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4 authors:

Fridolin Krausmann
BOKU University

Christian Lauk
BOKU University

Willi Haas
BOKU University

Dominik Wiedenhofer
BOKU University

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From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015

Fridolin Krausmann*, Christian Lauk, Willi Haas, Dominik Wiedenhofer

Institute of Social Ecology (SEC), Department of Economics and Social Sciences, University of Natural Resources and Life Sciences, Vienna, Schottenfeldgasse 29, 1070 Wien, Austria

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A B S T R A C T

The size and structure of the socioeconomic metabolism are key for the planet's sustainability. In this article, we provide a consistent assessment of the development of material flows through the global economy in the period 1900–2015 using material flow accounting in combination with results from dynamic stock-flow modelling. Based on this approach, we can trace materials from extraction to their use, their accumulation in in-use stocks and finally to outflows of wastes and emissions and provide a comprehensive picture of the evolution of societies metabolism during global industrialization. This enables outlooks on inflows and outflows, which environmental policy makers require for pursuing strategies towards a more sustainable resource use.

Over the whole time period, we observe a growth in global material extraction by a factor of 12 to 89 Gt/yr. A shift from materials for dissipative use to stock building materials resulted in a massive increase of in-use stocks of materials to 961 Gt in 2015. Since materials increasingly accumulate in stocks, outflows of wastes are growing at a slower pace than inputs. In 2015, outflows amounted to 58 Gt/yr, of which 35% were solid wastes and 25% emissions, the reminder being excrements, dissipative use and water vapor. Our results indicate a significant acceleration of global material flows since the beginning of the 21st century. We show that this acceleration, which took off in 2002, was not a short-term phenomenon but continues since more than a decade. Between 2002 and 2015, global material extraction increased by 53% in spite of the 2008 economic crisis.

Based on detailed data on material stocks and flows and information on their long-term historic development, we make a rough estimate of what a global convergence of metabolic patterns at the current level in industrialized countries paired with a continuation of past efficiency gains might imply for global material demand. We find that in such a scenario until 2050 average global metabolic rates double to 22 t/cap/yr and material extraction increases to around 218 Gt/yr. Overall the analysis indicates a grand challenge calling for urgent action, fostering a continuous and considerable reduction of material flows to acceptable levels.

1. Introduction

Global population growth, industrialization and rising levels of consumption have driven the demand for material resources and resulted in fundamental changes in the global socioeconomic metabolism (Krausmann et al., 2016). The global extraction (DE) of fossil and mineral materials as well as of biomass has multiplied in the 20th century (Krausmann et al., 2009). The environmental pressure arising from the extraction of these materials and from their discard after processing and use is threatening global sustainability (Steffen et al., 2015; Wackernagel et al., 2002). Results of recent material flow studies indicate that after a period of slowed physical growth in the 1970s and 1980s, during which global material demand rose by and large with population but much slower than GDP, growth of global DE accelerated at the beginning of the 21st century (Schandl et al., 2017).

Economy-wide material flow accounting (MFA) provides a toolbox to investigate the flow of material resources through economic systems and indicators to measure the size and structure of the socioeconomic metabolism (Fischer-Kowalski et al., 2011; Krausmann et al., 2017a). MFA is a mass balanced approach which allows consistently linking flows of materials into and out of a socioeconomic system. It is widely used in sustainability science to investigate biophysical characteristics of economic systems and in environmental policy to monitor and guide progress towards a more sustainable use of resources (Bringezu et al., 2009; Hashimoto and Moriguchi, 2004). So far, both at the national and global scale, MFA has mainly been used to assess the extraction of and trade with materials and to calculate indicators such as material consumption (DMC) and material productivity (Fischer-Kowalski et al.,

* Corresponding author.
E-mail address: Fridolin.krausmann@boku.ac.at (F. Krausmann).

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2011). Several recent studies have investigated the development of global material extraction in the last decades. A first global assessment of the long term development of global DE was published by Krausmann et al. (2009) covering the period 1900–2005; Giljum et al. (2014) presented an analysis of global material consumption and resource productivity for the period 1980–2009; Schaffartzik et al. (2014) analyzed the evolution of global material flows for world regions between 1950 and 2010 and most recently Schandl et al. (2017) discussed direct material flows and material footprints for country groups from 1970/90 to 2010 on the basis of a new MFA database provided by UNEP (2016). Only few studies have attempted to provide a mass balanced picture of both input and output flows of national economies; noteworthy exceptions are the seminal studies published by the World Resources Institute (Matthews et al., 2000) and more recently of Ščasný et al. (2003) and Haas et al. (2015). Among the reasons why only few studies have attempted to close the material balance is that data on output flows are fragmentary and the system boundaries applied in waste and emissions statistics are not fully consistent with those applied in MFA. Closing the material balance is therefore difficult to achieve on the basis of statistical data on wastes and emissions alone, but requires consistent stock-flow modelling taking material accumulation within socioeconomic systems (net additions to stock, NAS) into account. MFA methods to quantify NAS and output flows are still in their infancy (Eurostat, 2013; Moriguchi and Hashimoto, 2016) and far from the level of standardization that has been achieved for DE and trade flows.

While MFA claims to link material inputs to outputs in a mass balanced way, this strength so far has rarely been exploited. Here we present an innovative approach that traces global material flows from extraction and use to the outflow of wastes and emissions, using the MFA framework combined with dynamic stock-flow modelling. We significantly expand the perspective of previous research which has focused on global extraction of materials and for the first time also include in-use stocks of materials, net additions to stock and output flows in a systemic and consistent way into one account. In addition to the traditional classification of material flows by material characteristics we show data by a typology of material use distinguishing e.g., food and feed, materials used to provide technical energy or to build up stocks of manufactured capital. We quantify net additions to stock (NAS) and domestic processed output (DPO) and present an expanded and updated estimate of global stocks of manufactured capital, humans and livestock. Finally, we demonstrate, how this approach can be used to develop novel stock-driven scenarios of future material use. All results can be download at: *https://www.wiso.boku.ac.at/sec/data-download/*.

In the next section we briefly introduce the methodological approach and the data sources we used. We then present the results for DE, the development of stocks, NAS and DPO. We discuss how the size and composition of material inputs, use and outputs has developed since 1900 with a focus on the most recent developments in the 21st century. Based on the stock-flow relations revealed by our approach and long term trends in material use we finally develop a scenario how global material use might evolve until 2050, assuming convergence of per capita in-use stocks of materials at the level currently prevailing in industrialized countries and continuation of past efficiency gains and discuss the implications for sustainable development.

