physical as they comprise biophysical elements including humans, the built environment, and all artifacts. For the production and reproduction of these physical structures of society, to fuel them, and to provide services from them, a continuous throughput of materials and energy is required. In the words of Pauliuk & Hertwich (13, p. 85), "SEM constitutes the self-reproduction and evolution of the biophysical structures of human society. It comprises those biophysical transformation processes, distribution processes, and flows, which are controlled by humans for their purposes. The biophysical structures of society (in-use stocks) and socio-economic metabolism together form the biophysical basis of society." SEM not only provides a framework to analyze physical stock-flow dynamics, it also allows linking of physical processes to economic processes and human activities in a consistent way; i.e., it contributes to bridging natural and social science approaches to sustainable development (26). SEM can be applied at different spatial and temporal scales and for different systems, from cities and regions (27–30) to national economies and the global scale (31, 32). Fischer-Kowalski & Weisz (26) advanced the linkage to social systems theory, Krausmann et al. (33, 34) investigated the evolution of socio-metabolic patterns as metabolic transitions, and Gonzales de Molina & Toledo (35) applied the concept to study historical change. The concept is increasingly used in the context of prospective models and scenarios of future resource use (36, 37).

An important method to operationalize the concept of SEM and to conduct quantitative research at the macroscale is economy-wide MFA. Recognizing the importance of natural resources has a long history, and economic powers such as the Soviet Union and the United States have established accounts of their natural resource base, resource requirements, and the state of resource supply (38). The Paley Report (39) may serve as a prominent example. In the context of interdisciplinary sustainability science, MFA reemerged in the early 1990s, with research groups in Austria, Germany, and Japan (40–42) pioneering the new accounting standards. A few years later, a first comparative study presenting time series data on material inputs and outputs of industrial economies was published in two seminal reports by the World Resources Institute (43, 44). These studies, for the first time, provided a comprehensive assessment of the amount and composition of all materials (excluding water) that industrial economies extract, trade, and consume, and how these are converted into wastes and emissions, fueling discussion about how to dematerialize the industrial economy. Since then, MFA methods and indicators have been advanced and standardized, and a broad empirical knowledge base has been established. Data and indicators from MFA are widely used in sustainability science and have been adopted by national and international organizations for environmental reporting. In 2001, Eurostat (19) published the first methodological guidelines, and in 2011 the European Union (EU) made the reporting of MFA data obligatory for its member states; the Organisation for Economic Co-operation and Development (OECD) has also adopted MFA in its reporting system (20, 45). MFA has been integrated into the United Nations System of Environmental-Economic Accounting (46), and MFA research also has a prominent role in the United Nations Environment Programme's (UNEP's) International Resource Panel (e.g., 47).

2.2. Accounting Principles

The MFA accounting principles are well documented in several scientific publications and handbooks (16, 19, 47, 48). Economy-wide material flow accounts are consistent compilations of overall

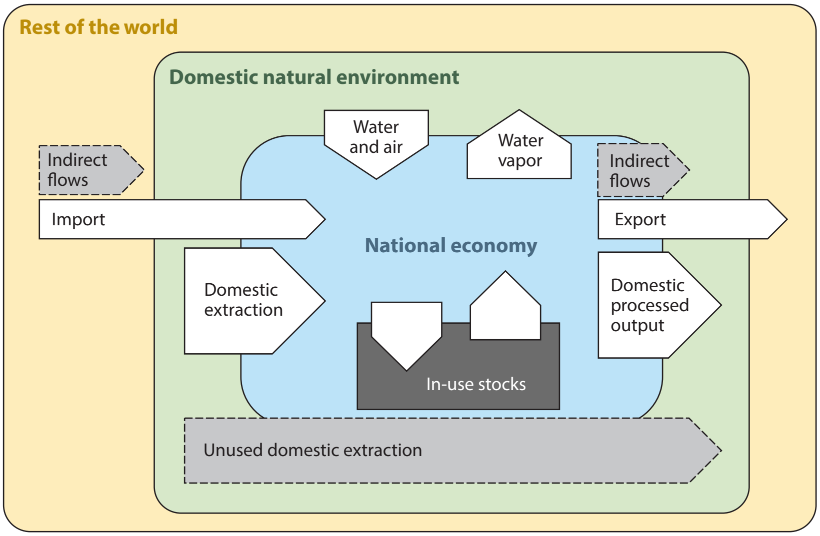

Figure 2

Accounting framework for economy-wide material flows. Figure adapted with permission from Reference 16.

material inputs to national economies, changes in material stocks within the economic system, and material outputs to other economies and the environment measured in metric tons per year (49). They apply the mass balance principle (second law of thermodynamics): Material input into a system must always equal material output plus changes in material stocks in the system. Material stocks (i.e., the physical structures of society) have been defined to comprise humans, livestock, and all in-use artifacts. MFA measures material flows that are related to building up, maintaining, and using these stocks. This requires the definition of two types of system boundaries (**Figure 2**): one between the national economy and its domestic natural environment from which materials are extracted and to which wastes and emissions are discharged; the second with other economies, which defines imports and exports. The system boundaries in MFA are largely consistent with the system of national accounts to ensure compatibility between physical and monetary accounting frameworks and indicators, a key feature of MFA and a main requirement for policy relevance (16). To broaden the scope of the analysis and for application to different systems (e.g., economic sectors or cities) and different research questions (e.g., for assessing environmental impacts related to material flows or to analyze flows within the economy and recycling), MFA can be combined with other SEM methods such as substance flow analysis, life-cycle assessment (LCA), or environmentally extended input-output analysis (50, 51); material flow data can also be converted into energy units by applying gross calorific values and are often used to derive socio-ecological energy flow indicators to study the energetic metabolism of economies (34, 52).

MFA distinguishes between different types of material flows (**Figure 2**). Direct flows are those that actually cross national system boundaries, for example, domestic extraction (DE) of materials for further socio-economic use, trade flows (imports and exports), or domestic processed outputs (DPO) of wastes and emissions. In addition to direct flows, some accounts also include unused and indirect flows: Unused extraction comprises materials that are mobilized by economic activities but do not become an input in production or consumption processes, e.g., soil and rock overlying mineral deposits and removed in surface mining. Although unused flows are not assigned any economic value, they do cause impacts on the environment (e.g., water pollution, landscape change). Indirect flows are upstream flows associated with direct imports and exports (e.g., biomass used as feed to produce imported meat or ores and energy required to produce copper cable). These can be included to measure raw material equivalents (RMEs) of imports and exports and consumption-based indicators, such as the material footprint (MF), as discussed below. Most existing MFA research has focused on the input side, compiling data on extraction, trade, and consumption of materials; only a few studies have included consistent accounts of outputs of wastes and emissions (44, 53). One reason for this is that outputs are, in part, well covered in conventional environmental statistics, but beyond that, methods for comprehensive output accounts and actually closing the material balance are less advanced and not yet standardized (16). Even though difficult, closing the balance and using the consistency of the overall framework can assist in developing more reliable waste and emission accounts, especially in developing economies that have less advanced statistical capacity.

Raw material equivalents (RMEs): all materials that have been used in the production of a commodity

Material footprint (MF): all material flows associated with domestic final demand, regardless of where they occur (consumption perspective)

Circular economy (CE): an economy in which material loops are closed as far as possible either within the economic systems (e.g., reuse, recycling) or via ecological cycles (e.g., renewable biomass)

Domestic material consumption (DMC): all materials directly used in the national production system (production perspective)

Material productivity (MP): the amount of GDP per ton of material consumption (domestic material consumption or material footprint); its inverse is termed material intensity

2.3. Material Flow Accounting Indicators and What They Measure

MFA is a tool to describe and analyze SEM. It provides detailed and comprehensive databases of flows into and out of socio-economic systems consistent with the system of national accounts. This information is used to monitor the development of the physical economy in relation to monetary flows and to support the development of strategies and targets for, and to measure progress toward, more sustainable resource use. **Table 1** provides an overview of the different types of material flow indicators that can be calculated from material flow accounts (54–57). Several of these indicators have been discussed as headline indicators for sustainable resource use and sustainable development and are referred to in policy documents in the context of improving resource productivity, decoupling resource use and economic growth, dematerialization, and circular economy (CE) strategies (18, 58, 59; see also Section 7). The most prominent indicators are domestic material consumption (DMC), total material requirement (TMR), material footprint (MF) and material productivity (MP) or its inverse, material intensity (MI) (see **Table 1** for definitions).

But what do material flow indicators actually measure? Although almost any environmental impact can, in one way or another, be linked to the flow of certain materials, MFA indicators do not provide information on specific impacts but rather measure pressure on the environment. Material flows (e.g., DE, DMC) are regarded as proxies for the aggregate pressure the economy exerts on the environment. MFA indicators have been criticized for aggregating a broad variety of materials with very different impacts on the basis of pure mass (50). In response, impact-oriented indicators such as the environmentally weighted material consumption (EMC) indicator, which attribute material-specific impacts derived from LCA to information from MFA accounts, have been developed (60, 61). Another approach to assess aggregate impacts of material use is the Macro-level LCA indicator developed by the Joint Research Centre of the European Commission (62). The challenge for aggregate impact indicators is to define and then weigh impacts, as both are strongly context dependent and change with scientific progress and prevailing value judgments. Solid aggregation of impacts requires the availability of a large number of geographic- and product-specific impact factors for a broad range of materials and products, which are still often lacking. It has been argued that the simplicity of aggregating measurable mass flows is a strength of MFA indicators. In addition, on a macroscale, a reasonable correlation has been found between EMC and DMC that underpins the quality of DMC as a pressure indicator, and reducing material use can be considered progress toward sustainable development (50).

There has been debate on the suitability of indicators that measure direct flows [direct material input (DMI) or DMC] and those that measure total flows (including both unused and indirect flows) (TMR, TMI). Although unused flows are related to some environmental impacts generated by material extraction, their inclusion has been criticized, in particular, as data quality for these

Table 1 Main material flows and indicators derived from economy-wide material flow accounts (adapted from 47, 50)

Type	Acronym	Name and definition	Description
Input	DE	Domestic extraction	Materials extracted domestically for further socio-economic use
	UDE	Unused domestic extraction	Materials that are moved by human activities but not used further
	DMI	Direct material input (DE + Import)	Materials entering domestic production and consumption processes
	TMR	Total material requirement (DMI + UDE + indirect material inputs)	All used and unused materials required globally for domestic production and consumption
Trade	PTB	Physical trade balance (import–export)	Measures net trade in physical terms (positive values = net imports; negative values = net exports)
	RME_{im} and RME_{ex}	Raw material equivalents of import and export (direct trade flows + upstream material use)	Measures all materials embodied in imports or exports
Output	DPO	Domestic processed output	Materials released to the domestic environment in the form of wastes, emissions, or purposeful output (e.g., fertilizer)
Consumption	DMC	Domestic material consumption (DE + PTB)	Materials used within the national economy (production perspective); equals the domestic waste potential; the indicator DMC per capita is also referred to as metabolic rate
	MF or RMC	Material footprint or raw material consumption ($\text{DE} + \text{RME}_{\text{im}} - \text{RME}_{\text{ex}}$)	Global material use associated to domestic final consumption (consumption perspective)
Stock	NAS	Net additions to stock	The yearly net growth of in-use stocks
	MS	Material stock	Materials accumulated in in-use stocks of artifacts, population, and livestock
Productivity	MP MI	Material productivity or resource productivity (e.g., GDP/DMC) Material intensity (e.g., DMC/GDP)	Value added produced per unit of domestic material consumption Material used per unit of GDP

often very large flows is still weak. This impairs the overall validity of MFA indicators rather than adding information. In contrast, accounting methods for direct flows are largely standardized, and data are considered robust for the majority of materials (16).

More recently, the debate has shifted toward the significance of a production versus consumption perspective in MFA. It has become obvious that leakage effects and burden shifting related to growing trade flows have an increasing impact on resource flow patterns. Measuring direct flows is not sufficient to capture these effects (63–65). Whereas direct flows measure the resources used in national production systems and the wastes and emissions occurring within a specific economy and under its direct control (often termed production perspective), RME or MF indicators measure resource flows associated with domestic final demand, regardless of where they occur (consumption perspective) (65–67). The debate around whether direct flow indicators or footprint-type indicators are more relevant for monitoring sustainable resource use and resource productivity links to issues of environmental responsibility and whether it should be allocated to producers or consumers or shared between the two (68, 69). Overall, the consumption and production perspectives provide complementary information and both perspectives are required to fully understand the dynamics of socio-metabolic patterns (70).

Indicators that relate material use to economic performance such as MP or its inverse, material intensity, have also gained significance and are widely used in policy documents concerned with sustainable resource use. MP has, however, been criticized as an indicator of progress toward more sustainable resource use and for setting targets as it obscures whether productivity gains actually lead to dematerialization of the economy and absolute reductions in material use (see Section 5).

2.4. Accounting Methods

Standard MFA accounts distinguish up to 70 material groups, which are usually aggregated to four main material groups: biomass, fossil energy carriers, metal ores, and nonmetallic minerals. Water is not accounted for in material flow accounts and, together with air, is only considered as a balancing item required for closing the material balance (e.g., changes in moisture content of materials, oxidization processes) (**Figure 2**). As much as possible material flow accounts make use of existing data from production statistics (agriculture and forestry statistics, energy statistics, mining statistics) and foreign trade statistics that provide robust data for most flows. However, several large flows not covered by statistics need to be estimated: the amount of biomass grazed by livestock using physical input data such as livestock numbers and roughage demand, used crop residues using harvest indices, gross metal ore production based on information on metal production and ore grades in mining, and natural aggregates used in construction activities based, e.g., on the production of concrete and asphalt (49).

Methods to account for used extraction and direct trade flows are internationally standardized (20, 47, 48). Unused extraction, e.g., overburden in mining and quarrying, soil excavation and soil erosion, can be estimated on the basis of LCA coefficients from a database maintained by the Wuppertal Institute (71) but are not internationally standardized. The output side of MFA has largely been neglected; methods to account for direct processed outputs of wastes and emissions in a way consistent with input flows and to actually close the material balance are less advanced (48).

Accounting for upstream material flows associated with traded commodities (RMEs) is enabled through three methods: LCA approaches, environmentally extended input-output models, and hybrid methods combining both (72–74). Most widely used are multiregional input-output (MRIO) models, which consistently allocate physical amounts of material extraction to products of final consumption using monetary information about the sectoral structure of economies and taking global processing chains and trade into account. These methods are data intensive and bear several problems related to the sectoral resolution of the models and how monetary inputs and outputs are linked to physical flows (70, 72, 75), but the databases and methods have greatly improved over the past few years. Several MRIO models have been made available that provide increasingly robust results (66, 70, 76–78).