2. Methods and data

2.1. Material flow accounting framework

Fig. 1 depicts the system boundaries and the stocks and flows relevant for accounting of global material flows in this study; Table 1 provides a brief nomenclature of MFA parameters. Closing the material balance requires opening the black-box of the MFA framework and shifting from a perspective of material properties towards a rough typology of material uses. Following MFA conventions, we consider three

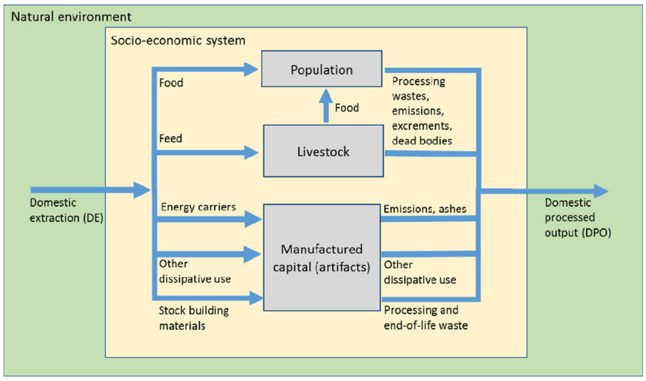

Fig. 1. Material flow accounting (MFA): System boundaries, stocks (grey boxes) and flows (blue arrows) as considered in the global analysis of material flows. Balancing flows (oxygen and water) are not shown (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1
Nomenclature of main parameters of material flow accounting (MFA) used in this study.

MFA parameter	Definition
DE	Used extraction of materials (excluding water and air). At the global scale, in the absence of imports and exports, extraction equals apparent material consumption (DMC) and the sum of NAS and DPO*.
Stocks	Physical structures of society: humans, livestock and manufactured capital
Manufactured capital	All in-use artifacts (buildings, infrastructures, durable goods)
NAS	Net additions to stock; year to year change of stocks
DPO	Domestic processed output of wastes and emissions including deliberately applied materials (e.g., fertilizers)
DPO*	DPO excluding balancing flows of oxygen and water, i.e., the fraction of DPO actually contained in DE
Balancing flows	Oxygen taken up during combustion and respiration and water uptake by humans and livestock.
Metabolic rate	Material consumption per capita of population
Material intensity	Material consumption per unit of GDP

types of physical structures of society (termed stocks): Humans, livestock and manufactured capital (i.e., all in-use artifacts). MFA accounts for all materials (excluding water and air) that are extracted to produce or reproduce these stocks or to provide services from them (Fischer-Kowalski et al., 2011). On the input side we distinguish materials by their material properties and further allocate these flows to five major use types (Fig. 1): We distinguish primary materials destined to be used as feed for livestock, as food for humans, to generate technical energy, for other dissipative use (e.g., seed, fertilizer minerals, salt) and to build up and renew stocks of manufactured capital. Technical energy carriers and materials for other dissipative use are considered to flow through stocks of manufactured capital where they are converted and provide services, but they do not add to stocks. Net additions to stock (NAS) denote the material flow that corresponds to the year to year change of stocks. Domestic processed output (DPO) comprises all materials that leave the system as wastes and emissions or as deliberate applications to the environment (e.g., fertilizers). In the case of the global system, no import and export flows have to be taken into account, the extraction of materials (DE) equals material consumption (DMC). DMC equals the sum of NAS and DPO. In order to close the material balance also oxygen uptake (e.g., through combustion, respiration) and water (e.g., changes in water content of materials, water uptake by humans and livestock) have to be taken into account as “balancing flows”. In this study we present DE by material group and use type, stocks and NAS by stock type and DPO by gateway or type. We propose a novel combination of accounting, mass balance based estimation procedures and top down stock-flow modelling to advance the traditional MFA framework and to quantify all stocks and flows of materials.

2.2. Material extraction and use

We updated the existing global DE series (Krausmann et al., 2009) which distinguishes around 150 materials or material groups which are aggregated to four main groups: biomass, fossil energy carriers, ores and non-metallic minerals. We used the data sources and estimation procedures described in detail in Krausmann et al. (2009) to update the series to 2015, the most recent year for which all primary data were available. We made several methodological improvements: the most significant adjustment was the inclusion of additional sand and gravel used as subbase and base-course layer for roads and buildings in order to reduce the systematic underestimation of DE of sand and gravel in material flow accounts. Most available MFA studies only take sand and gravel for concrete and asphalt production into account and therefore underestimate the actual use of sand and gravel for construction (Miatto et al., 2016). Based on coefficients derived from Miatto et al. (2016) and assumptions on the use of downcycled construction and demolition waste used as substitute for primary materials (Krausmann et al., 2017b) we quantified the amount of additional sand and gravel extracted from the environment. This results in a flow of natural aggregates of 6 Gt/yr or 7% of total DE in 2015 (Fig. S1). Other improvements were estimates of the raw materials extracted for the production of bricks (clay) and of glass (silica sand, potash), which are not or only fragmentarily reported in statistical sources (see SI).

Extracted materials were allocated to the five types of material use distinguished in Fig. 1 and in Table 2. The allocation of materials from the MFA database to these use categories was made on the basis of information from production and industry statistics, mainly FAOSTAT commodity balances (FAO, 2017), IEA and UN energy statistics and balances (IEA, 2016; UNSD, 2013); USGS mineral statistics (Kelly and Matos, 2017) and previous work on material use (e.g. Krausmann et al., 2008a,b). Table 2 provides an overview of the definitions of material use types and the used sources.

2.3. Stocks

We distinguish three types of stock (Fig.1): Manufactured capital (i.e., all in-use artifacts), livestock and humans. The material use database provides the main input data for the Material Input Stocks and Output (MISO) model (Krausmann et al., 2017b) used to quantify materials accumulated in stocks of manufactured capital, the corresponding NAS and outflows of waste from processing of stock building materials as well as from discarded stocks at the end of their service life time. The MISO model is a top-down, dynamic stock flow model (Müller et al., 2014). The model and the assumptions made on losses, lifetime distribution and recycling rates are described in detail in Krausmann et al. (2017b). We expanded the model to also include glass and updated the model input data to 2015 (the original study covered 1900–2010). The model now distinguishes 13 types of in-use stocks of materials and the corresponding flows: Paper, timber, plastics, steel, copper, aluminum, all other metals, concrete, asphalt, bricks, container glass, flat glass and natural aggregates. We further expanded the stock estimate by including humans and livestock. To estimate these stocks we used population and livestock numbers sourced from UN-DESA (2017), Maddison (2013), FAO (2017), data collections of the IIA (e.g., 1922) and assumptions on average live-weight (see SI). NAS were calculated from the difference between stocks in consecutive years.

2.4. Domestic processed output

DPO comprises all outflows of solid and liquid wastes and emissions as well as deliberate material applications to the environment. We distinguish five DPO flows: Processing (and manufacturing) waste (incl. tailings and ashes), end of life waste (after recycling), excrements (from humans and livestock), emissions (from human and livestock metabolism and thermal energy generation), other dissipative use and water vapor. Table 3 provides an overview of the different types of output flows that result from the five material use types distinguished in this study and their allocation to DPO flows. In deviation from MFA conventions we also accounted for waste deposited in controlled landfills and excrements treated in sewage plant as DPO. We used statistical data, model results and stoichiometry to quantify the DPO flows and to close the mass balance of the material flow account.

Outflows from livestock and humans comprise excrements, CO_2 and CH_4 emissions and water vapor. They are estimated on the basis of a physiological model of the metabolism of humans and livestock that takes digestibility and stoichiometry into account and consistently relates the intake of food and feed to outflows. Wastes and losses from the production and distribution of agricultural products as well as food wastes from households were estimated on the basis of waste data from FAOSTAT (FAO, 2017) and coefficients derived from Alexander et al. (2017). Outflows from thermal combustion of technical energy carriers (fossils and biomass) comprise emissions as well as ashes and water vapor. We distinguish three main types of emissions: CO_2, SO_2 and N_2O. We used information on the chemical composition of the reactants in fuels and estimated the different outflows as combustion products by using stoichiometric equations. Details on the calculation of DPO flows from humans, livestock and energy production are provided in the SI. Waste flows related to the production and discard of manufactured capital are results from the MISO model and calculated on the basis of inputs of primary and secondary stock-building materials, material- and time-specific lifetime distributions, as well as on assumptions on

Table 2
Materials by use type. Definitions and main sources used to allocate DE to use types.

Material use flow	Composition	Main source
Food	Crops or parts of crops used to produce food for human consumption. Food products from livestock production are considered an internal flow. They are not part of domestic extraction but a flow from livestock to population.	FAOSTAT commodity balance (FAO, 2017)
Feed	Crops or parts of crops used to feed livestock (market feed); forage crops (e.g. hay, silage); crop residues used as feed; grazed biomass.	FAOSTAT commodity balance (FAO, 2017); global feed balance (Krausmann et al., 2013)
Technical energy	All fossil energy carriers (coal, oil, natural gas) used for energy generation; wood fuel and crops for biofuel production.	FAO, 2017; IEA, 2016
Other dissipative use	A small flow comprising a broad range of materials including seed, crop residues used for bedding, fossil materials used as feedstock in the petrochemical industry (excluding stock-building materials such as plastics and bitumen), fertilizer minerals, salt and other non-metallic minerals excluding stock-building minerals.	FAOSTAT commodity balance (FAO, 2017), USGS (Kelly and Matos, 2017), own calculations
Stock-building materials	Industrial wood, ores, sand and gravel, raw materials to produce plastics, bricks, glass, concrete and asphalt.	See Krausmann et al. (2017b)

Table 3
Overview of output flows related to the different types of material use, estimation procedures and allocation to domestic processed output flows (DPO). See SI for details.

Material use	Outflow	Estimation procedure	DPO
Food/population	-Food waste (production, processing and household waste)	-Calculation based on Alexander et al., 2017; FAO, 2017	-Processing
	-CO_2 from respiration	-Digestibility, metabolic reactions	-Emissions
	-Excrements (solid and liquid)	-Digestibility, metabolic reactions	-Excrements
	-Water vapor	-Moisture content change, respiration	-Vapor
	-Dead bodies	-Mortality rate (UN-DESA, 2017)	-End of life
Feed/livestock	-Feed waste	-Not considered (demand based feed estimate)	-
	-CO_2 and CH_4 from respiration and methanogenesis	-Digestibility, metabolic reactions, CH_4 emissions from FAO, 2017	-Emissions
	-Excrements (solid and liquid)	-Digestibility, metabolic reactions	-Excrements
	-Water vapor	-Moisture content change, respiration	-Vapor
Technical energy	-CO_2, SO_2 and N_2O from fossil energy carriers	-Mass balanced stoichiometric calculation based on material composition and assumptions on combustion technology	-Emissions
	-Ashes and soot from fossil energy carriers	-Mass balanced stoichiometric calculation based on material composition and assumptions on combustion technology	-Processing
	-CO_2 SO_2 and N_2O from biomass	-See fossil energy carriers	-Emissions
	-Ashes and soot from biomass	-See fossil energy carriers	-Processing
	-Water vapor from fossils and biomass	-Moisture content of energy carriers plus oxidized hydrogen based on stoichiometry	-Vapor
Stock building material/ manufactured capital	-Tailings from ore processing	-MFA database (ore grades)	-Processing
	-CO_2 from calcination (cement)	-Stoichiometric relations	-Emissions
	-Water vapor (brick production)	-Moisture content of clay	-Vapor
	-Wastage and losses from processing/manufacturing of wood, metals, plastics, glass, concrete and asphalt	-MISO model (Krausmann et al., 2017b)	-Processing
	-Discarded (end of life) stock (incl. hibernating stocks), after subtraction of re- and downcycled material	-MISO model (Krausmann et al., 2017b)	-End of life
Other dissipative use	-Deliberate application, dissipative loss/unknown use	-Input = Output	-Dissipative use

processing and manufacturing losses and recycling rates. The MISO model and the used data and assumptions are described in detail in Krausmann et al. (2017b). Processing waste includes all losses during the processing of primary and secondary materials used to produce manufactured capital (including tailings from ore processing) as calculated by the MISO model; end of life waste comprises solid waste from discarded stocks, including hibernating stocks (i.e. stocks which are not demolished but remain in place after the end of their service life time). For other dissipative use we simply assumed that inputs equal outputs. Due to lack of quantitative data, combustion of waste material for energy generation (incineration) has not been considered; this results in slight overestimation of waste flows and an underestimation of emissions. Assuming that 50% of all plastic and wood/paper waste in 2015 (0.48 Gt/yr) was incinerated would reduce end of life waste after recycling by 2% and increase emissions by 1.6%.

Closing the material balance requires to take balancing flows into account. These comprise oxygen input in thermal combustion and respiration and contained e.g. in CO_2 emissions and to water taken up by humans and livestock and contained in excrements. Balancing flows are large and account for around 50% of total DPO. Hence, we present DPO in two variants: DPO refers to the actual mass of outflows e.g., CO_2 or excrements at 75–85% moisture content; DPO* refers to the part of DPO that actually originates from DE inputs e.g., C contained in CO_2 or excrements at the water content of food and feed inputs.

2.5. Treatment of uncertainties

To assess the robustness of our results we conducted uncertainty analysis for key components of the material flow system based on literature and informed assumptions. We estimated uncertainty for global DE, derived from maximum upper and lower assumptions on the uncertainty of model input data and coefficients used in estimation procedures. For in-use stocks of manufactured capital and DPO from discarded stocks we utilize uncertainty information based on systematic error propagation via Monte Carlo Simulations developed in previous work (Krausmann et al., 2017b). Additionally, we conducted a sensitivity analysis for stocks of manufactured capital evaluating the effect of systematic changes to lifetime distributions. For DPO flows from energetic use and other dissipative use no specific uncertainty analysis was conducted. We assumed that uncertainties are similar to the corresponding input flows. Details are shown in the SI.