3. THE GLOBAL METABOLIC TRANSITION

In an early seminal text, Fischer-Kowalski & Haberl (79) argue that social metabolism has undergone major changes during the course of human history. They distinguish three main socio-metabolic regimes: hunter-gatherers, agriculturalists, and industrial society. These regimes share certain fundamental characteristics in their society-nature interactions and their energy system and material use patterns. At least hunter-gatherers and agriculturalists have remained in dynamic equilibrium over long periods of time. When a socio-metabolic regime transcends its boundary conditions and key biophysical requirements, a new socio-metabolic regime emerges. Fischer-Kowalski & Haberl (80) refer to this as a socio-metabolic transition. Krausmann et al. (33) describe the metabolic profiles of these regimes in more detail and investigate long-term trends in energy and material use. They estimate that hunters and gatherers extracted less than a ton of material per year, almost exclusively biomass, to provide food and heat. A sedentary lifestyle and the use of livestock increases the material use of agrarian societies to an average of 3 to 6 tons/capita/year, with biomass still accounting for more than 95% of material use. In contrast, modern industrial societies use on average between 15 and 25 tons/capita/year and massively extract nonrenewable materials from the lithosphere, with biomass accounting for less than one-third of material use. Taking population development into account, this implies a growth in global material use from 0.003–0.006 Gt/year before the Neolithic Revolution to 1.8–3.6 Gt/year at the onset of the Industrial Revolution.

Several long-term MFA studies of key industrial economies including the United Kingdom (81), the United States (82), Japan (83), Spain (84), the Union of Soviet Socialist Republics (USSR) (85), and Czechoslovakia (86) have confirmed a typical trajectory from the biomass-based agrarian metabolic regime to the fossil- and mineral-based industrial regime. **Figure 3** shows material flow trajectories for the United Kingdom, the United States, Japan, and the USSR/Former Soviet Union (FSU). There are differences in the beginning of the transition but development synchronizes after World War II (WWII), and there is also no fundamental difference in the trajectory between market and planned economies. All industrial economies develop a similar profile of material use (34). During the transition, the share of biomass declined to less than 30%, whereas the share of stock-building materials and fossil energy increased and per capita material use multiplied. Growth was fastest in the two decades after WWII when mass production and consumption drove up average per capita material use. A particular sequence of events plays out in the expansion of infrastructure and built environment during industrialization. Building and maintaining in-use stocks of materials require large amounts of materials and energy, and—once in place—providing services such as shelter and mobility requires resources (87). In most cases the growth of direct

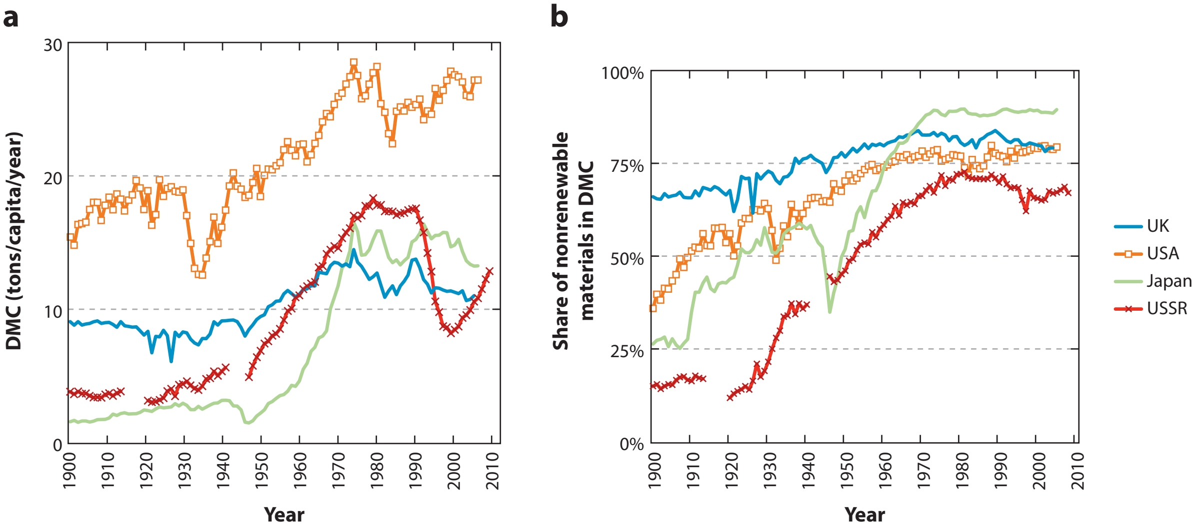

Figure 3

Long-term trends of domestic material consumption (DMC) in industrial countries: (*a*) Metabolic rate in DMC per capita population and year and (*b*) share of nonrenewable materials (fossil energy carriers, ores and nonmetallic minerals) in DMC. Adapted with permission from Reference 85.

material use slowed abruptly in the 1970s, in coincidence with the oil price shocks, and per capita direct material use stabilized at high levels (88).

Metabolic rate: domestic material consumption or domestic energy consumption per capita of population

Krausmann et al. (3, 33) have compiled a long-term time series of global material extraction and show that during the period of industrialization growth in global material use accelerated and increased from 3.7 Gt/year in 1850 to 7.1 Gt/year in 1900, to 14 Gt/year in 1950 to 70 Gt/year in 2010. Growth in material use was partly driven by population growth, which increased 6.5-fold in this period, but in particular in the second half of the twentieth century by rising income and consumption in the industrial world. In that period, the development in the industrial world drove up the average global metabolic rate (DMC/cap) from 5 tons/capita/year in 1945 to 8 tons/capita/year in 1973. Between 1973 and the late 1990s, the global metabolic rate was stable at ~8 tons/capita/year, but it increased again to 10 tons/capita/year in 2010, mainly driven by fast economic growth in China and other emerging economies (see Section 4). These long-term trends show that, at the global scale, a metabolic transition is in full swing as the largest part of the world population has not yet fully adopted an industrial mode of production and lifestyle and the associated metabolic profile. Although humanity has not fully accomplished the agrarian-industrial transition, these trends clearly demand the start of yet another transition to a more sustainable industrial metabolism at significantly lower per capita consumption levels. This requires fundamental changes to current production and consumption practices and the emergence of a new relationship between economic development, human well-being, and resource demand (see Section 5).

4. GLOBAL PATTERNS AND TRENDS OF MATERIAL USE ACROSS COUNTRIES

4.1. Global Material Use in 2010

Since material flow accounts were first published in the early 1990s, global material flows have been systematically investigated, leading to a comprehensive picture of global patterns and trends of material use. Several studies estimated global material extraction and arrived at a narrow range of 69–73 Gt for the year 2010 (3, 47, 89, 90). The most recent estimate derived from an MFA database maintained by UNEP (47), which we use here to present a brief account of global patterns of material use, arrives at 70 Gt/year or 10 tons/capita/year (**Table 2**). Renewable biomass accounts for roughly one-quarter of global extraction, and fossil energy carriers for one-fifth; the large remainder comprises ores and nonmetallic minerals. From a use perspective, 24% of all materials are used as food and feed, 21% provide technical energy, and a small fraction of 6% is other dissipative use, e.g., salt or fertilizer. The remainder, approximately half of all extracted materials, comprises raw materials required to build up and maintain manufactured capital (buildings, infrastructure, and machinery). A recent study estimated that global net additions to in-use stocks of materials amounted to 26 Gt/year in 2010, adding to a global stock of ~800 Gt (91).