3. Results

3.1. Material extraction

Fig. 2a shows the increase of global DE since 1900. Over the 115-year period observed, DE multiplied by a factor 12 and by 2015 had reached 89 Gt/yr (or 82 Gt/yr if additional sand and gravel used for subbase and base-course layers is excluded; see Fig. S1). The long term evolution of global material extraction in the 20th century has been discussed in detail in Krausmann et al. (2009); here we focus on the more recent developments. Fig. 2a indicates that growth in global DE has been accelerating since 2002. A comparison of growth rates during different periods of industrial development (Table 4) reveals that after the post-World War II (WWII) period of rapid industrialization (1945–1972) with annual growth rates of DE of 3.7%, growth in material use slowed down markedly to only 1.8%/yr between 1973 and 2002. Only after 2002, growth accelerated to an average of 3.3%/yr until 2015. The acceleration can be observed for all four material groups, biomass and ores even show higher growth rates than in the 1950s and 1960s. Also the metabolic rate (DE per capita of population) is growing faster than in the post-WWII period at 2.1% per year and rose from 9.3 to 12.1 t/cap/yr between 2002 and 2015 (Fig. 3). From 2014 to 2015 global DE remained stable and per capita rates even declined.

In the period since 2002, after several decades during which the global economy grew considerably faster than material extraction, relative decoupling of economic growth and material use stalled. From 1945 to 2002 material intensity (MI; DE/GDP) declined at an annual rate of -0.9% from 2.5 to 1.5 kg/$ (Fig. 3). Between 2002 and 2015 MI remained rather stable, fluctuating around 1.5 kg/$; only in the last two

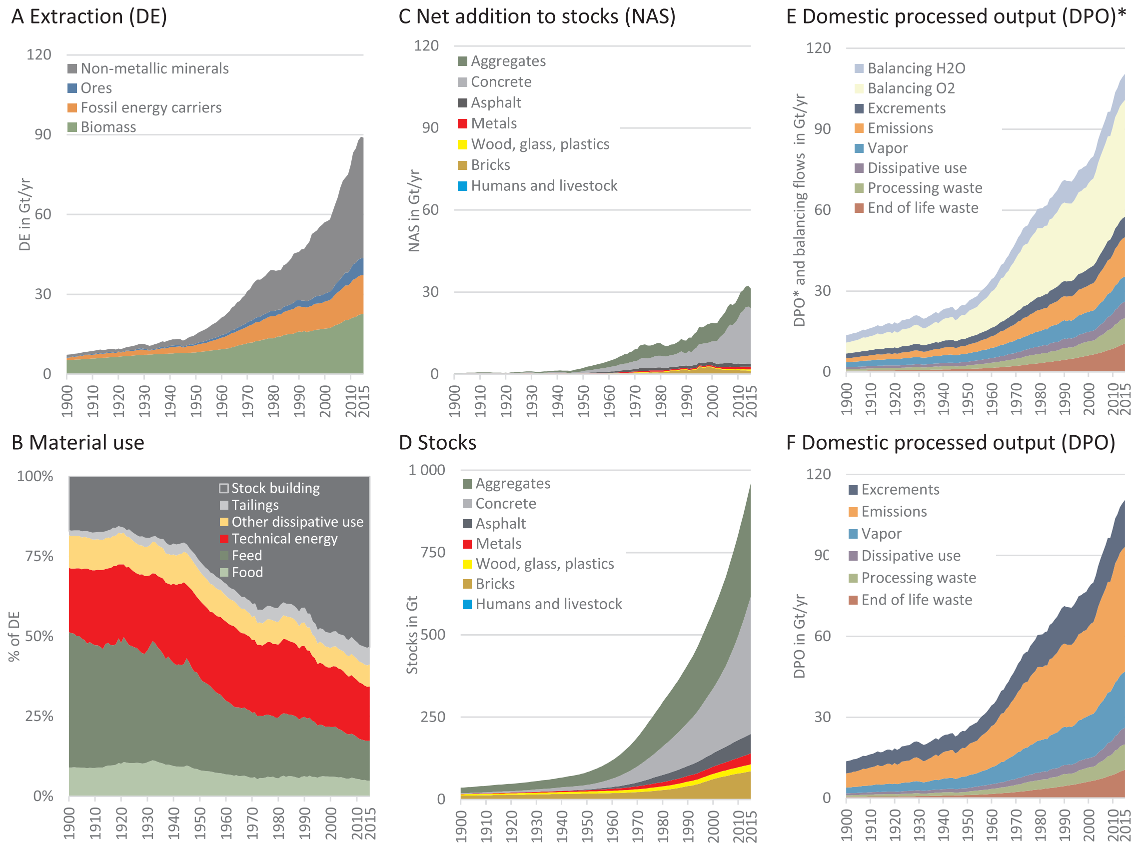

Fig. 2. Global material flows in Gt/yr and stocks in Gt from 1900 to 2015. A: material extraction by main material group; B: share of major use types in total extraction; C: yearly net additions to stock (NAS); D: stocks of humans, livestock and manufactured capital in Gt; E: the fraction of domestic processed output that actually originates from DE (DPO*) separate from balancing oxygen and water F: DPO by main type including balancing oxygen and water.

years it declined again. When measuring MI in terms of real GDP (at constant prices of 2011) instead of purchasing power parities (Fig. S5), we even observe a considerable increase in MI (0.4%/yr) in the last 13 years.

3.2. Material use

In Fig. 2b we show global material extraction by main use types. On a very principal level we can distinguish two main types of material use: Firstly, materials that are used in a dissipative way, that is, they are consumed typically within a year after extraction. This use type comprises materials that are used as food for humans or feed for livestock, as technical energy carriers for thermal conversion (fossil and biomass materials) and other dissipative use (e.g. salt or fertilizer materials, lubricants). Secondly, materials which accumulate in in-use stocks of manufactured capital, such as in infrastructures, buildings, machinery or other durable goods. These materials typically remain within the system for more than a year up to several decades or more. We denote these materials as stock-building materials which are used either for building up or renewal of stocks of manufactured capital. Fig. 2b shows that in the early 20th century the largest share of all extracted materials has been used in a dissipative way. In 1900 these were 6 Gt/yr or 72% of DE. Feed for livestock, mainly grazed biomass, accounted for the largest share, followed by energy carriers, food and other dissipative use. The share of materials used in a dissipative way continuously declined and since 1993 stock-building materials dominate the global socioeconomic metabolism. Until 2015 their share in global DE rose to 59% or 52 Gt/yr; however, roughly 9% of these stock building materials (4.8 Gt/yr) are discarded shortly after extraction as tailings from ore processing (Fig.2b). In 2015 the fraction of dissipative use had diminished to 41% of global DE: A material flow of 15.1 Gt/yr was used to provide technical energy, 11.1 Gt/yr were used to feed animals and 4.3 Gt/yr to produce plant based food for humans; other dissipative use amounted to 6.1 Gt/yr, the largest part being utilized in agriculture, e.g., crop residues used as bedding material, seeds and mineral materials used as fertilizers. Per capita of population on average 0.6 t of primary raw materials were used to provide food, 1.5 tons to feed livestock, 2 tons to provide energy, 0.9 t for other dissipative use and 7.1 tons as primary inputs to stocks in 2015 (Table 5). In 1900 the corresponding per capita flows were 0.4 t of food, 2 tons of feed,

Table 4
Average yearly growth rates of material extraction (DE) of main material groups, metabolic rate (DE/cap), material intensity (DE/GDP) and domestic processed output (DPO*) for the periods 1900–1945, 1945–1973, 1973–2002, 2002-2015. GDP in international $ at constant prices of 1990, sourced from Maddison (2013) and the World Bank (2017).

	DE Biomass	DE Fossils	DE Ores	DE Minerals	DE Total	DE/cap	DE/GDP	DPO*
1900-1945	0.9%	1.7%	2.1%	2.1%	1.2%	0.3%	−0.9%	1.2%
1945-1973	1.6%	4.5%	5.5%	6.7%	3.7%	2.0%	−0.5%	2.7%
1973-2002	1.2%	1.4%	2.1%	2.4%	1.8%	0.1%	−1.3%	1.7%
2002-2015	2.1%	2.6%	5.7%	4.0%	3.3%	2.1%	−0.5%	3.0%

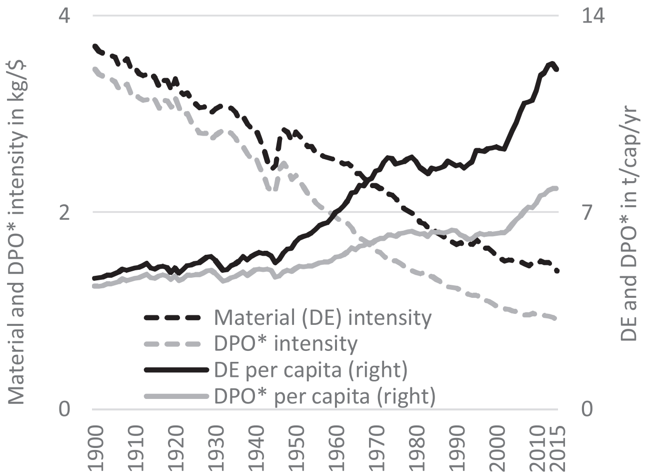

Fig. 3. Development of material extraction (DE) and domestic processed output (DPO*) per capita (right axis) and per GDP (left axis) from 1900 to 2015. GDP in international $ at constant prices of 1990, sourced from Maddison (2013) and The World Bank (2017).

Table 5
Domestic extraction in t per capita and year by material use type in 1900, 1950, 1973, 2002 and 2015.

	Food	Feed	Technical energy	Other dissipative use	Stock building
1900	0.4	2.0	0.9	0.5	0.9
1950	0.5	1.7	1.4	0.5	1.8
1973	0.5	1.7	2.0	0.7	4.1
2002	0.6	1.5	1.7	0.6	4.9
2015	0.6	1.5	2.0	0.9	7.1

0.9 tons of energy carriers and 0.5 t other dissipative use. Only 0.9 t were use as stock building materials in 1900.

3.3. Stocks and net additions to stock

Our analysis has shown that in the 20th century socioeconomic metabolism has changed from a throughput system in which most materials are used shortly after extraction to a system in which materials accumulate in stocks. Currently more than half of all materials are used to build up long living stocks of manufactured capital. In combination with technical energy, these in-use stocks provide essential services such as shelter, mobility, supply and discharge or communication (Haberl et al., 2017; Pauliuk and Müller, 2014). Materials remain in use in stocks for a certain period of time until they are discarded and either become end of life waste or they are reused, remanufactured or re- or downcycled into secondary material inputs. We find that 961 Gt of materials had accumulated in in-use stocks of manufactured capital in 2015 (Fig. 2d). Most of these materials were non-metallic minerals used in construction (concrete, asphalt, bricks, sand and gravel) but also 33 Gt of metals, 15 Gt of wood, 3 Gt of plastics and 3 Gt of glass were employed in in-use stocks. In the last century (and in particular after WWII) stocks of manufactured capital have grown at an exponential rate (by a factor 27), much faster than DE and at a similar pace as GDP. The stock of humans and livestock is very small in comparison to manufactured capital and, therefore, not visible in Fig. 2d. The mass of this stock has grown by a factor of 4 since 1900 to a total of 1.0 Gt in 2015 of which livestock accounted for 61%.

Year to year changes in the size of material stocks are captured by the flow indicator NAS. The exponential growth in stocks of manufactured capital in the last century implies high NAS and indeed this flow has increased tremendously. Around 1900 merely 0.5 Gt of materials were added to the stock of manufactured capital each year, by 2015 this flow had grown more than 69 fold to 31 Gt/yr (Fig.2c). In contrast NAS of humans and livestock were small and increased only three fold from 0.002 Gt/yr in 1900 to 0.006 Gt/yr in 2015. Overall, NAS grew faster than GDP, in particular in the decades after WWII until 1973, a period, when the stock of buildings, infrastructures and machinery rapidly expanded, above all in the industrialized countries. In this period NAS intensity of GDP grew from 0.2 kg/$ in 1945 to 0.7 kg/$ in 1973. Since, it has gone down again and fluctuates around 0.5 kg/$. Non-metallic minerals account for by far the largest part of NAS, but also 1.4 Gt of wood, metals, plastics and other materials were added to in-use stocks per year in 2015, more than double the amount in 2002. Overall NAS have been growing at a rate of 4.0%/yr in the period 2002 to 2015; the decline from 2014 to 2015 is mainly due to a reduction in global cement production.

3.4. Domestic processed outputs

Fig. 2f shows that in 2015 almost 111 Gt/yr of material were returned to the natural environment as DPO, up from 14 Gt/yr in 1900. Only about half of the actual outflow of wastes and emissions originates from DE, the other half stems from oxygen taken up during combustion processes and from water consumed by humans and livestock. DPO* (Fig. 2e) comprises the fraction of DPO originating from DE only; it equals the difference between DE and NAS. With rising material inputs, also the amount of DPO* has increased, but not to the same extent as inputs (Fig. 3). While all materials used in a dissipative way are converted into DPO shortly after extraction, the growing share of materials used to build up stocks of manufactured capital means that an increasing share of materials is returned to the environment with a considerable time lag, often several decades after extraction. While in 1900 wastes and emissions still amounted to 94% of all inflows, this share went down to only 65% in 2015. Between 1900 and 2015 DPO*, therefore, increased only 8 fold from 7 to 58 Gt/yr (Fig. 2e); with the rise in DE after 2002, also the growth rate of DPO* increased and at 3.0%/yr was higher than in previous periods (Table 4). Fig. 3 shows that in 2015 roughly 7.8 t/cap/yr were returned to the natural environment in the form of DPO* (up from 4.4 t/cap/yr in 1900) and 0.9 kg for each $ of GDP (down from 3.5 kg/$/yr in 1900). In 2015 the largest part of DPO* was solid waste (processing and end of life waste) with 35%, followed by emissions (25%) and excrements (13%). Materials that are deliberately applied to natural systems such as seeds or fertilizer minerals amounted to 6.1 Gt/yr or 11% of DPO* in 2015.