The global extraction of materials is unevenly distributed across countries (175 countries, excluding small island states and countries with incomplete data). The 10 countries with the lowest DE per capita are mostly least developed and a few highly import-dependent countries; on average, they extract only 2.2 tons/capita/year. The decile with the highest DE extracts 60 tons/capita/year on average and comprises major raw material (in particular oil) exporting countries. Approximately 10 Gt of the 70 Gt of extracted materials are traded internationally; the export share is highest for fossil energy carriers (40%) and ores (35%), whereas much lower, but growing, for biomass (8%) and nonmetallic minerals (3%). This indicates large transfers of materials across countries. On a regional scale, the UNEP data reveal Europe, North America, and more recently also East

Table 2 The share of country groups in global material consumption (DMC) by main material groups, population, and gross domestic product (GDP; in purchasing power parities and constant 2011 international dollars) in 2010[a]

		Share in global total					
		Global total	Industrial countries	China	Former Soviet Union	Least developed countries	Rest of the world
Population	Billion head	7	16%	20%	4%	14%	46%
GDP	Trillion const. 2011 intern. $	90	48%	14%	5%	2%	31%
DMC biomass	Gt/year	19	22%	17%	5%	9%	46%
DMC fossils	Gt/year	13	41%	29%	8%	1%	21%
DMC minerals	Gt/year	38	23%	44%	3%	2%	28%
DMC total	Gt/year	70	26%	34%	5%	4%	32%
DMC total	tons/capita/year	10.0	15.9	17.3	11.5	2.6	6.8

[a] Data for DMC and population are provided by the United Nations Environment Programme material flow database (47), for GDP by The World Bank Group's 2017 World Development Indicators database (**http://databank.worldbank.org/data/reports.aspx?source = world-development-indicators**). Industrial countries include Europe, North America, Australia, New Zealand, Japan, and South Korea; least developed countries according to United Nations classification.

Asia as major net-importing regions, whereas all other world regions are net-exporting regions. Highest exports are observed for the Middle East, Australia, and the FSU.

Not only the extraction but also the consumption of materials varies widely across countries, although GDP is even more unevenly distributed (92). DMC in the lower and upper deciles amounts to 3 tons/capita/year and 32 tons/capita/year, respectively. Steinberger et al. (92) found that the differences in per capita DMC between countries can be explained to a large extent by differences in income (GDP/cap/year); in particular, the consumption of fossil and mineral materials is coupled to GDP. Biomass, in contrast, is more closely tied to population. Weisz et al. (93) have shown for the EU that even among countries with similar levels of income, considerable differences in per capita DMC can be found. Among the factors explaining these differences, population density, climate, trade dependency, and the structure of the economy have been discussed (92–95). Findings by Steger & Bleischwitz (96) indicate that construction activities and the size of infrastructure are important factors behind differences in material use, corroborating the significance of in-use stocks of materials in driving flows (97). The significance of individual factors differs by material group, but there is a tendency for countries with low population density and high resource extraction, cold climates, and high exports to have above-average DMC, whereas densely populated and import-dependent countries use less.

4.2. Material Use Trajectories

Several studies (47, 89, 90) have investigated the development of global material flows in world regions and by development status in recent decades. This research has confirmed that DMC in industrial countries increased in the decades after WWII but slowed down markedly in the 1970s and eventually stabilized at a high level, in particular in Europe and Japan. Wiedenhofer et al. (88) have termed this the 1970s syndrome. The underlying factors of this trajectory are not fully clear; a mix of drivers including the declining significance of industry, the rise of information and communication technology, saturation effects in consumption and efficiency gains, and increasing

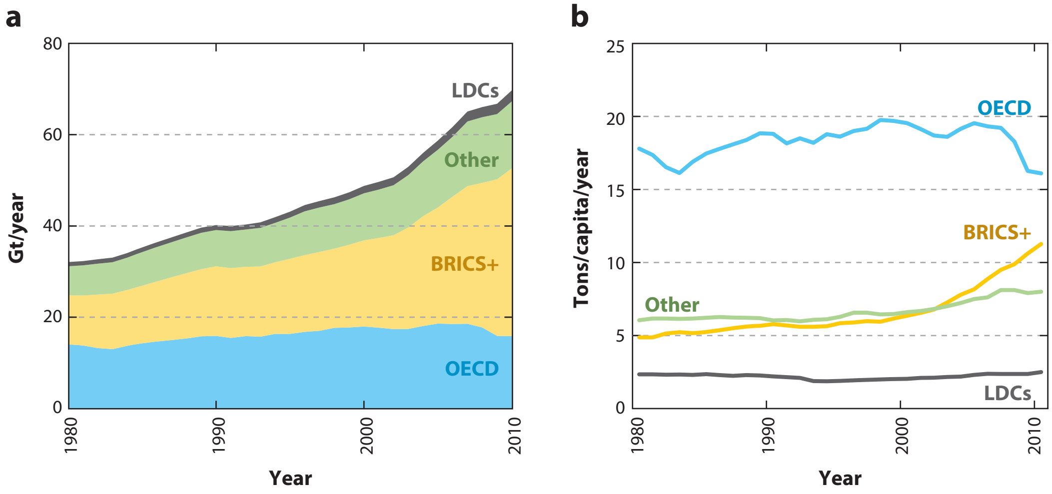

Figure 4

Global DMC by country groups in (*a*) Gt/year and (*b*) tons/capita/year. Figure adapted from Reference 89 (CC BY license), using data from Reference 47. Abbreviations: BRICS+, Brazil, USSR/FSU, India, China, South Africa, Mexico, South Korea, and Singapore; DMC, domestic material consumption; FSU, Former Soviet Union; LDCs, least developed countries (according to United Nations classification); OECD, Organisation for Economic Co-operation and Development (1980 member states); Other, all other countries; USSR, Union of Soviet Socialist Republics.

import dependency may have contributed. Giljum et al. (89) have shown that average per capita DMC in the OECD even declined in the aftermath of the economic crisis of 2008, although it remains to be seen whether this is a lasting improvement (**Figure 4**). Some countries such as Japan and the United Kingdom even show long-term reductions in direct material use, which has been attributed to deindustrialization or slow economic growth. MF studies have shown, however, that these signs of dematerialization in industrial countries at least partly disappear when upstream resource requirements are taken into account (67; see also Section 4.3).

In contrast, material use in a group of major emerging economies [the so-called BRICS+ (Brazil, USSR/FSU, India, China, South Africa, Mexico, South Korea, and Singapore) countries] has grown at an accelerated pace in the twenty-first century (**Figure 4**). These countries are increasingly driving global growth in material use. Metabolic rates in this group remained at a low level of ~5 tons/capita/year for several decades; in the 1990s, growth accelerated and DMC doubled from 5.8 to 11.3 tons/capita/year between 1995 and 2010 (**Figure 4*b***). A major driver of growth is the rapid expansion of the built environment (98), and the group is on a path toward developing a similar pattern of material use as the OECD countries, with high metabolic rates and a high shares of fossil and mineral materials. China is the country with the fastest growing material demand in this group; it almost tripled its per capita material use from 6 to 17 tons/capita/year between 1995 and 2010. Chinese material use has been growing at an even faster pace than its economy, lowering global MP (99, 100). Another interesting case in this group is the Russian Federation. It experienced a massive decline in DMC after the collapse of the USSR, but after a decade of restructuring the economy, DMC rapidly increased and Russia has evolved to be a major exporter of raw materials (e.g., fossil energy carriers and ores) (85, 101). The group of least developed countries (LDCs), mostly countries in Sub-Saharan Africa, shows little growth in material use at all (**Figure 4*b***). Their DMC has remained fairly constant at a very low level of 2.5 tons/capita/year with biomass accounting for 70 to 80%.