3.5. Cumulative flows 1900–2015

The results in Fig. 2 show how global material flows have surged during industrialization. The massive human draw on material resources in this period becomes even more obvious from a cumulative perspective. Since 1900 humanity has extracted a total of 3400 Gt of materials; the Sankey diagram in Fig. 4 traces these flows through the socio-economic system from extraction to use and discard to the environment: 1284 Gt of the extracted materials were biotic materials harvested from the biosphere and 2120 Gt were mined from the lithosphere of which 632 Gt were of fossil origin, the reminder being ores and minerals. Of all these extracted materials 925 Gt are still in use in buildings, infrastructures and other artifacts (NAS), 904 Gt have been used to feed humans and livestock and 713 Gt have been burnt to generate energy. Overall, 2470 Gt or 72% of all materials extracted since 1900 have been returned to the environment as waste and emissions. 1160 Gt have been emitted to the atmosphere of which 515 Gt was water vapor and 643 Gt emissions, mostly carbon (98%). The carbon from fossil fuels and partly also from biomass contributed to rising atmospheric CO_2 concentrations and climate change. Of the 1315 Gt which have been released to terrestrial or aquatic ecosystems, 40% were of biotic origin and degradable and 60% from fossil and mineral materials. These materials have been deposited in controlled or

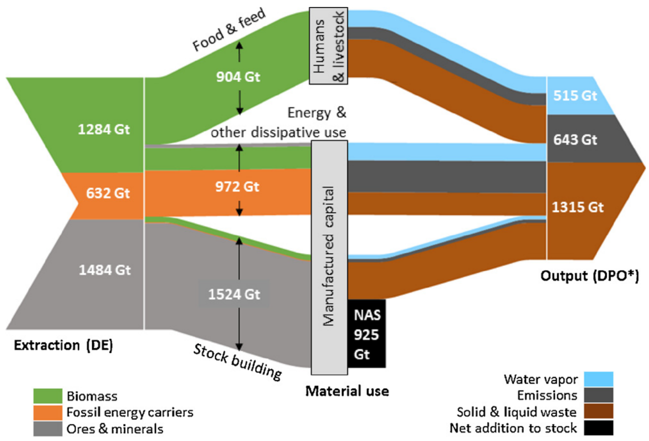

Fig. 4. Sankey diagram showing the cumulative flow of materials through the global economy from extraction to use and output of wastes and emission from 1900 to 2015. Note that NAS of humans and livestock (1 Gt) are not visible.

uncontrolled landfills, emitted to water bodies, have been applied or lost by dissipative use or simply remain in place above- or belowground as abandoned built structures. The size of these flows underlines that humans have become a global geophysical force in the Anthropocene (Steffen et al., 2007).

4. Discussion

4.1. Uncertainty and robustness of results

We have presented a comprehensive account of the global material flows in a long time series up to 2015. Our results are consistent with findings from other MFA studies, which investigated DE for shorter periods and using country level data. A comparison of all available estimates (Fig. S1a) shows that differences in the trend, size and composition of extraction are small. The inclusion of sand and gravel used as subbase and base-course layer increases global DE by 7–12% above previous estimates for 2010 (Fig. S1b), which have so far underestimated the extraction of these materials (Miatto et al., 2016). Overall, due to the high level of methodological standardization and the good quality of statistical data, estimates of global DE and other metabolic flows are considered robust (Fischer-Kowalski et al., 2011). Our uncertainty assessment indicates that global DE could vary by ± 23% in 1900 to ± 16% in 2015; uncertainty is largest for non-metallic minerals and lowest for fossil energy carriers (Fig. S2). Uncertainties for in-use stocks are lower and range from ± 18% to ± 10% as a sensitivity analysis and error propagation through Monte Carlo simulations show (Fig S3). Our results on in-use stocks also agree very well with results from previous studies investigating specific materials (see Krausmann et al., 2017a,b). Uncertainties for waste from discarded stocks decline from ± 20% in 1900 to ± 15% in 2015 (Fig. S4); all other DPO flows, that is, wastes and emissions from food and feed, energy and other dissipative use, are directly derived from input flows using process information and stoichiometry. We therefore assume that uncertainties for these aggregate outflows are in a similar range as for the corresponding DE flows. Crosschecks with results from emission studies have shown that differences are small and range between 1% and 2% for cumulative emissions of CO_2 and SO_2 over the observed period (see SI). Overall we conclude that our results and the discussed trends over time are robust.

4.2. Phases of the global metabolic transition

The long term perspective reveals that different phases in the global metabolic transition can be discerned, periods of fast growth of metabolic rates alternating with periods of slow growth or stable rates (Table 4; Fig. 3). The most recent data on global material flows presented here indicate an acceleration of global material use since the beginning of the 21st century. This acceleration, which took off in 2002, was not a short term phenomenon but continues since more than a decade; only in the last year we find a stagnation of DE. Our results show that the impact of the global financial crisis and the recession in 2008 on global material extraction and use was only moderate and did neither lead to a short term decline in DE nor to a long term deceleration of its growth. A cumulative perspective underlines the significance of the observed acceleration: In the 13 years between 2002 and 2015 alone over 1000 Gt of materials were extracted, that is, almost one third of the total extraction since 1900. Growth was fastest for non-metallic minerals and metals, which relates mainly to the fast expansion of the built environment occurring in China and other emerging economies (Huang et al., 2013; Miatto et al., 2016; Schandl and West, 2010). In contrast, materials used to produce technical energy and in particular fossil energy carriers were growing slower than in the 1950s and 1960s, which may be related to a shift from coal towards oil and gas, improvements in energy efficiency motivated by climate change mitigation and structural change in the economies (Jackson et al., 2017; Voigt et al., 2014). Quite remarkably, also the per capita use of materials used to produce food and feed is on the rise after a long period of slow decline, reflecting mainly a new dynamic in the change of dietary patterns towards a higher consumption of meat in emerging economies (Tilman and Clark, 2014).

The acceleration in global material extraction since 2002 is mirrored in the rise of outputs of wastes and emissions, although the share of DE that is returned to the environment in the form of DPO* has been steadily declining, since an increasing share of DE accumulates in stocks of manufactured capital. Overall, we find that humanity has deposited or emitted the huge amount of 2500 Gt of DPO* to the global environment since 1900 and 28% of this only between 2002 and 2015. The environmental pressure resulting from these wastes and emissions is large and contributes significantly to pushing humanity beyond planetary boundaries of a safe operating space (Steffen et al., 2015). The MFA approach provides a comprehensive perspective on all outflows to the environment. It reveals that emissions from fossil fuels, which are one of the few outflows well documented in the literature (Boden et al., 2009; Smith et al., 2011), currently account for only 15% of DPO*. The outflow of solid waste from construction and demolition, industry and households, for example, amounted to 20 Gt/yr or 35% of DPO* in 2015 and was growing at a particularly fast pace (4.2%/yr) since 2002. The large and growing DPO flows underline the need for absolute reductions of resource inputs, which might be achieved via a more circular economy which reduces wastes and the demand for primary inputs via recycling and improved resource efficiency (Akenji et al., 2016; Ghisellini et al., 2016).

We find that stocks of manufactured capital are of particular significance for the long term dynamics of global material flows. Stock growth constitutes a major challenge for a reduction in the demand for materials, since stocks of manufactured capital have a long service life time and their maintenance and use induces constant flows of materials and energy required to utilize them (Haberl et al., 2017; Pauliuk and Müller, 2014). The rise in stock building materials has resulted in an exponential increase in the size of global stocks of manufactured capital in the last century. Between 2002 and 2015 stock growth has accelerated from 19 to 31 Gt/yr. By 2015 roughly 961 Gt of materials had accumulated in in-use stocks and 40% of the net addition to the global stock of manufactured capital since 1900 occurred in the period between 2002 and 2015. Building and maintaining the growing stocks and above all providing services like shelter, mobility, communication or discharge from them requires large amounts of energy and causes CO_2 emissions (Müller et al., 2013; Pauliuk and Müller, 2014). Due their long lifetime stocks built up today have an impact on future resource demand and can create lock in situations for resource requirements (Lin et al., 2017). Growing stocks impede the closing of material loops since recycling flows cannot match input flows (Haas et al., 2015), but the fast increase in stocks during the last decades also implies that when these stocks reach the end of their lifetime, large amounts of end of life waste will accrue. A previous study using the MISO model has estimated that between 2010 and 2030 up to 240 Gt of waste material from discarded stocks of manufactured capital may become available, almost as much as in the whole 20th century (Krausmann et al., 2017b). This imposes a challenge for waste treatment and may constitute a major pressure for the environment. If appropriate measures are taken, however, these materials could also become available as secondary raw material substituting for primary materials.

The acceleration of growth in material flows has stalled improvements in material intensity of the economy. Per capita material use and outflows of wastes and emissions have been growing at a similar or even higher pace as in the post WWII era, in which industrialization and rising consumption in the industrialized core countries caused the average global metabolic rate to rise (Schaffartzik et al., 2014). The recent growth in the metabolic rate is a result of economic development in the emerging economies and above all in China, while domestic material use in industrialized countries is stable or even declining (Giljum et al., 2014; Schandl et al., 2017). An evaluation of country level DMC data reported by UNEP (2016) shows that China alone accounted for 61% of global gross increase in DMC of 21 Gt/yr between 2002 and 2010, followed by India with 8% and Brazil with 4%. Gross growth of DMC is defined here as the increase in DMC between 2002 and 2010 in 165 countries which exhibited DMC growth in this period. In major high income countries, in contrast, DMC declined, but global gross decline (62 countries) in the same period was much lower than gross increase. It amounted to 2.4 Gt/yr to which the USA contributed 43%, Japan 11% and Italy 9%. In spite of the recent catch up of emerging economies it is important to keep in mind that high income countries still appropriate a disproportionately high share of all materials. In 2010 OECD countries directly used 28% of all global DE; this share even rises to 38% if indirect flows (material footprints) are taken into account (UNEP, 2016). Most low income countries, in contrast, have a very low level of material use per capita paired with very moderate growth rates (Giljum et al., 2014). UNEP (2016) data show that in around 50 countries of the Global South inhabiting a total population of 1.4 billion DMC was below 4 t/cap/yr compared to a global average of 10 t/cap/yr in 2010. Per capita DMC in these countries on average grew by only 0.7%/yr in the period 2002–2010.

4.3. Towards a global convergence of material use patterns?

Our results suggest that the global economy may have entered a new phase in the metabolic transition towards a global convergence of resource use patterns typical for industrialized countries (Krausmann et al., 2008b; Schaffartzik et al., 2014). This raises the question if the period of relative decoupling of economic growth and material use and more or less stable global average metabolic rates in the 1980s and 1990s has come to an end. While such a convergence of metabolic patterns can contribute to rising levels of material wealth in the countries of the Global South, it also has the potential to drive up the global demand for primary materials beyond a safe operating space of material resource use, unless significantly more material and energy efficient ways to provide services from the extracted materials can be established (UNEP, 2017). In order to provide a rough but empirically grounded estimate of what such a global convergence of metabolic patterns paired with a continuation of past trends in efficiency gains might imply for global material demand, we can use the information from our material flow database and build a scenario of the development of global DE until 2050. The comprehensive historical information on global stocks and flows of materials allows to develop stock-driven scenarios based solely on physical data, in which we estimate the size of flows on the basis of the materials and energy required to build up and maintain the physical structures of society and on assumptions about the efficiency with which services are provided from stocks. This distinguishes our approach from the few existing scenarios which simply combined per capita flows and population numbers (UNEP, 2011) or were based on a stock flow model using economic information on capital stocks and flow intensities (Schandl et al., 2016). To estimate the demand for primary materials in 2050 we made the following basic assumptions, which are presented in more detail in Table S8 in the SI:

- Population grows to 9.1 bio by 2050 (medium variant of the United Nations (2015) population projection).
- Food and feed: By 2050 global average per capita food supply converges at the level prevailing in industrialized countries. Extrapolating historic trends since 1961, we assume that the conversion efficiency of primary biomass into plant and animal based food products improves by 12% and 30%, respectively.
- Manufactured capital and stock building materials: By 2050 per capita stock size converges at a level typical for industrialized countries in 2010 (Krausmann et al., 2017b). This enlarges the global in use-use stocks of manufactured capital to 3140 Gt by 2050. Assuming that stock growth follows an exponential trend, unchanged lifetime distribution of stocks and end-of-life recycling rates, this implies an increase in the input of primary and secondary materials for building up new stocks to 106 Gt/yr and for maintenance to 57 Gt/yr until 2050. We further assume that the share of recycled materials in inputs to stock doubles to 20%, that the share of processing and manufacturing losses of primary materials remains constant and that the material composition of inputs to stocks remains unchanged.
- Technical energy carriers: The demand for primary energy carriers is linked to building up and maintaining stocks of manufactured capital and to providing services from them (Pauliuk and Müller, 2014). Based on sectoral energy use data from IEA (2016) we assume that 29% of global final energy consumption is used for building up and maintaining these stocks; 71% are used for providing services from these stocks (e.g., regulation of room temperature, light, mobility, communication, supply and discharge). We assume that trends of efficiency improvements observed between 1971 and 2014 continue until 2050 following a power function. In combination with a shift in the energy mix towards less material (with respect to energy carriers) intensive energy forms (e.g. natural gas, hydropower, photovoltaics) this results in a reduction of energy intensity (final energy per material input or in-use stock) by 41% to 50%.
- Other dissipative use: Growth in the per capita demand for materials for other dissipative use observed in the past decades continues, following a linear trend.