These developments resulted in a considerable shift in the geographic dominance of global material use. For most of the time since WWII, by far the largest share of materials has been consumed in high-income industrial countries, but China's growth in the twenty-first century has rapidly increased its significance in global material use. In 2010, China was home to 20% of the global population and had a share of 14% in global GDP but used 44% of all mineral materials and 29% of fossil materials (**Table 2**). The industrial countries (16% of the population and 48% of GDP) still used 41% of all fossil materials, and the LDCs, comprising 12% of the global population and 2% of GDP, used only 1% of fossil materials and 2% of all mineral materials. In contrast, the share of biomass use is more closely related to the population with China accounting for 17% and the industrial countries for 22% of global biomass use.

4.3. Trade and Material Footprints

Physical trade flows are growing more rapidly than material extraction. Schaffartzik et al. (90) have shown that global exports increased from 0.9 Gt/year in 1950 to 10.6 Gt/year in 2010. The share of exports in global DE more than doubled from 7% to 16%. MFA research indicates that trade does not necessarily lead to more equal distribution of materials across countries but rather shifts environmental burden (66, 102). Key materials for industrial development, in particular fossil energy carriers and metals, are concentrated through trade and consumed in a small part of the world at high metabolic rates (103). Material flow studies have found that in countries that export raw materials, large amounts of production wastes often accrue, while the economic benefit of the exports remains modest (104–106). The impact of trade on DMC has been impressively shown for Chile, the largest producer and exporter of copper (107). Of the 600 million tons of copper ore mined in Chile in 2010 only 3 million tons of metal concentrate and metal were exported. The large difference adds to Chile's DMC, leading to a DMC of 44 tons/capita/year of which 85% comprises mining waste.

Overall, the shift from industry to services in the industrial countries, high labor costs, and rigorous environmental standards result in externalizing resource-intensive industries to the Global South where raw materials are processed and "light" products are exported to meet the needs of high-tech industries and consumers in the industrial world. To assess the effects of burden shifting and to quantify material use associated with final consumption, RMEs of trade flows and MFs are calculated (**Table 1**), which reallocate resource extraction and use during production to the ultimate point of consumption. In recent years several global assessments have become available, providing robust results for MF indicators (63, 66, 67, 102). Research has shown that RMEs can be a multiple of direct trade flows (70, 102), but as all countries both import and export goods, the difference between DMC and MF is mostly smaller. In a seminal study, Wiedmann et al. (67) calculated MFs for individual countries for the period 1990 to 2008, and a recent UN report showed a similar analysis for the period 1990 to 2010 (47). These studies found that as economies mature, their MF becomes considerably larger than their DMC. The United Kingdom (see **Figure 5**) and also Japan, with their postindustrial structure and very high dependence on imports for final consumption, appear at the extreme end of the spectrum. While these countries are among the few that recorded significant reductions in DMC, including indirect flows in the account showed that their MF was actually growing. In contrast, large raw material exporters such as Australia, Russia, or South Africa had significantly smaller MF than DMC, whereas for many emerging economies, e.g., Brazil (**Figure 5**) and India, the difference was moderate. A systematic assessment (47) showed that between 1990 and 2010, the gap between MF and DMC widened in all world regions. In Europe and North America, DMC developed from 20% and 0%, respectively, to 40% above MF. In Africa the trajectory was inverse, with MF moving from 20% to 40% below DMC; in China,

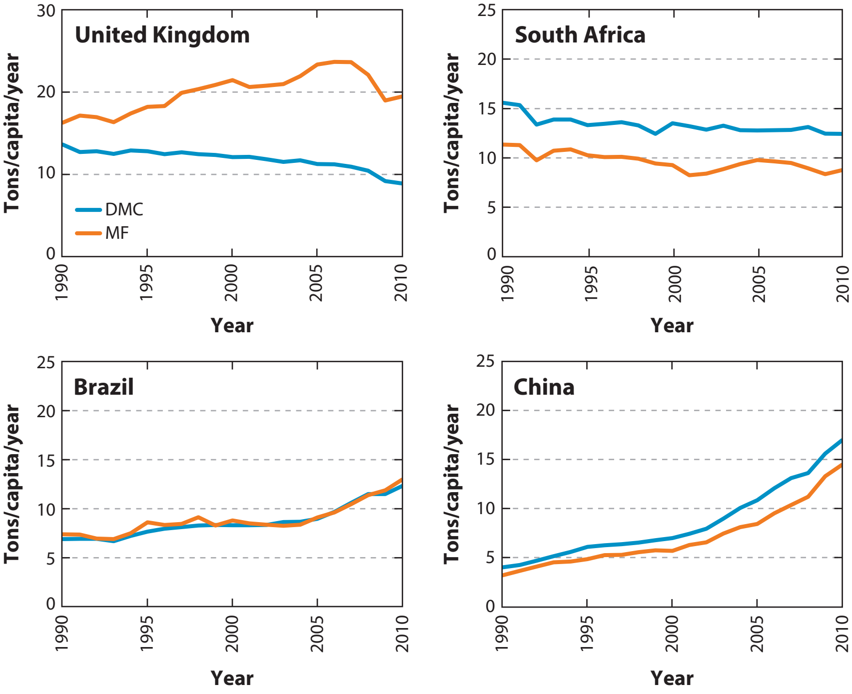

Figure 5

Domestic material consumption (DMC) and material footprint (MF) per capita population and year from 1990 to 2010 for selected countries. Source: Data are provided by the UNEP material flow database (47).

the country with the fastest growing DMC, MF was 20 to 25% lower than DMC. The rising differences between MF and DMC also have a significant impact on the interpretation of trends in resource productivity and decoupling of material use and economic development (47, 67).

5. MATERIAL USE, ECONOMIC GROWTH, AND DECOUPLING

The relation of material use and economic development was a focus of material flow studies early on (108–110). Research has shown that at the macrolevel growth in affluence (GDP/cap) is the main driver of growth in material use. To a lesser extent population growth also contributes to the growing use of materials, and efficiency gains, measured in terms of MP (GDP/DMC), often have a mitigating effect. The significance of these factors, however, varies by world region, development phase, and also by material type (47, 92, 100, 111).

At the global scale, the consumption of biomass has largely been growing with population, whereas the use of mineral and fossil materials has been growing more or less in unison with GDP. Taken together, this resulted in a continuous increase in global MP of roughly 0.85% per year over the twentieth century (3). This global trend obscures that countries in different phases of the metabolic transition (Section 3) exhibit different patterns of coupling of economic growth and material use. Long-term MFA studies show that during early phases of the transition material use grows at a similar pace or even faster than the economy; later, during industrial development, growth in material use slows down while GDP continues to grow (85). In a panel analysis across 40 countries, Steinberger et al. (112) found that over the longer term, emerging and developing countries tend to have significantly larger material-economic coupling than mature industrialized economies.

Breaking the strong coupling of economic growth and the use of natural resources and the production of waste and emissions is at the heart of concepts such as green growth (18) or smart growth (113). The hypothesis underlying these concepts is that it is possible to further expand economic activities, while at the same time reducing levels of resource use as well as negative environmental impacts resulting from resource use. This is often discussed under the notion of decoupling (114, 115).

Relative decoupling: signals that the material productivity of an economy is improving, but not necessarily that material use is declining in absolute terms

Absolute decoupling: when material use declines as GDP grows

It is vital to distinguish relative decoupling from absolute decoupling (116, 117). The former merely refers to an increase in MP of the economy, i.e., an increase in the economic output generated per unit of material input. Although relative decoupling signals an improvement in the resource efficiency of the economy, it does not necessarily imply that fewer materials are used. In contrast, absolute decoupling refers to a situation when material use declines in absolute terms, even as economic output grows. Whether a certain rate of MP improvement translates into relative or absolute decoupling therefore depends on its relation to the rate of economic growth: If the rate of economic growth is greater than the rate of improvements in MP, relative decoupling occurs. Only if MP increases faster than economic growth is absolute decoupling achieved.

There are different reasons why an economy might decouple its level of products and services from material input and the generation of waste and emissions. One simple reason is structural change, moving from resource-intensive low added value economic activities in agriculture and mining to less resource-intensive economic activities in the service sectors, which create higher added value. This shift in economic structure earns a country a free dividend of decreasing material and emissions intensity (118). Another important cause of decoupling is outsourcing of material, energy, and emissions-intensive processes to third countries, i.e., burden shifting. This is the path many high-income countries have taken over the past few decades. They have shifted from domestic production of goods to purchasing imported goods, with the upstream resources and emissions located in the countries where the export products are produced (67, 102).

Analyzing the worldwide trends in material use in relation to the development of global GDP reveals that relative decoupling was the norm throughout the twentieth century (47, 89, 119). Globally, material extraction and use increased by a factor of eight between 1900 and 2005, whereas GDP grew by more than a factor of 20 (3). However, in the twenty-first century this relative decoupling of the global economy has disappeared; MP began to deteriorate in 2002 and has since declined at an average rate of 1.3% per year (47, 120). Due to the rapid expansion of material extraction in many world regions, growth rates in extraction exceed those of global GDP. Currently, the world economy is therefore on a path of rematerialization and far away from even relative decoupling. The key reason is very rapid and large-scale industrial and urban transition in many countries in the Global South, and a shift in global economic activity from very resource-efficient countries and regions such as Japan and the EU to less efficient economies, particularly China and Southeast Asia. This development is characterized by rapidly growing per capita consumption levels and requires large amounts of materials and energy to build up housing, energy, and transport infrastructure in the emerging economies (98, 100, 112).

Empirical evidence for continuous absolute decoupling is rare. The only countries that have apparently achieved absolute decoupling of their material consumption from economic growth throughout longer phases are a few high-income importing economies such as Japan and the United Kingdom (99, 112, 121). Once their material consumption and intensity indicators are corrected for international trade, the success in decoupling, however, vanishes (66, 67). Despite the limited empirical evidence of successful decoupling of material use and economic growth, there is lively debate regarding the potential to accelerate decoupling. The literature features many examples of the potential to reduce resource use and emissions in major systems of provision including food and agriculture, construction and buildings, and transport and mobility (120). Scholars also identify ample potential for improving material efficiency in heavy industry, new materials, and new processes that may all underpin decoupling (122). Allwood et al. (123) emphasize that large opportunities for reducing material demand through material efficiency lie particularly in longer-lasting products, modularization and remanufacturing, component reuse, and designing products with less material requirements. Regarding the impacts on economic costs and growth potentials, the decoupling hypothesis claims that in the short term there are many cost-effective opportunities for greater resource efficiency that will offset, wholly or partially, any costs incurred in this decoupling (120, 124).

However, the decoupling hypothesis is subject to controversial debate. Critics argue that the efficiency gains required to offset continuous economic growth and expected population growth are impossible to achieve (125–127). Gains in resource efficiency may actually contribute to further economic growth and to lowering costs of primary resource inputs. This creates a rebound effect of lower prices resulting in overall higher use levels offsetting the resource-saving effects of efficiency gains (128–131). Also, the analysis of MFA data indicates that absolute dematerialization may not be compatible with high economic growth rates but rather occurs when the economy is in a steady state or growing at low rates (112). Therefore, many scholars doubt that absolute decoupling of economic growth from material use and environmental impact is possible at all and instead call for a far-reaching transformation of the economic system and a shift in focus from economic growth toward human well-being or prosperity (125, 132).

6. SCENARIOS OF FUTURE MATERIAL USE

Most studies of material use of economic activities have focused on representing historical trends at the national, regional, or global level. There is much less scientific evidence, however, for the amount of materials that will be required in the future. Whereas scenarios and projections for energy use and greenhouse gas (GHG) emissions have become a prominent feature in sustainability science (133), modeling of future material use is still in its infancy.

A modeling approach that has been used to investigate scenarios of future material use at the national level is macroeconomic models that describe the relationship between economic activity and natural resource use econometrically using historical data. A study for Germany found that resource efficiency policies could result in GDP growth, reduce public debt, and raise MP between 2005 and 2020. This would, however, only result in relative decoupling and not reduce the TMR of the German economy (134). An application of this model for the EU showed that a well-designed mix of micro policies to stimulate resource efficiency of companies and products and macro policies to limit rebound effects could achieve favorable outcomes for the economy and the environment (135). This study also found that stabilization of DE would be accompanied by growing imports of material-intensive products. A different macroeconomic model was employed to inform the European Commission's policy review on the economic implications of increased resource efficiency (136). The study found that ambitious improvements in resource productivity in the EU of 2% to 2.5% per year could be achieved in such a way that economic benefits from resource productivity would outweigh the investment costs of improving resource productivity and would yield absolute decoupling of GDP and raw material consumption (RMC).

A study using a physical stock and flow model framework developed a dematerialization scenario for the Australian economy, focusing on key material- and emission-intensive sectors and involving a series of policy strategies to reduce material and energy flows (137). In this scenario, Australian DMC would peak around 2030 at a high rate of 55 tons/capita/year and then decrease to levels slightly above the level of 2005 (35 tons/capita/year) in 2050. Energy use, however, would decrease to a much lesser extent because a reduction in material consumption creates a trade-off in energy use. The scenario also shows that trade and economic growth may continue, but at a reduced rate compared with the business-as-usual scenario.

A report of the International Resource Panel prepared a quasi-modeling approach for global material use, making assumptions on the development of metabolic rates for different types of countries (115). Assuming that industrial countries stabilize their per capita DMC at the level of the year 2000 and that all other countries catch up to this level by 2050, global material use would more than double and reach 140 Gt/year or 16 tons/capita/year in 2050. Halving metabolic rates in industrial countries and a global convergence at this lower level would still increase global DMC by 40% between 2000 and 2050. A more elaborate scenario analysis of future global material demand that combined an integrated assessment model (IAM) with a technology-based physical stock and flows model of the global economy projects even stronger growth in global material use (37). This study finds that in a business-as-usual case global material use could grow to ∼180 Gt/year or 20 tons/capita/year by 2050. Scenario calculations assuming increases in carbon pricing and high gains in resource efficiency, however, result in a 30% to 50% lower level of global material use compared to the business-as-usual case with only moderate reductions in economic growth.