Based on these assumptions we calculated the demand for primary materials to provide food and feed, technical energy, to build up and renew stocks of manufactured capital and for other dissipative use, i.e. of global DE. The results of this global convergence scenario exercise are presented in Fig. 5. While population is expected to increase by 34% from 2015 to 2050, the yearly demand for crops rises by 44% and that for forage by 95%, the extraction of fossil energy carriers increases by 90% and that of stock building materials even by 194%. Overall DE increases by 140% to around 218 Gt/yr in 2050, resulting in a cumulative extraction of 1000 Gt biomass and 4100 Gt fossil and mineral materials in 35 years. Our scenario yields a considerably larger demand for primary materials than previous scenario calculations estimated. A very rough scenario assuming a global convergence of metabolic rates at the level of industrialized countries in the year 2000 distinguishing a high and a low population density trajectory arrived at 140 Gt/yr for 2050 (UNEP, 2011). A more sophisticated business as usual scenario also based on a stock-flow modelling approach, but relying on monetary

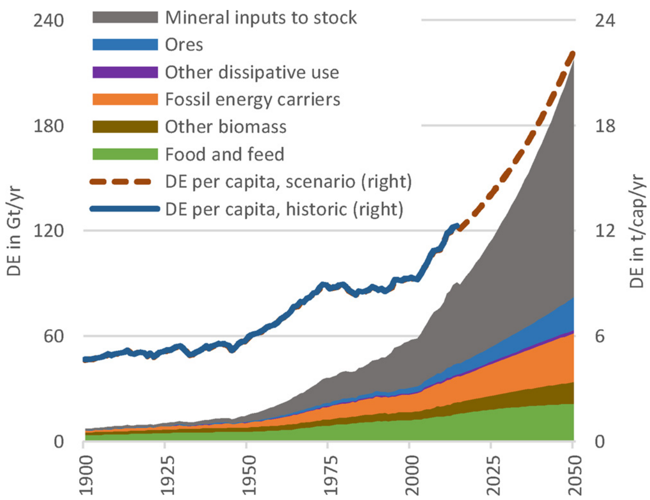

Fig. 5. Global convergence scenario of global material extraction in Gt/yr by main material groups (left axis) and in t/cap/yr (right axis). 1900–2015 historic data, 2016–2050 scenario results. The scenario assumes a convergence of diet patterns and of per capita stocks of manufactured capital at the 2010 level of industrialized countries by 2050, a continuation of past trends in energy and material efficiency and a growth of global population to 9.1 bio.

information on capital stock formation and assumptions on investments and resource intensities of capital stocks estimated global material demand in 2050 at 180 Gt/yr (Schandl et al., 2016).

While the development of DE from 2015 to 2050 in the scenario (Fig. 5) seems like a continuation of historic trends, the scenario is not designed as a business as usual scenario, but assumes considerable change in metabolic dynamics, since it implies that stock growth comes to an abrupt halt in industrialized economies and further accelerates in the Global South. The assumed global convergence in global metabolic patterns results in a 2.4-fold increase of material extraction until 2050. The global metabolic rate doubles to 22 t/cap/yr, which is more than currently observed in most industrialized countries and far beyond the global target corridor of 6–8 t/cap/yr, which has been proposed by the International Resource Panel as a goal for 2050 in order to remain within a safe operating space (IRP, 2014). The largest part of the 218 Gt/yr of primary materials that would be extracted in 2050 is sand, gravel and rock. While these materials have a comparatively low relative impact on the environment, the sheer amount of annual extraction is worrisome, and increasingly caveats are raised concerning local scarcity, environmental and biodiversity impacts and social pressure related to their extraction (Gavriletea, 2017; Torres et al., 2017). Also pressure on global croplands, grasslands and forests would rise considerably by increasing biomass harvest by 66% (Haberl et al., 2007). The annual demand for fossil energy carriers would double; that of metals even triple, exceeding extraction rates considered sustainable (e.g., Henckens et al. (2014)). The outflow of wastes and emissions (DPO*) would double to around 112 Gt/yr, which is considerably less than inputs, due to the massive expansion of stocks of manufactured capital. Krausmann et al. (2017b) have estimated that such a development could drive up cumulative CO_2 emissions by 53% to 542 Gt. This exceeds the remaining global carbon budget assumed to comply with a 50% probability that the 2 °C target can be met by 30–132% (IPCC, 2014). Not only the environmental but also social pressures associated with such a rise in material use are likely to exacerbate (Muradian et al., 2012). Overall, we do not consider this a very feasible scenario, unless the demand for primary materials and output of waste and emissions can be drastically reduced through e.g., ambitious resource efficiency measures, far reaching closing of material loops or increases in the service live-time and more intense use of stocks (Allwood et al., 2011; Hatfield-Dodds et al., 2017; UNEP, 2017). Finally, rather than convergence, as assumed in the scenario, we currently observe increasing inequality in resource use both across (Duro et al., 2018; Hubacek et al., 2017) and within countries (Wiedenhofer et al., 2017). The upward trend in global DE since 2002 results from infrastructure development and rising consumption in a few countries only and large fractions of the global population hardly participate in this development at all (Giljum et al., 2014).

5. Conclusion

During industrialization, humanity has become a geophysical force on a planetary scale. Our data show, how the size of societies metabolism has multiplied since 1900, resulting in a massive draw on material resources from the biosphere and the lithosphere and corresponding outflows of wastes and emissions. We find that biophysical growth has been speeding up significantly since the turn of the 21st century, with growth rates of material flows comparable to the decades after WWII, a period which has been denoted as “Great Acceleration” (Steffen et al., 2007). Roughly one third of all materials that have been extracted or discarded since 1900 have been mobilized between 2002 and 2015 only. This acceleration may be seen as heralding a newly invigorated phase in the global metabolic transition towards an industrial metabolic profile. Such a convergence of metabolic patterns might result in a further doubling of DE and DPO until 2050. Although an agreement of what can be considered a sustainable level of global material extraction is lacking, such a stark rise is clearly beyond a level of below 100 Gt/yr considered as potentially sustainable (Bringezu, 2015). Such an increase also does not comply with urgently needed efforts to phase out fossil fuels in order to mitigate climate change. Our results underline that a sustainable pathway requires urgent action, fostering a continuous and considerable reduction of material flows in industrialized countries, as these countries directly and indirectly still appropriate the largest and a disproportionally high share of key materials extracted globally (Giljum et al., 2014; Schandl et al., 2017). In addition to that, less material intensive provision of essential services in the emerging economies of the Global South, whose economic development is a driving force behind the recent rise in global DE, is required. Incremental change and moderate efficiency gains, such as those achieved in the past, most likely will not be sufficient to absorb the demand for services from material use arising in the Global South (UNEP, 2017).

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