The recent resource efficiency assessment of the Group of Seven (G7) leading economies also involves material consumption. The scenarios indicate economically attractive potential for resource efficiency and considerable cobenefits for climate mitigation in the G7 economies and globally (138). The authors show that the level and mix of economic and environmental benefits achieved would depend on the detail of policies and approaches implemented, and they argue that policymakers would need to develop and test a smart and practical package of resource efficiency measures. A scenario that combines resource efficiency and climate mitigation policies yields a 62% reduction in GHG in 2050 compared to 2015, which is commensurate with a 50% change to stay within 2°C of warming (139). The reduction of GHG emissions coincides with a 28% reduction in material use, compared to 180 Gt/year in a business-as-usual case, and global GDP growth would be 1% higher compared to existing trends.

In summary, existing scenario calculations find that in a business-as-usual path global and regional material use will grow beyond what can be considered a sustainable level of global material use (140, 141). The scenario calculations further indicate that a policy mix, i.e., a combination of natural resource pricing at source, carbon pricing, investments in resource efficiency, a demand shift from material-intensive sectors of production to less material-intensive sectors, and measures to minimize rebound effects could reduce material use and related environmental impacts compared to business-as-usual paths with only moderate impacts on economic growth. None of these scenarios show, however, an absolute reduction in material use, including in the wealthiest parts of the world.

7. APPLICATION IN POLICY

7.1. Sustainable Resource Use Policies in Japan, the European Union, and China

In the late 1990s, environmental policies shifted from a fairly narrow focus on pollution issues and the abatement of harmful substances toward a broader perspective of sustainable resource use.

This was supported by the promotion of the concept of SEM (142) and the establishment of the first material flow accounts (43).

Japan has been the frontrunner in the application of material flow indicators in policy development. In 2000, Japan instituted a high-level policy principle of a Sound Material-Cycle Society (143). Japanese policy was initially driven by a waste minimization objective but was extended to a life-cycle perspective on waste and material inputs under the 3Rs (reduce, reuse, and recycle) notion, which has also become influential internationally especially in the context of the G7 economies. Japan uses three MFA-related indicators to monitor success of its sustainable resource use policies: the material intensity of the national economy, the amount of waste that goes to landfill, and the recycling rate (143, 144). Using indicators measuring direct flows, Japan is on track to achieve its policy targets. However, MFA research indicates that the global impact of Japan's economy as measured by the MF has not been declining over the past two decades (67).

The EU also recognized the need for data and indicators on natural resource use to support policy development and promoted the establishment of an MFA framework in its environmental reporting system (19). In 2011 this led to a regulation that put MFA on the list of mandatory reporting for all EU member states. In 2005, the EU adopted a Thematic Strategy for the Sustainable Management of Natural Resources (**http://www.eea.europa.eu/policy-documents/thematic-strategy-on-the-sustainable**), driven by the need to enhance the resilience of the import-reliant European economy to price fluctuations and supply risks for strategic natural resources. In 2011 this was expanded by the implementation of the flagship initiative Resource-Efficient Europe (**http://ec.europa.eu/resource-efficient-europe/pdf/resource-efficient_europe_en.pdf**) and the corresponding Roadmap to a Resource-Efficient Europe (**http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011DC0571**), which aim to increase resource efficiency and decouple resource use from economic growth. In 2015, the EU adopted an Action Plan for the Circular Economy (**http://ec.europa.eu/environment/circular-economy/index_en.htm**), setting explicit targets for closing material loops and reducing waste flows. In its policy development the EU draws heavily on MFA data and uses MFA-derived headline indicators, among them the DMC and MP.

China has developed a comprehensive policy framework to address natural resource issues in its rapidly growing economy. The Circular Economy Promotion Law in force since 2009 (145, 146) seeks to change the model of economic growth and industrial development by radically increasing material efficiency and sharply reducing pollution discharges. CE principles are now mainstreamed into the Chinese Development Plan and coordinated with other policy frameworks such as, for instance, the Cleaner Production Promotion Law (147). Implementation barriers persist, however, including the speed at which current polluting industrial structures can be replaced, lack of funding, support for advanced technologies, a lack of environmental awareness in the public and private sectors, and the absence of effective enforcement mechanisms (148).

7.2. Challenges for Sustainable Resource Use Policies

Closing material loops in a CE is seen by policymakers and industry as a key strategy to reduce material demand and waste production (149). Although many examples of eco-industrial towns, eco-industrial parks and industrial symbiosis (150), and green buildings and transport infrastructure exist, there are also limitations for reuse and recycling posed by the characteristics of industrial metabolism. CE strategies typically focus on products and specific industries (18, 151), but systemic effects receive little attention. Haas et al. (152) have used an MFA approach to assess the circularity of the global economy. They highlight that only half of all materials used globally come into consideration for recycling, the remainder being used as food, feed, or for energy provision.

They found that in 2005, recycled materials contributed only 6% to global material inputs. They criticize that measurable criteria under which biotic resources can contribute to CE are largely absent. Also, the importance of long-lasting in-use stocks of materials for future material demand, waste production, and recycling has not yet been adequately considered in CE policies (91, 97). MFA should be advanced to provide better information and indicators for circularity on the macroscale (153).

All existing policy initiatives for resource efficiency and waste minimization are based on the premise that it is possible for economic growth to continue in industrialized countries and emerging and low-income economies while reducing both natural resource use and environmental impacts not only in relative but also absolute terms. However, evidence for absolute decoupling at the global level is minimal at best. Furthermore, the technological challenge of reducing material intensity at a rate fast enough to offset projected economic growth is heroic. Quantitative targets about reductions in material use are hardly ever defined; policies focus on improvements in MP rather than actual reductions in DMC or MF. One problem is that quantitative targets for aggregate material use are difficult to formulate (140, 141), and—in contrast to, e.g., greenhouse gas emissions, for which reduction targets have been negotiated internationally—agreement about a globally sustainable level of material use does not exist.

Although ample potential to increase MP and the circularity of the economy exists, changes in SEM are not easy to achieve. They will not happen spontaneously but will require well-designed policies to transition current systems of production and consumption to sustainable systems (123, 154; see also Section 5). There is evidence that although incremental policies are necessary for sustainable development, they may not be sufficient to manage a transition of the scope and scale required to steer the global economy within planetary limits (12). Transformational policies that fundamentally change incentives for businesses and households have been suggested. These include cap and trade systems for GHG emissions, green budget and tax reform, and phasing out subsidies for primary producers; they usually include compensation for low-income households, revenue neutrality and no-loser principles (114). These vital policy changes still operate within a green growth paradigm, and some scholars have asked for more fundamental social and institutional transformations that go beyond growth (125) while still maintaining high employment, lowering inequality, and reducing financial instability (155). Others have suggested a new global governance mechanism for natural resource use (156).

The new Sustainable Development Goals (SDGs) (157) represent a new level of commitment and ambition at the highest policy level to achieve human well-being while simultaneously acknowledging that achievements in human development for a large number of people necessitate more ambitious strategies to conserve natural resources, reduce waste and emissions, and ensure healthy ecosystems. The SDGs have three main targets that relate to the metabolic performance of a national economy. These are Target 8.4 resource productivity, Target 12.2 sustainable use of natural resources, and Target 12.5 waste reduction. With this, the SDGs put a strong focus on the underpinning roles of sustainable resource management, resource efficiency, and waste minimization achieved through more sustainable consumption and production (SCP) (158). They request ambitious policy responses on SCP to enable the successful implementation of the SDGs to achieve the desired development outcomes for a growing world population. The science of how to do this—and which policies may simultaneously achieve environmental and economic goals—is still in its infancy, however. The SDGs require a sound knowledge base, data, and indicators that allow the policy community to set targets and monitor and evaluate the effectiveness of their policies. This also demands further advancement of MFA tools to support this endeavor.

8. OUTLOOK

The transition to a new and more sustainable industrial metabolic regime with a substantially lower level of material use represents a major challenge for society. In recent decades, MFA research has contributed significantly to a better understanding of SEM, but it needs to be further advanced to support the development of transformation strategies, to develop targets and assess the impacts of policies, and to conduct forward-looking analysis. Here we highlight a few promising issues for further research.

In a recent volume on frontiers of industrial ecology, Pauliuk & Hertwich (36) emphasize the need for advanced models of the physical economy to conduct prospective studies of the next socio-metabolic transition. They argue that on the one hand, SEM principles and MFA knowledge should be better integrated into IAMs. This would improve the quality and policy relevance of resource scenarios created by these models, which currently lack detail and consistency with regard to material requirements, waste production, and recycling (159). On the other hand, novel types of models that build on and combine SEM methods such as MFA, LCA, and input-output analysis have been developed and hold great promise. In this context, MFA needs to be expanded to adequately take stock-flow dynamics into account. In dynamic material stock-flow models, the size of in-use stocks of materials and their lifetime distribution determine the demand for materials and energy and the production of wastes and emissions. This also requires more detailed consideration of the industries that build up, maintain, and dispose of these stocks in MFA. Although at the substance level stock-flow dynamics have been investigated for some time (160–162), this is fairly new in MFA research, which has so far focused mainly on flows. It is, however, increasingly recognized that in-use stocks of materials link flows of energy and materials to services such as shelter and mobility and that better knowledge of stock-flow dynamics is essential for dematerializing the economy (97, 152, 163). Consequently, more and more empirical studies investigating in-use stocks and stock-flow dynamics of materials are becoming available (87, 91, 164–166).

Moriguchi & Hashimoto (167) emphasize that the output side of the metabolic system has been neglected, reducing the explanatory utility of MFA for environmental impact assessment. In the context of waste management and closing material loops in CE strategies, advancements of MFA concerning the output side and the consistent integration of recycling flows are required (144, 167). The advancement of MFA toward an explicit consideration of stock-flow relations would also be beneficial as the size of in-use stocks and their lifetimes determine when and where waste materials become available for recycling or need to be disposed of (166).

Another important future research strand involves material flow and MF studies for economic sectors and product groups to bring the accounts closer to the system of national accounts. A recent study (168) illustrates that disaggregating the analysis of global material flows to the level of supply chains, economic sectors, and products allows for better connection with current policy debates. A focus on intermediate supply-chain structures for certain products or the analysis of single raw materials instead of aggregated material groups can create additional policy relevance and bring MFA closer to true satellite accounts of national accounting. Furthermore, most assessments of material use have focused on the national level and have been related to national policy issues. However, as some pilot studies illustrate (169, 170), environmental and social impacts of material use can vary significantly depending on the actual geographical location of the economic activity. Moving to spatially explicit assessments of material extraction and use could further strengthen links between MFA results and key regional and local sustainability debates such as deforestation, biodiversity loss, and water scarcity, as well as social issues such as land use conflicts or unequal regional development.

SUMMARY POINTS

1. Economy-wide material flow accounting (MFA) provides detailed mass balanced accounts of material flows into and out of socio-economic systems. MFA is consistent with the system of national accounts and offers standardized tools and indicators to monitor the physical economy.
2. Domestic material consumption (DMC) accounts for all materials consumed within the national economy (production perspective); material footprint (MF) indicators also include indirect flows of materials used to produce traded commodities and measure all materials embodied in final consumption (consumption perspective).
3. Global material consumption reached approximately 70 Gt/year or 10 tons/capita/year in 2010 and is growing. Differences in per capita material use across countries vary by an order of magnitude and range from 3 tons/capita in least developed countries (LDCs) to more than 30 tons/capita/year in resource exporting or high-income countries.
4. Trade in materials is growing faster than extraction and is related to burden shifting as material-intensive industries are relocated from industrial countries to the Global South. This contributes to a stabilization and even decline of direct material use in industrial countries.
5. Growth in global material consumption has accelerated in recent years and is expected to continue to grow as emerging economies build up stocks of buildings and infrastructure and develop industrial consumption patterns.
6. Material productivity (GDP/DMC) has been increasing in many industrial countries due to efficiency gains but also structural change and externalization of resource-intensive industries. Most countries, however, show only relative decoupling; that is, material use is growing but at a slower pace than the economy.
7. Global business-as-usual scenarios of future material demand project that world-wide material use will more than double until 2050, with unprecedented negative effects on the natural environment.
8. Scenario analyses indicate that the implementation of a well-designed mix of policies, including resource pricing, investments in resource efficiency, and demand shifts, could enable substantial economic growth while slowing down growth in global material use.

FUTURE ISSUES

1. Accounting methods need to be advanced to provide a comprehensive and consistent picture of all flows of materials through society including stocks and outflows of wastes and emissions to better support waste management and recycling policy.
2. Material flow accounting and derived indicators need to be expanded to consistently take secondary resource use (recycling and down-cycling) into account to provide comprehensive measures of circular economy (CE).

3. Global resource and environmental impacts must be met with stronger focus on regional and local actions, which require better understanding of socio-metabolic flows and their criticalities and uncertainties at different system scales.
4. Breaking down the analysis of global material flows to the level of supply chains, economic sectors, and products will allow the results to be better connected with ongoing policy debates.
5. There is a need to further improve global input-output-type models to trace flows of materials along global supply chains and to assess the environmental impacts of trade.
6. The role of in-use stocks of materials requires more attention in socio-economic metabolism (SEM) research. In-use stocks link material and energy throughputs to services and quality of life and, due to their long lifetimes, shape future flows.
7. Prospective modeling to conduct dynamic scenario analysis of future material flows needs to be advanced. This includes better integration of SEM principles into integrated assessment models (IAMs) to allow for more consistent and realistic scenarios of societies' future metabolism.
8. What are the potentials and limitations of sustainable resource use strategies such as CE, bio-economy, increasing material efficiency, and changes in the lifetime and intensity of the use of in-use stocks of materials to downsize social metabolism?

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RELATED RESOURCES

The United Nations Resource Panel publishes reports and assessments of important topics related to material flows (**http://www.unep.org/resourcepanel/**).

The United Nations Environment Programme maintains a global material flow database covering ∼200 countries, the time period 1970 to 2010, and direct and indirect flows (**https://uneplive.unep.org/material#.WjxRc_KnTVJ**).

Materialflows.net provides access to a comprehensive material flow database and data visualization tools and covers more than 200 countries, the time period of 1980 to 2013, and more than 300 different materials aggregated into 12 categories of material flows (**http://www.materialflows.net/home/**).

The Institute of Social Ecology's material flow database provides long-term series of material use for individual countries and globally (**https://www.aau.at/soziale-oekologie/data-download/**).

The European Statistical Office provides guidelines and tools for material flow accounting (**http://ec.europa.eu/eurostat/web/environment/methodology**) and detailed MFA data for European countries (**http://ec.europa.eu/eurostat/web/environment/material-flows-and-resource-productivity/database**).

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